CULLOMPTON EASTERN DISTRIBUTOR ROAD

Design and Calibration Hydrology Report

0007-UA005763-NER-01

MARCH 2017

Incorporating

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Design and Calibration Hydrology Report

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Report No	0007-UA005763-NER-01
Date	MARCH 2017

VERSION CONTROL

Version	Date	Author	Changes
01	16.03.17	LD	Final for Issue

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1 Introduction and Background

1.1 Project Context

Arcadis Consulting (UK) Limited (Arcadis) has been commissioned by Devon County Council to prepare a Flood Risk Assessment (FRA) in support of a planning application for an Eastern Distributor Road (EDR) around Cullompton in Mid Devon. The proposed scheme crosses the floodplain of the River Culm and, to inform the FRA, Arcadis has undertaken detailed hydrological and hydraulic analysis of the River Culm and its tributaries.

The study began in 2013 and, in order to ensure a robust baseline for assessment, the Environment Agency has requested a report which documents all the hydrological analysis carried out on the Culm catchment throughout the duration of the study, starting in 2013. This report has therefore been written to address this requirement and also to document the finalised design flows that have been agreed by the Environment Agency as suitable for taking forward inform the FRA.

Three main stages of assessment have been undertaken to date. Section 1.2 summarises the work undertaken during the first stage of the commission, during 2013, which centred on a review of an existing Environment Agency hydraulic model of the River Culm and initial hydrological analysis to generate updated inflows to this model. The second stage, progressed in 2014, is described in Section 1.3 and involved hydraulic model updates, calibration and baseline runs. The scope of the most recent stage of work, commissioned in 2016, is described in Section 1.4 and the remainder of the report documents the results of and conclusions drawn from the 2016 analysis and the final agreed hydrology.

1.2 Hydraulic Model Review and Hydrological Analysis - 2013

An existing ISIS 1D model, built by Posford Haskoning[1] (Haskoning) on behalf of the Environment Agency in 2002 was supplied in 2013 for use in the study.

The Haskoning ISIS model was reviewed and the findings reported on in 2013 by Arcadis (formerly Hyder Consulting)[2]; this work generated revised inflows to the model using Revitalised Flood Hydrograph (ReFH) boundaries, by applying catchment descriptor based models. Hydrograph peaks were scaled to fit flow frequency estimates provided by the Environment Agency from the Devon Hydrology Strategy (DHS 2013 version). A consistent design storm (14 hour duration), based on the catchment of the River Culm at the downstream model limit (NGR ST 01682 04945), was imposed upon all of the ReFH boundaries. The hydrological schematisation represented in the Haskoning model, and illustrated in Figure 1, was largely retained, with the following exceptions:

- Checks made to sub-catchment boundaries identified the need for updates to two catchments (Ken South (KS1417) and Ken North (KN0889)), that were incorrectly represented in the Flood Estimation Handbook (FEH) CDROM.
- A boundary unit was established for St. Georges Well Stream, a right bank tributary of the Spratford Stream, located between Heron's Bank and St Andrew's Well Stream, which was not modelled by Haskoning. Environment Agency DHS flows were not available so the FEH Statistical method was

[1] Now Royal HaskoningDHV

[2] 5001-UA005763-UU41R-02 Technical note

applied to derive flood frequency estimates due to the highly permeable nature of its catchment. The same method was applied to the St. Andrew's Well Stream sub-catchment.

- To generate design event hydrographs for the Crow Green Stream, the catchment was divided and the modified ReFH method applied in the lower catchment, due to its highly urbanised nature, and the FEH Statistical method applied in the upper catchment.

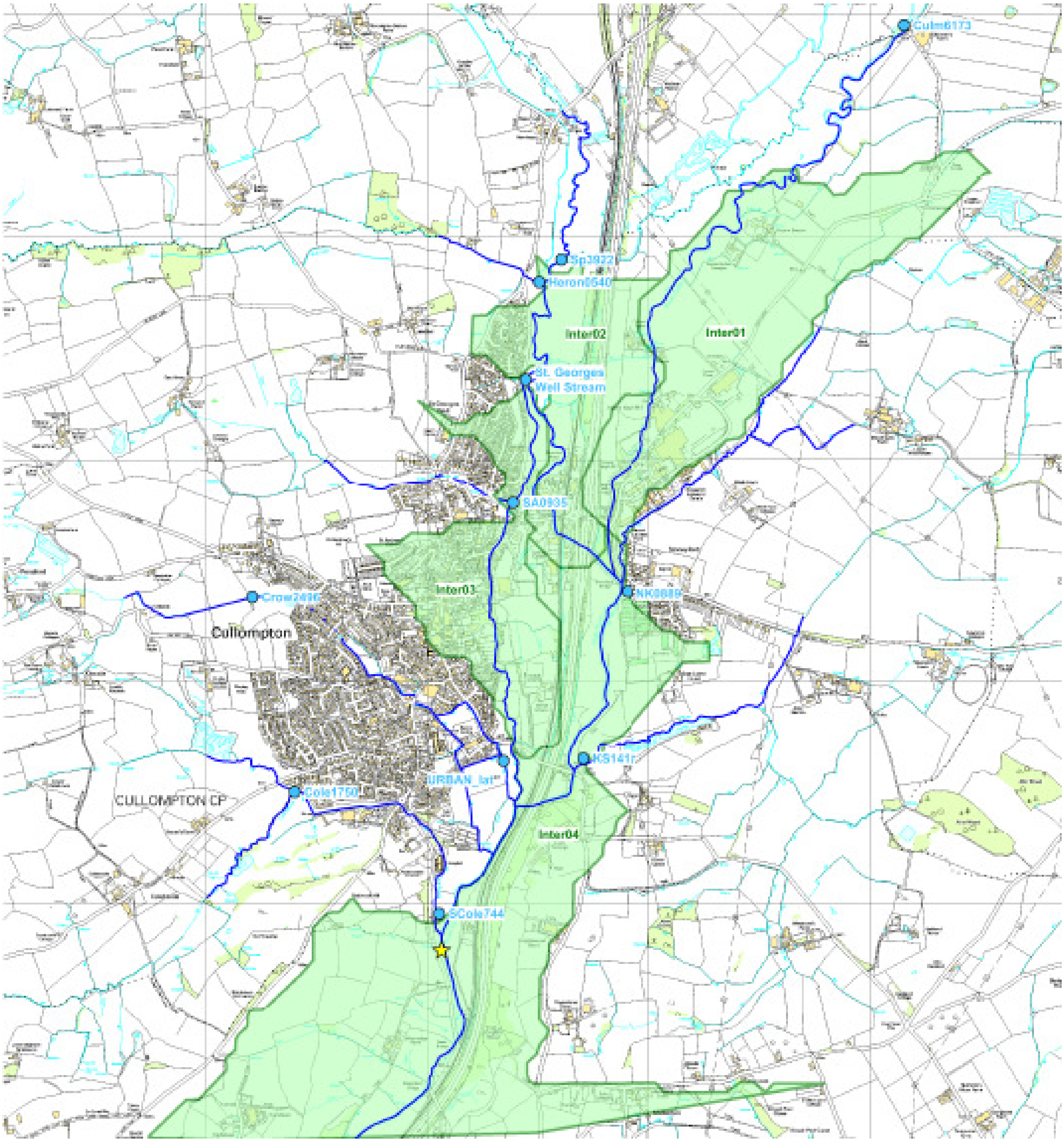


Figure 1 Hydrological schematisation

Legend – yellow star shows location of the Woodmill gauging station; blue dots represent flow estimation points (FEPs) and green shaded areas represent intervening catchments.

1.3 Model Updates and Calibration - 2014

Following the model review a number of updates and refinements to the hydraulic representation of the watercourses were completed, hydraulic model calibration was attempted and baseline model runs were undertaken. Key features of these model updates, which were undertaken during 2014, and the results of and commentary on the baseline model runs are documented in report 5004-UA005763-UU41R-01 - Model Operation Manual.

The gauged flow record from the Woodmill gauge, situated on the River Culm 1km upstream of the downstream model boundary, together with rainfall data from local tipping bucket and storage rain gauges (detailed in Section 3.2), were inspected to identify past flood events suitable for model calibration purposes. Three events were selected: 30 October 2008, 03 January 2012 and 21 November 2012. For each of these events, catchment average event rainfall was derived in accordance with the FSR/FSSR16 method and the hydraulic model was run using the event rainfall. The key results and findings of the calibration runs are summarised in Table 1 and plots of the simulation results are provided in Appendix A.

Table 1 2014 Model Calibration Results Summary

Parameter	Commentary
Time to Peak	For all three calibration events, using un-optimised rainfall-runoff model parameters, there was good agreement between observed and simulated time-to-peak.
Peak Stage/Flow – October 2008	Simulated peak flows 61% less than observed and stage underestimated by 648mm.
Peak Stage/Flow – January 2012	There was very close agreement between observed and simulated peak water level for this in-channel event (simulated +38mm). Simulated peak flow approximately 6 $m^3 s^{-1}$ less than the observed.
Peak Stage/Flow – November 2012	Simulated peak flows 64% less than observed and stage underestimated by 834mm.

Differences in model performance across the 1D and 2D model domains were attributed primarily to the uncalibrated ReFH boundaries, rather than issues with the hydraulic model. In an attempt to better understand the causes of the discrepancies, the hydraulic model was re-run for the two out-of-bank calibration events (October 2008 and November 2012) with the rainfall-runoff model maximum soil moisture capacity (C_{max}) parameter optimised. This resulted in closer agreement between observed and modelled stage during the two events (See Appendix A). However, peak modelled flows were still underestimated when compared to observed flow peaks.

1.4 Key Recommendations of the 2014 Modelling Study and 2016 Scope of Work

Model results suggested that the rating at the Woodmill gauging station overestimated flow for a given stage, the discrepancy increasing with increasing flood magnitude. The Environment Agency also suspected that the Woodmill rating overestimated high flows.

To increase confidence in model outputs and enable the hydraulic model to be used in the future, for purposes other than the Cullompton EDR FRA, the following work was recommended:

- A review of the Woodmill rating, in particular at high flow conditions; and

- Detailed hydrological assessment of the River Culm and its tributaries, including an evaluation of the peak flow estimates from the DHS and hydrological calibration.

These two items of work have since been progressed. A rating review has been undertaken by Capita URS[3] which has revised and extended the station rating to include flows up to 323 m^3/s, which equals the DHS 0.1% Annual Exceedance Probability (AEP) flow for the River Culm at Woodmill.

The remainder of this report documents the findings of a detailed hydrological appraisal of the River Culm and its tributaries, which has been informed by the Woodmill rating review.

[3] Capita URS (May 2015) Operational Flood Forecasting Model Improvements for Devon and Cornwall – Rating Assessment Woodmill

2 Catchment Characteristics

2.1 Catchment Description

The River Culm flows through the Devon Redlands and is the longest tributary of the River Exe. It rises in the Blackdown Hills at a spring near RAF Culmhead in Somerset, and flows west through Hemyock, then Culmstock to Uffculme. The river turns south through Cullompton and flows alongside the M5 motorway, skirting the northern boundary of Killerton Park to join the River Exe on the north-western outskirts of Exeter. In the headwaters, the underlying geology is Greensand and Gault Clay, with predominantly Permo-Triassic sandstones, breccias and marls further downstream, with extensive valley gravels and alluvium. The catchment has a subdued relief and is predominantly agricultural with small areas of woodland in the eastern catchment, and receives an average annual rainfall of approximately 970mm. The largest area of urban development in the catchment is Cullompton.

The hydraulic model of the Culm covers a 7 km stretch of the river, extending from Skinner's Farm in the north (NGR ST 04156 09932) to the vicinity of Highdown in the south (NGR ST 01680 04946; Figure 2). The Spratford Millstream and the lower reaches of Heron's Bank Stream, the St. Georges Well Stream, St. Andrew's Well Stream, Spratford Stream, Crow Green Stream, Cole Brook and the River Ken (North and South), are also represented.

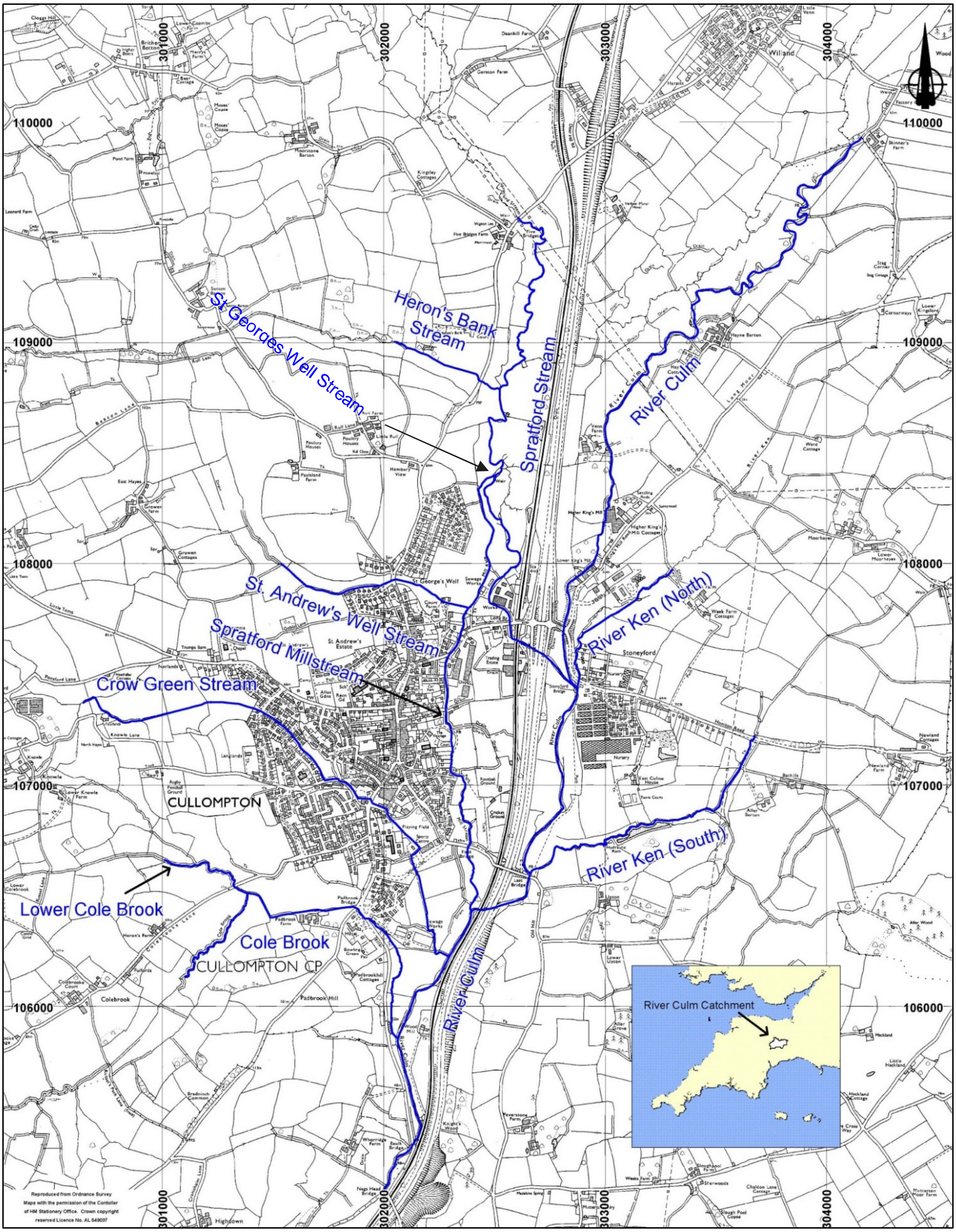


Figure 2 River Culm and tributaries – modelled extents

2.2 Summary of Flow Estimation Points

Table 2 provides a summary of flow estimation points (FEPs) included in the assessment, also illustrated in Figure 1, and their key FEH catchment descriptors, which were extracted from the FEH CD-ROM and verified by checks on the more recently published FEH Web Service[4].

Table 2 Summary of FEPs and catchment descriptors

Model Inflow IED	AREA	URBEXT2000[a]	SAAR	PROPWET	SPRHOST	BFIHOST	DPLBAR	DPSBAR
KS1417	7.42	0.015	914	0.40	29.34	0.565	3.00[c]	32.70
Culm6173	128.15	0.075	1001	0.40	35.69	0.530	14.29[c]	74.11
NK0889	12.13	0.019	929	0.40	28.20	0.629	3.93[c]	72.09
Sp3922	55.57	0.017	938	0.40	24.97	0.633	9.04[c]	61.78
Heron0540	8.47	0.000	956	0.44	21.09	0.764	4.51	79.20
SA0935	1.63	0.051	923	0.40	17.67	0.832	1.51	72.30
Crow2496	2.68	0.008	941	0.44	14.22	0.883	1.46	114.00
Cole1750	2.00	0.002	932	0.42	15.32	0.862	1.69	102.00
SCole744	4.46	0.004	923	0.42	19.04	0.748	2.27[c]	114.30
Inter01	1.16	0.008	897	0.40	35.61	0.635	1.09[c]	5.96[d]
Inter02	0.53	0.063	834	0.40	30.92	0.672	0.71[c]	16.03[d]
Inter03	0.62	0.051	905	0.40	26.27	0.720	0.77[c]	35.33[d]
Inter04	1.94	0.014	871	0.40	29.15	0.608	1.44[c]	114.00[d]
RullLeat	0.77	0.019	923	0.40	19.11	0.814	1.77	86.10

[a] updated to 2016

[c] calculated according to equation 7.1 of the FEH vol. 5

[d] estimated using LiDAR data

A review of FEH catchment boundaries was undertaken as part of the 2016 hydrological review, using LiDAR data and OS contours, with revisions made where necessary, and FEH descriptors describing catchment soils and geology (SPRHOST and BFIHOST) were checked with reference to Sheet 5 of the Soil Survey of England and Wales 1:250k Mapping. Adjustments made to FEH descriptor values are documented in Appendix B.

[4] Centre for Ecology and Hydrology, FEH Web Service accessed via https://fehweb.ceh.ac.uk/

3 Data Review

3.1 Flood History

The River Culm meanders and is prone to flooding in the vicinity of Cullompton, where there is a complex arrangement of channel splits and diversions[5]. The list below details some flood events that have taken place in recent history:

- 17/11/1980 North Farm estate flooded. Estimated that 40 properties flooded
- 24/05/1989 Approximately 10 properties flooded
- 07/08/1997 Estimated 30 properties affected by flooding
- 01/01/1999 Several houses flooded on the Kingswood estate
- 30/10/2000 Road and railway flooded, property numbers unknown
- 07/12/2000 At least one property flooded
- 15/10/2002 At least one property flooded
- 29/10/2008 Land flooded, no properties believed to have been affected

A flood event that peaked on Wednesday 21 November 2012, caused by heavy rain falling onto already saturated ground, saw the highest recorded river levels in the Culm since 1962. The main areas affected by the flood event were the Alexandria Industrial Estate, Rivermead, Pound Square, Duke Street and Meadow Lane as the River Culm overtopped a localised stretch of the earth embankment, water backed up through drains and the capacity of culverts was exceeded. Forty-seven properties were impacted.

3.2 Hydrometric Data

3.2.1 Rainfall Data

A network of rain gauges is located within and neighbouring the River Culm catchment, including tipping bucket rain gauges at Clayhanger, Craze Lowman, Culmstock, Dunkeswell, Hemyock and Tiverton and storage rain gauges at Hemyock Marl Pit, Dunkeswell Aerodrome, Sampford Peverell and Clayhanger. The Environment Agency supplied records of data from these gauges for use in the hydrological assessment. Further information about the location of these gauges and the data record lengths provided by each gauge is provided in Appendix C.

3.2.2 Flow/Level Data

The tributaries of the River Culm that are included in this assessment are not routinely gauged for water level or flow.

Along the River Culm there is an Environment Agency operated gauge at Woodmill (Station No. 45003) 1km upstream of the model downstream boundary, where the river drains a catchment area of approximately 226km^2. The station comprises a shallow V weir that was built in 1972 to replace a velocity-area section with cableway that had been in operation since 1962.

As discussed in Section 1.3, due to concerns over high flow performance, the gauge has been re-rated following a study by Capita URS[3] and an updated Annual Maxima (AMAX) flow peak data set[6] was supplied by the Environment Agency to inform this analysis. The AMAX data series are provided in Appendix D.

[5] Devon County Council (2013) Devon Floods 21st-25th November 2012 Flood Incident Report

[6] 2016 Woodmill updated AMAX for A Emblin.xls; supplied by R Stroud by email – 1/12/16

3.2.3 Devon Hydrology Strategy

The DHS, developed by Haskoning in 2007[7], is a method of flow estimation that takes into account regional equations for different parts of Devon. Where available, for each FEP, peak flows from the most appropriate DHS model node were supplied by the Environment Agency. It is noted that these represent flow estimates for lumped catchments draining to each DHS model node and that the flow estimates generated are applicable to catchment critical storm durations for that lumped catchment. As a result of this approach, during earlier stages of this commission inconsistencies in DHS flow estimates at confluences were noted, as illustrated in Figure 3. When DHS inflows were routed through the hydraulic model, the routed design flows arriving at the Woodmill gauge were concluded to be conservative, and are greater than the DHS flow from the model node representing the lumped catchment of the River Culm to the gauge location.

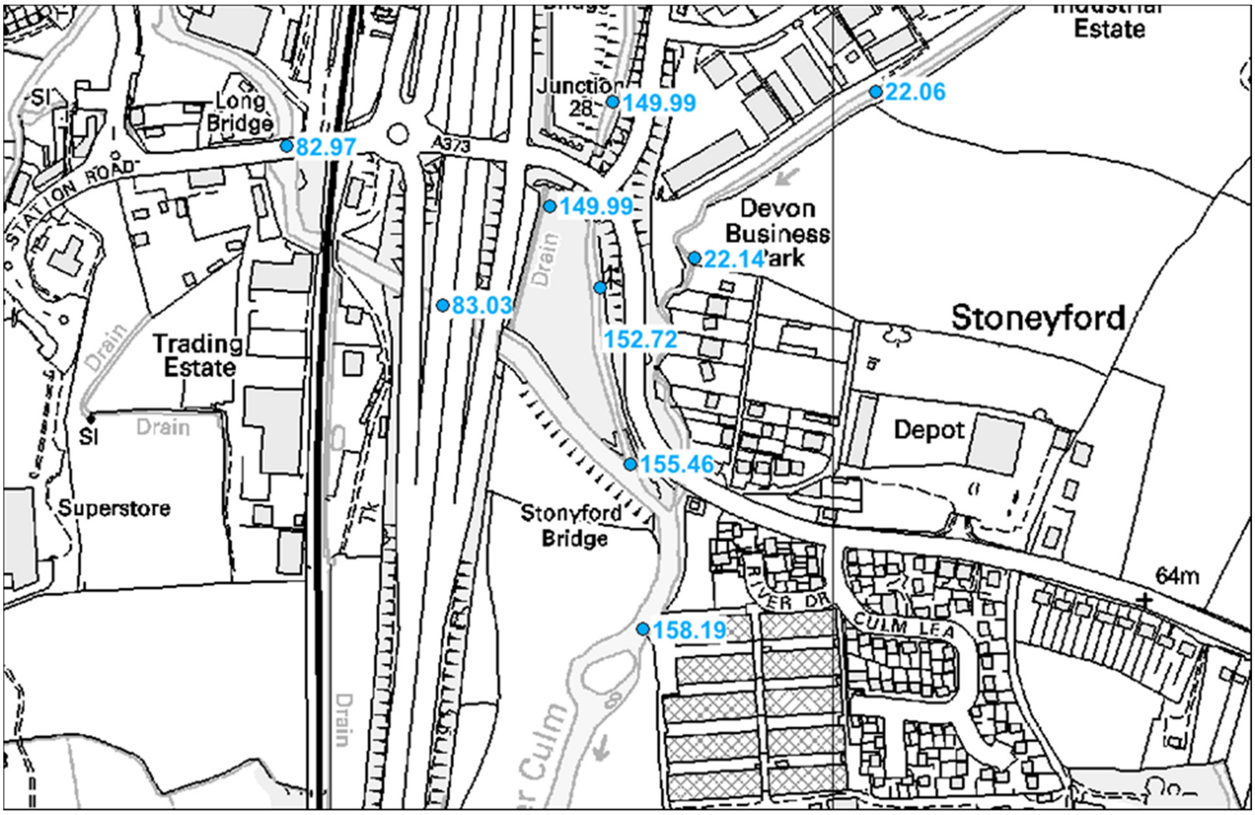


Figure 3 Example - inconsistencies in DHS peak flow estimates (m³/s) at confluences

(N.B flow values shown are for the 2% AEP event)

This map is reproduced from Ordnance Survey material with the permission of Ordnance Survey on behalf of Her Majesty's Stationery Office © Crown Copyright. Devon County Council. 100019783. [2014]

[7] Haskoning, 2007. *Devon Flood Hydrology Strategy*. Report on additional analyses. Report to Environment Agency South West Region.

4 Assessment Methodology

4.1 Design Flow Estimation

Comparative design flow estimates have been derived using both FEH Statistical and ReFH methods. The analysis has been informed by available hydrometric data records. Peak flows, generated for the 50%, 2%, 1%, 1% plus climate change and 0.1% AEP events, have been compared with DHS flow estimates at appropriate nodes.

4.2 Calibration Hydrology

Fluvial inflows for two of the largest magnitude flood events in recent history (October 2008 and November 2012) have been derived and routed through the hydraulic model. Event inflows were modelled using ReFH, with an event specific value of C_{ini}, describing soil wetness at the start of a rainstorm event. C_{ini} was calculated by the ReFH model from a catchment average antecedent rainfall data series derived using records of rainfall data recorded by the storage rain gauge network. The ReFH model also included user defined values of C_{max}. These values were defined on the basis of a flood event analysis undertaken for the lumped catchment draining to the Woodmill gauge.

5 Design Flow Results 2016

5.1 FEH Statistical Method

5.1.1 Qmed Estimation

Estimates of design flood flow peaks have been made using the FEH Statistical method at all flow estimation points (FEPs) detailed in Table 2. Following a search for appropriate donor gauges (within a centroid distance of less than 35km) using WINFAP FEH, the Woodmill gauge was selected as a donor to inform estimation of the median annual flood flow (QMED) at all FEPs. This choice was made on the basis of geographical proximity and data quality, whilst noting that the majority of the FEPs drain catchments that are significantly smaller and some of which are more permeable than the donor catchment.

QMED at the donor gauge was calculated from both FEH catchment descriptors and from the AMAX data series, as summarised in Table 3. The full AMAX data series is reproduced in Appendix D.

Table 3 Donor station Qmed data

NRFA No.	Method	Period of Record	QMED from flow data (A)*	QMED from catchment descriptors**	Adjustment Ratio (A/B)
45003	AM	1962-2016	71.25m^3/s	43.32m^3/s	1.64

**Excluding incomplete water years **Urban adjusted to 2016*

Recent re-rating of the Woodmill gauge, the results of which were supplied by the Environment Agency in November 2016, has resulted in a reduction in the magnitude of QMED estimated from the observed flood peak data series, from 72.46m^3/s (NRFA Peak Flows Data database) to 71.25m^3/s. It is also noted that the FEH catchment descriptor equation appears to significantly underestimate QMED for the subject catchment.

Geographically moderated donor adjustment factors were then calculated for each FEP and a summary of the results is presented in Table 4.

Table 4 Summary of QMED Estimates

FEP	Method	Initial QMED* (m^3/s)	NRFA No. of Donor Site Used	Distance between centroids (km)	Power term, a	Moderated QMED adjustment factor (A/B)[a]	Final QMED estimate (m^3/s)**
KS1417	DT	2.14	45003	3.84	0.51	1.29	2.88
Culm6173	DT	32.67	45003	4.65	0.48	1.26	42.62
NK0889	DT	2.73	45003	5.66	0.45	1.25	2.84
Sp3922	DT	9.89	45003	7.80	0.41	1.22	12.73
Heron0540	DT	1.20	45003	10.42	0.38	1.21	1.46
SA0935	DT	0.20	45003	8.54	0.40	1.22	0.31
Crow2496	DT	0.20	45003	10.16	0.38	1.21	0.26
Cole1750	DT	0.19	45003	10.27	0.38	1.21	0.23
SCole744	DT	0.70	45003	11.33	0.37	1.20	0.86

FEP	Method	Initial QMED* (m^3/s)	NRFA No. of Donor Site Used	Distance between centroids (km)	Power term, a	Moderated QMED adjustment factor (A/B)[a]	Final QMED estimate (m^3/s)**
Inter01	DT	0.33	45003	4.46	0.48	1.27	0.43
Inter02	DT	0.13	45003	4.83	0.47	1.26	0.19
Inter03	DT	0.14	45003	8.54	0.40	1.22	1.24
Inter04	DT	0.53	45003	0.04	0.99	1.63	0.92
RullLeat	DT	0.11	45003	8.06	0.40	1.22	0.15

**QMED Rural   **Urban adjusted to 2016*

Table 4 demonstrates that the effect of adopting the Woodmill gauge as a donor is to increase the catchment descriptor estimates of QMED at FEPs by approximately 20 to 30%, with the exception of Inter04 where catchment centroid distance is very small and the moderated adjustment factor is therefore significantly larger.

5.1.2 Pooling Group Composition and Flood Growth Curves

A number of pooling groups were formed, using WINFAP FEH v3, to generate flood growth curves for the catchments draining to the subject FEPs. Initially, default pooling groups were generated for each FEP and the composition of each pooling group was compared. Where pooling groups shared similarities in terms of the gauging stations included and the weighting given to these stations, subject sites were grouped and a common pooling group was applied to the FEPs in that group.

The outcome was the generation and detailed review of four pooling groups. The decisions taken during pooling group reviews are provided in Tables 5 to 8 and growth curves are compared in Figures 3 to 6. Final pooling group compositions are provided in Appendix E.

Table 5 Pooling Group 1

Name of group	Site code from whose descriptors the group was derived	Changes made to the default pooling group	Weighted average L-moments, L-CV and L-skew (before urban adjustment)
Pool 1	Cole1750	The default pooling group contains 17 stations and 515 station years. It is heterogeneous and the WINFAP-FEH software reports that a review of the pooling group is desirable. The group does not include Culm @ Woodmill. The following changes were made: **49006 Camel @ Camelford** – removed as station rating needs revision as gaugings show significant deviations which may account for the discordancy of the station. In addition, there is a short record of only 6 years of data. To investigate the effect of including the Culm at Woodmill data series **Station 45003 Culm @ Woodmill** was added and **91802 Allt Leachdach @ Intake** was removed (as HiFlows advises Use with caution). The adopted pooling group contained 16 stations and 529 station years. The pooling group is possibly Heterogeneous (H2=1.9675) with a review optional. Flood growth curves, fit to the recommended GL distribution, from the default and revised pooling groups are compared in Figure 3.	Default: L:CV: 0.234 L-SKEW: 0.238 Adopted: L:CV: 0.244 L-SKEW: 0.245

Note: also applied to FEPs SCole744, HERON0540, SA0935, CROW2496, RULLEAT and the four FEPs representing intervening areas

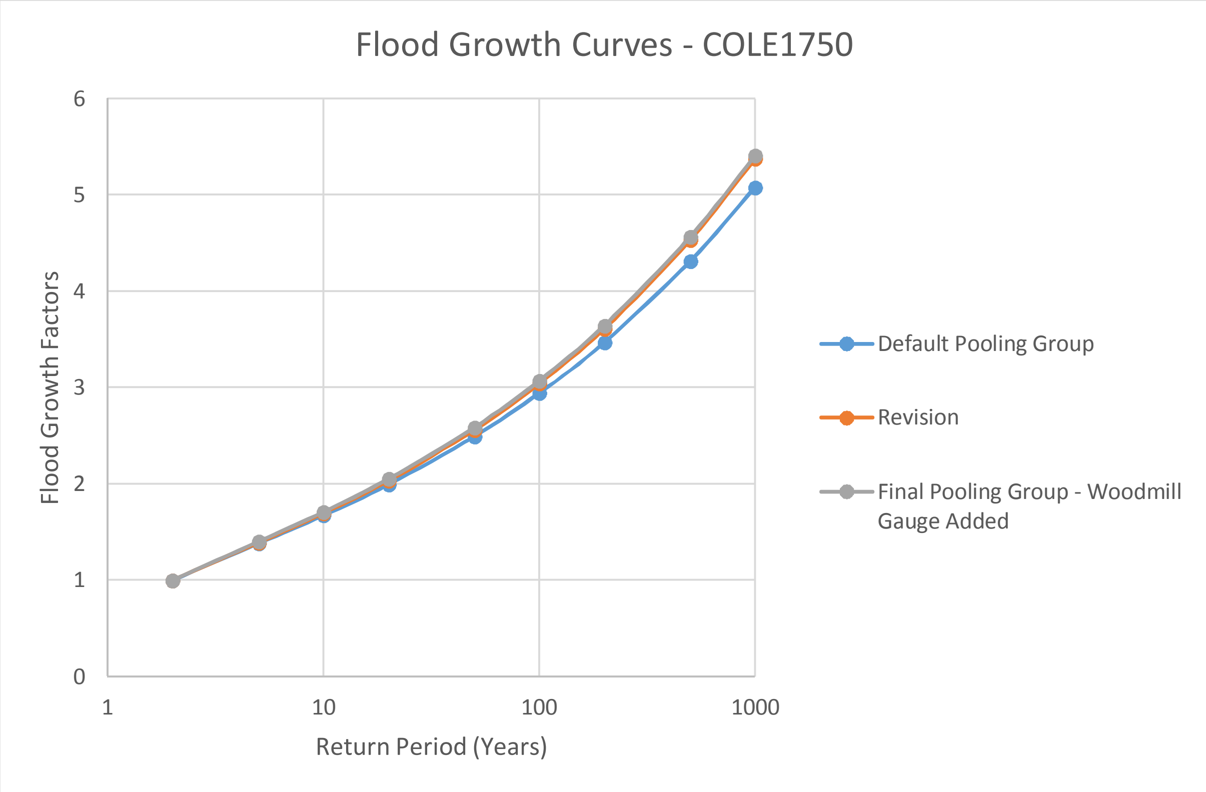


Figure 4 Comparison of flood growth curves - Pool 1

The comparison shows that revisions to the default pooling group, including the addition of the Culm at Woodmill data series has a small effect of steepening the flood growth curve, increasing the 1% AEP growth factor applied at FEP Cole1750 from 2.94 to 3.07. Following urban adjustment, the final pooling group (with the Culm @ Woodmill Gauge added) has a 1% AEP flood growth factor of 3.04.

Table 6 Pooling Group 2

Name of group	Site code from whose descriptors the group was derived	Changes made to the default pooling group	Weighted average L-moments, L-CV and L-skew (before urban adjustment)
Pool 2	SP3922	The default pooling group contains 14 stations and 500 station years. It is heterogeneous and the WINFAP-FEH software reports that a review of the pooling group is desirable. The group does not include Culm @ Woodmill. The following changes were made: **53017 Boyd @ Bitton** – removed as few high flow gaugings have been collected so therefore rating is unconfirmed. **42008 Cheriton Stream @ Sewards Bridge** – removed as drowns out at high flows due to downstream high levels.	Default: L-CV: 0.235 L-SKEW: 0.223 Adopted: L-CV: 0.235 L-SKEW: 0.197

Name of group	Site code from whose descriptors the group was derived	Changes made to the default pooling group	Weighted average L-moments, L-CV and L-skew (before urban adjustment)
		Two stations **203043 Oonawater @ Shanmoy, 84009 Nethan @ Kirkmuirhill** added to maintain the required number of station years. To investigate the effect of including the Culm at Woodmill data series **Station 45003 Culm @ Woodmill** was added and **48012 Fal @ Trenowth** was removed. The adopted pooling group contained 14 stations and 520 station years. The pooling group is possibly heterogeneous (H2=1.7310) with a review optional. Flood growth curves, fit to the recommended GL distribution, from the default and revised pooling groups are compared in Figure 4.	

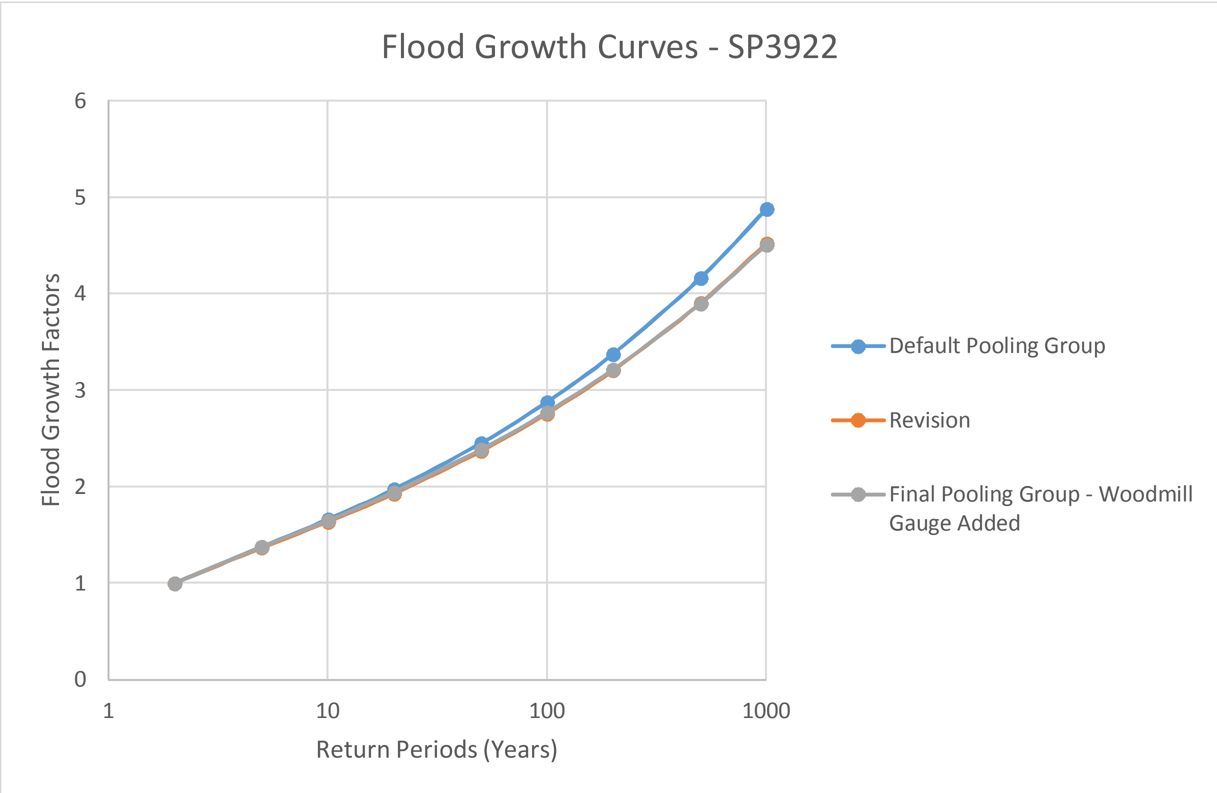


Figure 5 Comparison of flood growth curves - Pool 2

The comparison shows that revisions to the default pooling group, including the addition of the Culm at Woodmill data series, has a small effect of flattening the flood growth curve, reducing the 1% AEP growth factor applied at FEP SP3922 from 2.88 to 2.77 (following adjustment for urbanisation in WINFAP).

The third pooling group was formed for the FEP Culm6173, as detailed in Table 7.

Table 7 Pooling Group 3

Name of group	Site code from whose descriptors the group was derived	Changes made to the default pooling group	Weighted average L-moments, L-CV and L-skew (before urban adjustment)
Pool 3	Culm6173	The default pooling group contains 15 stations and 510 station years. It is heterogeneous and the WINFAP-FEH software reports that a review of the pooling group is essential. The group does not include Culm @ Woodmill. The following changes were made: **23002 Derwent @ Eddys Bridge** – removed owing to heavy reservoir influence **44014 Piddle @ Briantspuddle** – removed as drowning out is an issue at this station, in addition to an unstable bed. **27055 Rye @ Broadway Foot** – removed as this station should be treated with caution. **21024 Jed Water @ Jedburgh** – removed as bypassing occurs at this station. **27056 Skell @ Alma Weir** – removed as overtopping occurs at this station. **8011 Livet @ Minmore** – removed as bypassing occurs at this station. **68018 Dane @ Congleton Park** – removed owing to discordancy. The following sites were added, based on the WINFAP distance weighting and suitability of the station characteristics: 201007 Burn Dennet @ Burndennet 28023 Wye @ Ashford 28061 Churnet @ Basford Bridge 21024 Jed Water @ Jedburgh To investigate the effect of including the Culm at Woodmill data series **Station 45003 Culm @ Woodmill** was added. The modified pooling group contains 13 stations and 513 station years. The pooling group is acceptably homogeneous (H2=0.8663) and a review of the pooling group is not required. Flood growth curves, fit to the recommended GL distribution, from the default and revised pooling groups are compared in Figure 5.	Default: L-CV: 0.207 L-SKEW: 0.196 Adopted: L-CV: 0.215 L-SKEW: 0.17

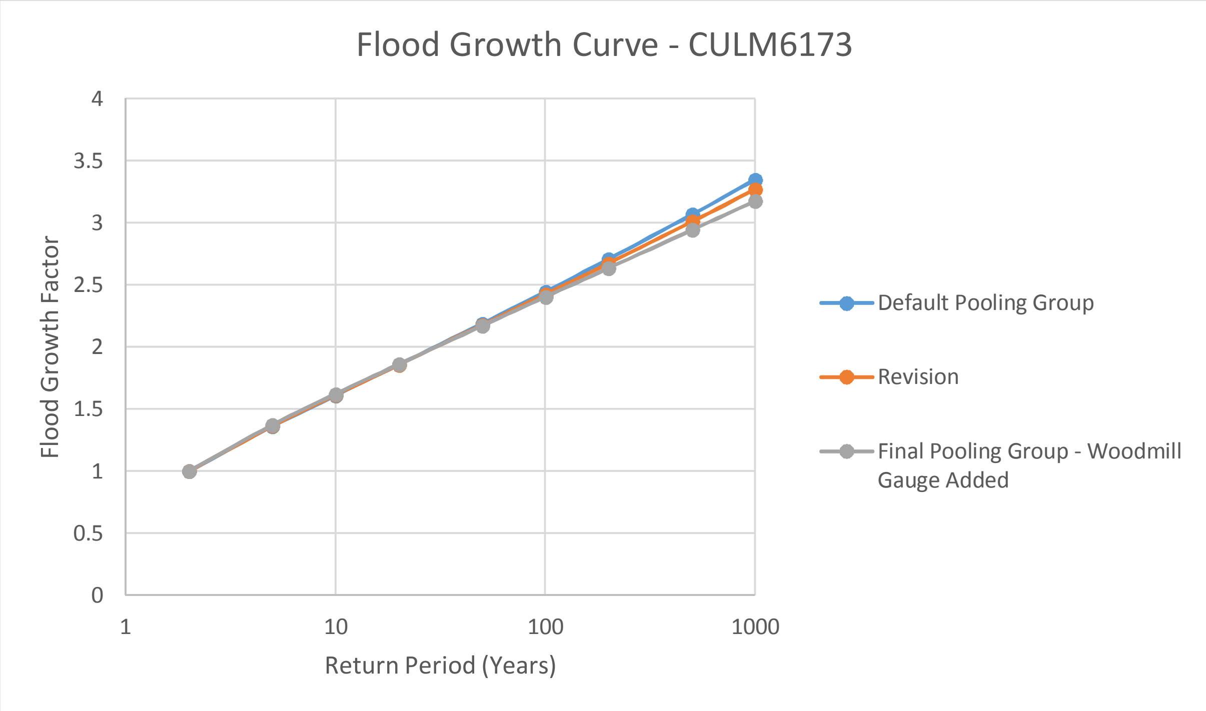


Figure 6 Comparison of flood growth curves - Pool 3

The comparison shows that changes to the default pooling group have made very little difference to the flood growth curve at the higher flood frequencies but there is a flattening of the curve at return periods beyond the 50 year. The 1% AEP growth factor applied at FEP Culm6173 reduces from 2.45 to 2.40 (following urban adjustment in WINFAP) as a result of the pooling group review.

Details of the fourth pooling group generated and reviewed are provided in Table 8. This group was formed on the basis of KS1417 and was also applied to FEP NK0889.

Table 8 Pooling Group 4

Name of group	Site code from whose descriptors the group was derived	Changes made to the default pooling group	Weighted average L-moments, L-CV and L-skew (before urban adjustment)
Pool 4	KS1417	The default pooling group contains 18 stations and 533 station years. It is possibly heterogeneous (H2=1.9619) and the WINFAP-FEP software reports that a review of the pooling group is optional. The group does not include Culm @ Woodmill. The following changes were made: **49006 Camel @ Camelford** – removed as station rating needs revision as gaugings show significant deviations which may account for the discordancy of the station. In addition, there is a short record of only 6 years of data. **48009 St Neot @ Craigshill Wood** – removed owing to discordancy linked to reservoir influence.	Default L-CV: 0.230 L-SKEW: 0.220 Adopted L-CV: 0.255 L-SKEW: 0.251

Name of group	Site code from whose descriptors the group was derived	Changes made to the default pooling group	Weighted average L-moments, L-CV and L-skew (before urban adjustment)
		To investigate the effect of including the Culm at Woodmill data series **Station 45003 Culm @ Woodmill** was added. The modified pooling group contains 17 stations and 569 station years. The pooling group is possibly heterogeneous (H2=1.4088) and a review is optional. Flood growth curves, fit to the recommended GL distribution, from the default and revised pooling groups are compared in Figure 6.	

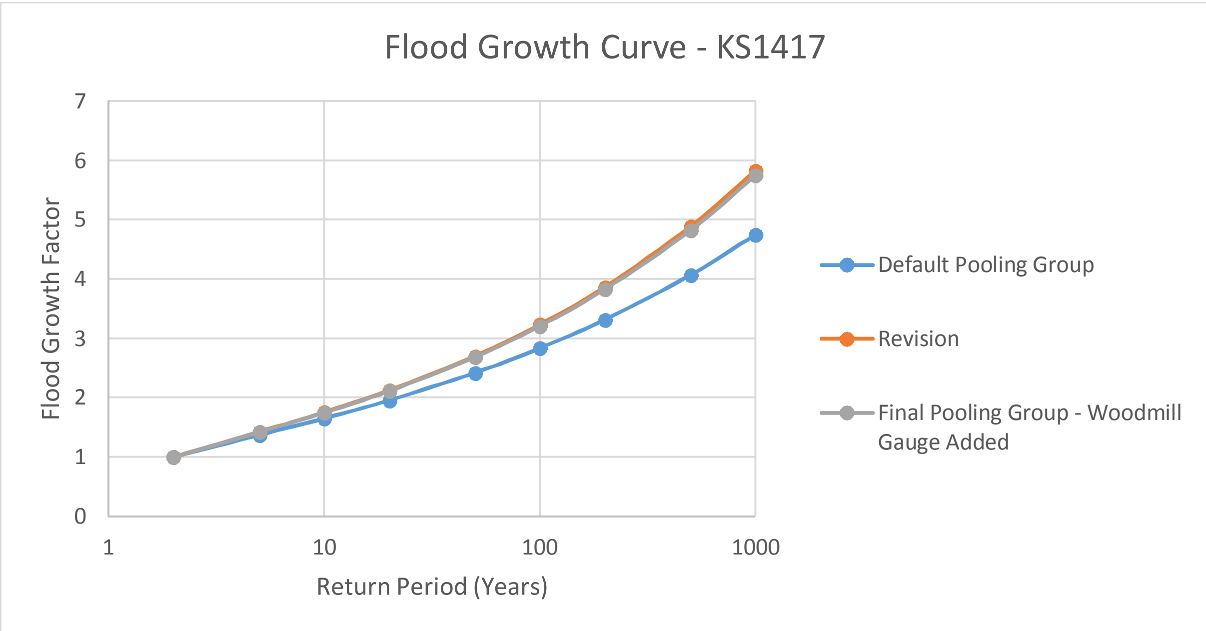


Figure 7 Comparison of flood growth curves - Pool 4

The comparison shows that inclusion of the Woodmill data series has an effect of steepening the flood growth curve, increasing the 1% AEP growth factor applied at FEP KS1417 (following urban adjustment) from 2.84 to 3.21.

Revisions to the default pooling groups formed used WINFAP FEH, including addition of the River Culm at Woodmill flood peak data series in two cases (Pool 1 and Pool 4) results in steeper growth curves that will produce higher design flow estimates. In one case (Pool 3) the revisions have only a very minor effect on the default growth curve and in the case of Pooling group 2 the revised growth curve is less steep.

5.1.3 Single Site Analysis at Woodmill

In order to contextualise the design flow estimates once they are routed through the hydraulic model, hydrological analysis of the lumped catchment of the Culm draining to the gauge has also been undertaken. QMED was calculated directly from the observed AMAX data record (excluding incomplete water years) supplied by the EA, following re-rating of the station in November 2016, and is equal to 71.25m^3/s.

Flood growth curves were then derived using single site (SS) and enhanced single site (Enh SS) analysis in WINFAP FEH (Figure 8).

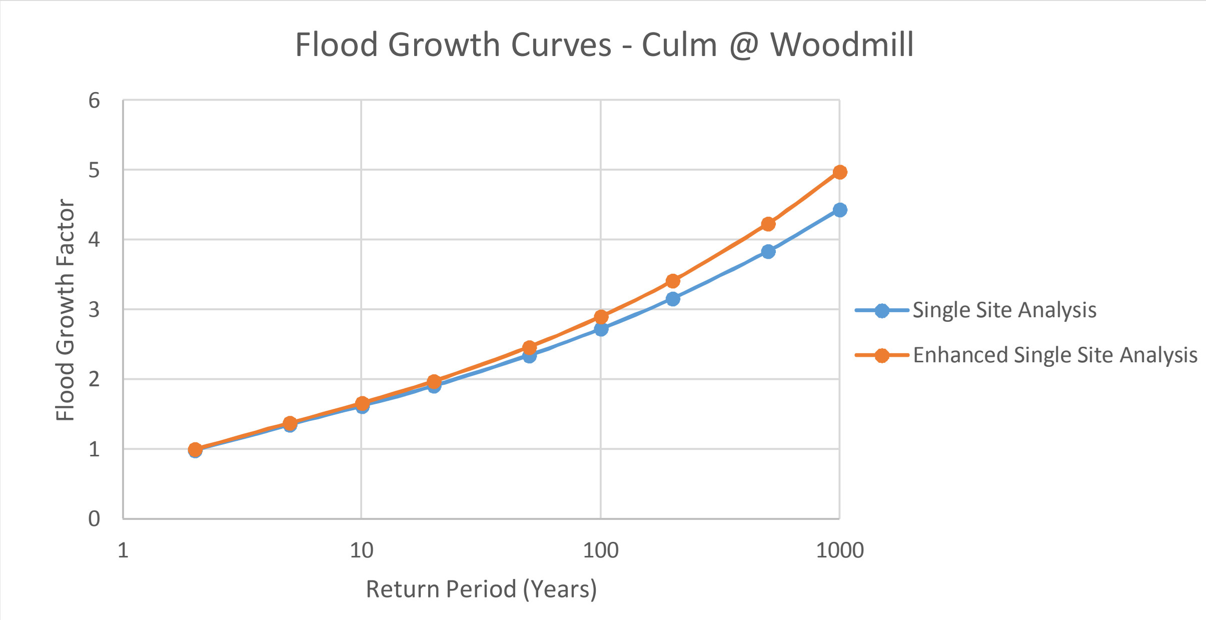


Figure 8 Flood growth curves - Culm at Woodmill

The growth curve produced from enhanced single site analysis is steeper than the curve produced from single site analysis at all return periods, with divergence increasing beyond the 1 in 25 year return period (4% AEP). The Woodmill gauge provides a 55 year long record. In line with FEH guidelines confidence is highest in a single site growth curve where the gauged record length is greater than twice the target return period. In this case, therefore, at return periods exceeding approximately the 1 in 30 year (3.33% AEP) there is diminishing confidence in the single site growth curve.

In order to make best use of the available data, a hybrid curve has therefore been developed, using the average ratio of SS to Enh SS growth factors at the 5 to 10 year return period (0.98). This adjustment factor has been used to scale growth factors developed from the enhanced single site analysis at return periods exceeding the 1 in 25 year (4% AEP). Table 9 compares the flow estimates derived from the three flood growth curves. The table also reports DHS flow estimates for the lumped catchment of the Culm for comparison.

Table 9 Comparison of design flows for the lumped catchment of the River Culm at Woodmill

Return Period (AEP)	Enh. SS Flood Growth Factor	Enh. SS Flow Estimate (m^3/s)	SS Flood Growth Factor	SS Flow Estimate (m^3/s)	Hybrid Flood Growth Factor	Hybrid Flow Estimate (m^3/s)	DHS Flow (m^3/s)
2 (50%)	1.00	71.25	1.00	71.25	1.00	71.25	73
10 (10%)	1.66	118.26	1.62	115.41	1.62	115.41	131
20 (5%)	1.98	141.06	1.91	136.07	1.91	136.07	-
50 (2%)	2.47	175.96	2.35	167.41	2.42	172.40	191
100 (1%)	2.90	206.60	2.73	194.49	2.84	202.32	218
1000 (0.1%)	4.98	354.78	4.44	316.31	4.88	347.65	323

SS and Enh. SS analysis produce lower flow estimates than the DHS, at all return periods up to and including the 100 year (1% AEP event), with these methods producing higher flow estimates at the 1000 year return period (0.1% AEP event).

5.1.4 FEH Statistical Design Flows Summary

The design flow estimates from the FEH Statistical analysis are presented in Table 10.

Table 10 Peak flows from the FEH Statistical method

FEP	50% AEP Flow (m^3/s)	10% AEP Flow (m^3/s)	5% AEP Flow (m^3/s)	2% AEP Flow (m^3/s)	1% AEP Flow (m^3/s)	0.1% AEP Flow (m^3/s)
KS1417	2.88	5.10	6.25	8.07	9.77	18.47
Culm6173	42.6	69.2	79.4	92.6	102.5	135.4
NK0889	2.84	5.00	6.10	7.87	9.51	17.95
Sp3922	12.7	20.9	24.8	30.4	35.3	57.4
Heron0540	1.46	2.50	2.90	3.79	4.49	7.91
SA0935	0.31	0.48	0.54	0.67	0.78	1.31
Crow2496	0.26	0.44	0.50	0.65	0.77	1.34
Cole1750	0.23	0.40	0.46	0.60	0.71	1.25
SCole744	0.86	1.46	1.69	2.20	2.61	4.58
Inter01	0.43	0.73	0.85	1.11	1.31	2.31
Inter02	0.19	0.30	0.35	0.44	0.52	0.89
Inter03	0.20	0.32	0.37	0.47	0.55	0.95
Inter04	0.92	1.56	1.80	2.33	2.77	4.85
RullLeat	0.15	0.25	0.29	0.37	0.44	0.76

5.1.5 Hydrograph Shape

Analysis has also been undertaken in an attempt to improve upon design hydrograph shape to apply to the FEH Statistical method, with the following two methods applied:

- Analysis of the Woodmill gauged data record to identify a typical/average hydrograph shape.
- ReFH flood event analysis, using gauged rainfall and river flow data recorded during a series of historical events to improve upon the catchment descriptor based estimate of C_{max}.

The ‘ReFH catchment descriptors’, ‘ReFH C_{max} optimised’ and ‘Woodmill average’ 1% AEP hydrographs are presented for comparison in Figure 8. The hydrographs are all fitted to the FEH Statistical design peak flow and are representative of the catchment draining to CULM6173.

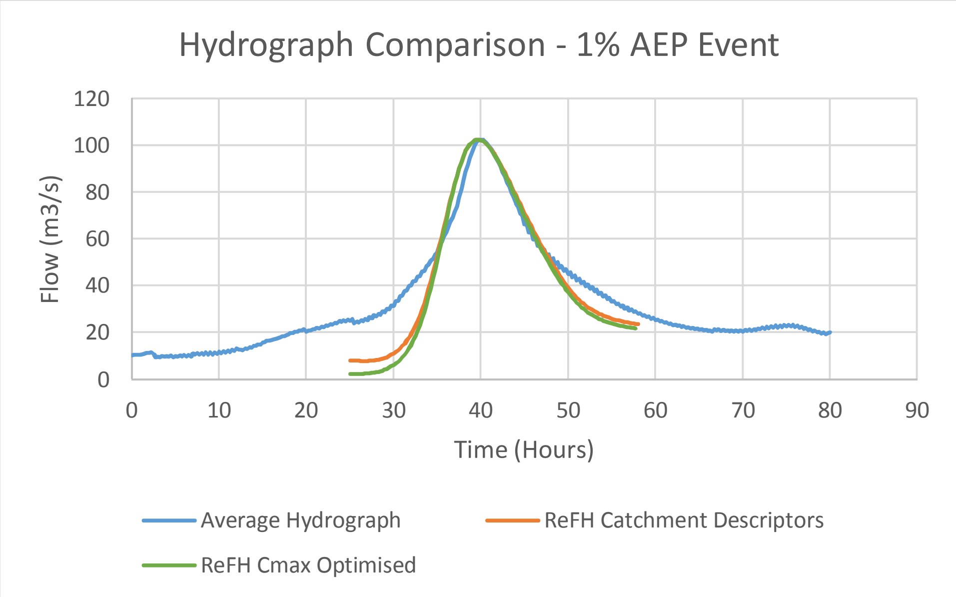


Figure 9 Hydrograph shape comparison

As illustrated, the hydrographs generated by the three different methods share a similar shape around the event peak. However, the hydrograph produced by analysis of the Woodmill gauged record suggests a larger baseflow component and less steep rising and recession limbs, resulting in overall a larger event flow volume. On the basis that the Woodmill average hydrograph shape represents a larger event volume for a given peak flow, it was recommended that this hydrograph shape was adopted for use in producing the design flow hydrograph suite.

5.2 ReFH Method

5.2.1 Catchment Descriptor Models

ReFH models, informed by catchment descriptors, were applied using ReFH boundary units in the Flood Modeller Pro software package. This method was applied in only those catchments that are not deemed as permeable (i.e. BFIHOST < 0.65) or urbanised in line with best practice guidelines[8]. The results are reported in Table 11.

Table 11 Peak flows from the ReFH catchment descriptor models

FEP	50% AEP Flow (m^3/s)	10% AEP Flow (m^3/s)	5% AEP Flow (m^3/s)	2% AEP Flow (m^3/s)	1% AEP Flow (m^3/s)	0.1% AEP Flow (m^3/s)
KS1417	2.99 (*2.88*)	4.51 (*5.10*)	5.19 (*6.25*)	6.25 (*8.07*)	7.21 (*9.77*)	12.64 (*18.47*)
Culm6173	36.5 (*42.6*)	54.0 (*69.2*)	61.9 (*79.4*)	74.0 (*92.6*)	84.9 (*102.5*)	145.8 (*135.4*)
NK0889	3.44 (*2.84*)	5.10 (*5.00*)	5.97 (*6.10*)	7.10 (*7.87*)	8.28 (*9.51*)	14.47 (*17.95*)
Sp3922	11.7 (*12.7*)	17.3 (*20.9*)	19.8 (*24.8*)	23.6 (*30.4*)	27.0 (*35.3*)	46.1 (*57.4*)
Inter01	0.38 (*0.43*)	0.58 (*0.73*)	0.70 (*0.85*)	0.81 (*1.11*)	0.94 (*1.31*)	1.69 (*2.31*)
Inter04	0.76 (*0.92*)	1.16 (*1.56*)	1.34 (*1.80*)	1.62 (*2.33*)	1.90 (*2.77*)	3.30 (*4.85*)

[8] Environment Agency Flood Estimation Guidelines – Technical Guidance 197_08 (January 2015)

Note: bracketed flows are FEH Statistical peak flows, provided for comparison.

Generally, estimates from catchment descriptor based ReFH models produce flow peaks that are lower in magnitude to the FEH Statistical method results. At the 1% AEP, FEH Statistical flows are, on average, 30% higher than the ReFH peaks, with ratios between the two methods varying between 1.15 (NK0889) and 1.46 (Inter04).

5.2.2 ReFH Model Optimisation

Flood event analysis was undertaken on the lumped catchment of the River Culm to the Woodmill gauge, using gauged rainfall and river flow data recorded during a series of historical events, detailed in Table 11, to optimise catchment descriptor based estimates of C_{max} in an attempt to improve the ReFH models. The analysis was undertaken using the ReFH1 modelling software tool.

The gauged flow record for Woodmill, together with rainfall data from local tipping bucket and storage rain gauges[9], were inspected to identify past flood events that are suitable for use in flood event analysis. Sufficient data was available for four recent events, summarised in Table 12.

Table 12 Observed flood events selected for flood event analysis

Event	Event Rainfall Depth (mm)	Peak Flow (m^3/s)
30-Oct-08	48.2	137.01
29-Apr-12	36.7	100.21
21-Nov-12	70.6	192.32
24-Dec-13	24.6	89.96

For each event a value of initial soil moisture (C_{ini}) was calculated by the ReFH software using antecedent rainfall data series derived from local storage rain gauge records and the software was run to optimise C_{max}. On the basis of these four events, C_{max} from catchment descriptors (422.33) was optimised to a value of 223.87, resulting in a donor correction factor of 0.53. The reduction in C_{max}, the maximum soil moisture capacity, induces a larger runoff response from the catchment and subsequently larger magnitude modelled flows. Table 13 provides a comparison of the modelled and observed event flow peaks for the lumped catchment of the River Culm to Woodmill. Plots of observed compared to modelled stage and flow hydrographs are provided in Appendix F.

Table 13 Flood Event Analysis Results

Event	Observed Flow (m^3/s)	Modelled Flow (m^3/s) – C_{max} CDs	Modelled Flow – C_{max} Optimised (% diff from observed flow)
29-Oct-08	137.01	75.3	142.8 (+4%)
30-Apr-12	100.21	38.4	72.6 (-28%)
21-Nov-12	192.32	94.0	177 (-8%)
30-Dec-13	89.96	32.0	64.1 (-29%)

Optimisation of the C_{max} parameter produces modelled event flows that are in much closer agreement with observed flows than the estimates produced by the catchment descriptor models. In three of the events

[9] Tipping bucket rain gauges - Clayhanger, Craze Lowman, Culmstock, Dunkeswell, Hemyock, Tiverton; Storage rain gauges - Hemyock Marl Pit, Dunkeswell Aerodrome, Sampford Peverell and Clayhanger

(November-12, April-12, December-13 modelled flows are still under-predicted, but during the October-08 event there is close agreement, with a small over-prediction by the optimised ReFH model.

C_{max} donor correction factors were subsequently applied to generated design flow estimates. These results are compared for the 2% and 1% AEP events with FEH Statistical flows in Table 14.

Table 14 Comparison of Design Flow Estimates - FEH Stat and ReFH Optimised Models

FEP	2% AEP Optimised ReFH Flow (m^3/s)	2% AEP FEH Statistical Flow (m^3/s)	1% AEP Optimised ReFH Flow (m^3/s)	1% AEP FEH Statistical Flow (m^3/s)
KS1417	7.16	8.07	8.56	9.77
Culm6173	83.6	92.6	99.45	102.5
NK0889	7.90	7.87	9.36	9.51
Sp3922	26.4	30.4	31.45	35.3
Inter01	0.96	1.11	1.16	1.31
Inter04	1.94	2.33	2.31	2.77

Design flow estimates from the optimised ReFH models are higher than flow estimates produced by the catchment descriptor based models (See Table 11), and compare more closely with (although are still lower than) the FEH Statistical peaks. At the 1% AEP, ratios between the two methods vary between 1.03 (Culm6173) and 1.19 (Inter04).

On this basis it was recommended that the slightly more conservative design flow estimates from the FEH Statistical method be taken forward for routing through the hydraulic model.

6 Calibration Hydrology Results

Calibration of the hydraulic model has centred on the October 2008 and November 2012 events. The peak flow recorded on the River Culm at the Woodmill gauge during the November 2012 event is the largest in recent times and has been exceeded only once during the 55 year record. The October 2008 event peak ranks at No.4 in the AMAX series.

When the recorded flow peaks, of 192m^3/s in November 2012 and 137m^3/s in October 2008, are compared with the design flow estimates produced for the lumped catchment of the Culm draining to the gauge (reported in Section 5.1.3 – Table 9), the November 2012 event would be placed between a 2% AEP and a 1% AEP event, and matches closely with the DHS 2% AEP flow. The smaller October 2008 event would be placed between a 10% AEP and 5% AEP event, with the event peak matching closely with the DHS 10% AEP design flow.

However, when the recorded event peaks are compared to modelled flows generated by routing FEH Statistical design inflows, a greater event rarity is assigned, with the November 2012 event exceeding a 1% AEP routed design flow (156.6m^3/s) and the October 2008 event peak aligning more closely to a 2% AEP routed design flow (138.1m^3/s).

7 Discussion

7.1 Results Appraisal

As evidenced by the available gauged data record at the re-rated Woodmill gauge and the results of a model calibration exercise centred on the November 2012 flood event, it is considered that FEH methods underestimate design flow estimates in the study catchment.

Despite efforts to optimise one of the key parameters in the ReFH model, and use of local hydrometric data records to inform the FEH Statistical method, routed flows from the FEH Statistical method (the methodology producing the higher flows of the two FEH methods) do not result in sufficient flow at the Woodmill gauge to tally with the gauged flow record. For example, routed 50% AEP FEH Statistical flow estimates do not generate enough flow (60.6m^3/s) to match with the QMED flow calculated from the AMAX data series (71.25m^3/s). Also, these flows indicate that the magnitude of the November 2012 flood was in excess of the 1% AEP, when available evidence indicates a more likely AEP of around 2%.

Woodmill is the only suitable donor for use in informing FEH flow estimates. Whilst situated on the study reach of the River Culm it is at the downstream limit of the study catchment and the effect of using the gauged data is moderated by the distance weighting factor in the QMED equation. The model also represents several small tributaries of the Culm that are quite different hydrologically to the Culm catchment itself. These tributaries are not gauged for flow so no data records are available to improve FEH flow estimates for these FEPs.

As the Culm6173 FEP makes the largest contribution of flow to the model, followed by the FEP representing the Spratford Stream (SP3922), a test was undertaken whereby the higher DHS flows were routed through the model for these two FEPs, with FEH Statistical flows retained for the other tributaries. Three design events were run through the hydraulic model (5% AEP, 2% and 1% AEP); the routed flows were then compared to the results of lumped catchment analysis at the Woodmill gauge and the DHS peak flows for the lumped catchment at the gauge. Table 15 provides a summary of the results.

Table 15 DHS flow test run results

Model Node	DHS 1% AEP Inflow	Routed Flow	FEH Statistical Lumped Catchment Flow	DHS Lumped Catchment Flow
Culm6173	165	-	-	-
SP3922	79	-	-	-
Woodmill	-	269	202	218
Model Node	**DHS 2% AEP Inflow**	**Routed Flow**	**FEH Statistical Lumped Catchment Flow**	**DHS Lumped Catchment Flow**
Culm6173	144	-	-	-
SP3922	70	-	-	-
Woodmill	-	234	172	191

Model Node	DHS 5% AEP Inflow	Routed Flow	FEH Statistical Lumped Catchment Flow	DHS Lumped Catchment Flow
Culm6173	120	-	-	-
SP3922	58	-	-	-
Woodmill	-	194	136	159

Note that results are based on the draft model pending receipt of survey data

This comparison indicates that adopting DHS lumped catchment inflows for the two largest contributing catchments results in too much flow in the model. Routed flow at Woodmill exceeds the DHS lumped catchment estimates at Woodmill. Also, when comparing the routed flows at Woodmill to the November 2012 flood event peak (192m^3/s), this event would be assigned an AEP of around 5% AEP, which is more frequent than evidence suggests.

A further suite of model runs was therefore undertaken with DHS peak inflows at FEPs Culm6173 and SP3922 (which contribute by far the most flow to Woodmill) reduced by 20%. The reduction factor was selected based on the differential between the DHS lumped catchment flow and the routed DHS inflows, to account for the fact that the DHS inflows represent individual catchment critical storm flows, so are more conservative than flows that would be generated during a catchment wide storm. At Woodmill, routed flows for the 1%, 2% and 5% AEP events equal to 220 m^3/s, 192 m^3/s and 156 m^3/s respectively were extracted from the model. These flows compare very closely to the DHS lumped catchment flows and the simulated peak of the 2% AEP design event matches that of the observed November 2012 flood event peak.

A comparison of modelled 2% AEP flood extents and levels with the anecdotal evidence from the November 2012 event has also been carried out.

A drawing showing the difference between the levels of the wrack marks surveyed after the November 2012 event and the modelled 2% AEP flows is included in Appendix G. The Environment Agency Fluvial Design Guide[10] gives an indicative model water level accuracy for a flood defence model as +/- 250mm; at 40 of the locations surveyed, water levels are within 250mm of the modelled levels. At the majority of the remainder of the survey points modelled floodwater depths are over estimated by between 250mm and 500mm, with some isolated locations where surveyed levels are under-estimated. Given that the vast majority of modelled water levels are within expected tolerances, or slightly overestimate surveyed levels (by up to 500mm), this is considered to be satisfactory, taking a conservative approach.

As part of the calibration review, flood levels have also been estimated from photographs taken during the flood event. A summary of the findings is provided below.

[10] http://evidence.environment-agency.gov.uk/FCERM/en/FluvialDesignGuide/Chapter7.aspx?pagenum=5

Photo and description	Estimated Water Level	2% AEP modelled information
Control Structure (Sluice) at 302435, 107892 	Estimate that water level is 300mm below crest which gives an estimated stage of **52.79mAOD** at approx. 2 hours before event peak.	The modelled flood hydrograph shows the stage at the structure rising from 52.82mAOD 5 hours before the peak to 52.9mAOD around 2 hours before the peak. This is 110mm higher than the estimated water level which is within the +/- 250mm tolerance referred to in the Fluvial Design Guide.
Embankment at 302475, 107811 	The modelled crest of the embankment is **52.52mAOD** and based on the photo, the EA reported in their Flood Reconnaissance Report[11] that the observed water level is within 0-50mm of this (photo labelled as the peak of the event).	The 2% AEP modelled results show a peak water level of **52.46mAOD** adjacent to the bund. This level is just short of overtopping the bund and hence modelled extents for the 2% AEP in this location are similar to those observed during the November 2012 event. Given that the modelled 2% AEP peak stage is around 110mm higher than observed it is within the +250mm tolerance quoted in EA Guidance

[11] Environment Agency (2012) Cullompton recce Industrial Estates DRAFT

Photo and description	Estimated Water Level	2% AEP modelled information
Cattle fence at 302792, 107745 (fence is causing the weir effect shown on the photo below) 	The cattle fence was modelled assuming a 1.5m high structure. Water levels have been estimated to be overtopping the structure by approximately 100mm, giving an estimated water level of **52.2mAOD.**	The 2% AEP modelled results show the water level at the structure to be **52.2mAOD.** The afflux is also represented as a drop of 250mm, matching the observed.

7.2 Adopted Design Flows

Following discussions with the Environment Agency regarding the information and data presented in Section 7.1, Table 16 provides a summary of the adopted design flow estimates. These flows are derived from the FEH Statistical method, with the exception of catchments Culm6173 and SP3922, representing the River Culmn and Spratford Stream, where flows are those from the DHS model reduced by a factor of 20%.

Table 16 Adopted design flows

FEP	2 year Flow (m^3/s)	10 year Flow (m^3/s)	20 year Flow (m^3/s)	50 year Flow (m^3/s)	100 year Flow (m^3/s)	1000 year Flow (m^3/s)
KS1417	2.88	5.10	6.25	8.07	9.77	18.47
Culm6173*	**44.66**	**79.54**	**96.00**	**115.83**	**132.33**	**197.15**
NK0889	2.84	5.00	6.10	7.87	9.51	17.95
Sp3922*	**19.52**	**39.03**	**46.40**	**56.44**	**63.29**	**87.82**
Heron0540	1.46	2.50	2.90	3.79	4.49	7.91
SA0935	0.31	0.48	0.54	0.67	0.78	1.31
Crow2496	0.26	0.44	0.50	0.65	0.77	1.34
Cole1750	0.23	0.40	0.46	0.60	0.71	1.25
SCole744	0.86	1.46	1.69	2.20	2.61	4.58
Inter01	0.43	0.73	0.85	1.11	1.31	2.31
Inter02	0.19	0.30	0.35	0.44	0.52	0.89

FEP	2 year Flow (m^3/s)	10 year Flow (m^3/s)	20 year Flow (m^3/s)	50 year Flow (m^3/s)	100 year Flow (m^3/s)	1000 year Flow (m^3/s)
Inter03	0.20	0.32	0.37	0.47	0.55	0.95
Inter04	0.92	1.56	1.80	2.33	2.77	4.85
RullLeat	0.15	0.25	0.29	0.37	0.44	0.76

**DHS flow reduced by 20%*

8 Conclusion

The river network through Cullompton is extremely complex and the availability of gauged river flow records is limited to the main reach of the River Culm at Woodmill, toward the downstream limit of the study reach. FEH methodologies have been applied to the study catchment to derive design flow estimates and, whilst best practice methods have been followed and all efforts made to use available hydrometric data, these methods have been shown to underestimate the flow response of the catchment.

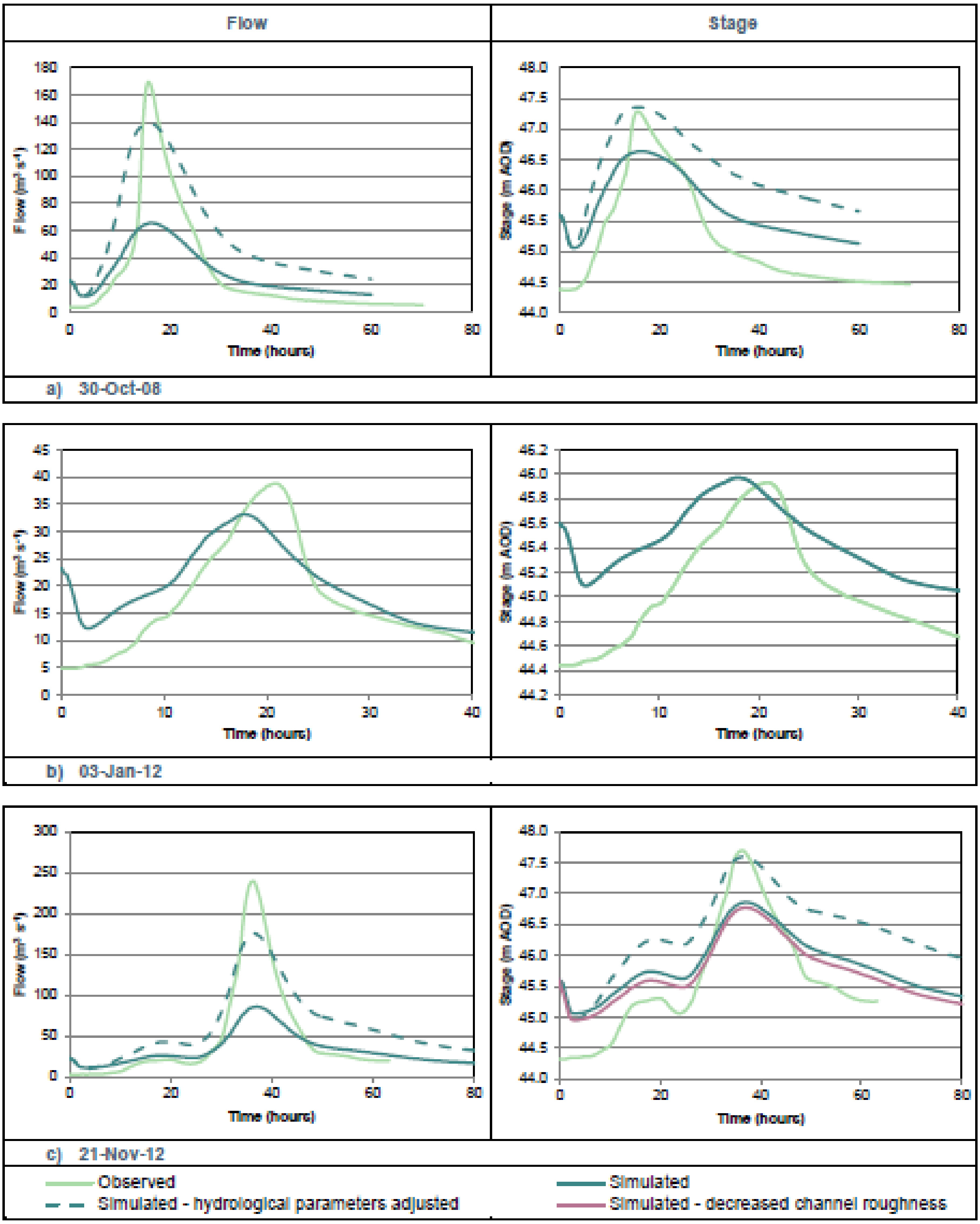
Of the two FEH methods applied, the FEH Statistical method produces the higher flow estimates, but flows from comparative DHS model nodes are higher. However, the adoption of DHS flow estimates at all model inflow nodes has been demonstrated to result in too much flow being routed through the hydraulic model. This results in modelled water levels and flood extents that do not tally with anecdotal flooding history and routed flows that contradict the results of the hydrological analysis of the lumped catchment draining to Woodmill.

Following discussion with the Environment Agency, FEH Statistical inflows have therefore been adopted for all except the Culm6173 and SP3922 FEPs, where DHS flows reduced by 20% at the peak have been taken forward. The adopted flows are presented in Table 16.

When routing these, design flows at the Woodmill gauge closely align with DHS flows for the lumped catchment of the River Culm at this location. There is also good agreement between the 2% AEP design flood conditions and the model flood predictions and anecdotal history of the November 2012 flood event. These results provide confidence in the choice of design inflows, which were approved by the Environment Agency in March 2017.

APPENDIX A

2014 Model Calibration Hydrographs



APPENDIX B

FEH Catchment Descriptor Checks

FEP	Comments
KS1417	FEH catchment at 302700, 106650 minus FEH catchment at 305550, 108550 Also removed a small area (1.46 km^2) draining out of the catchment - not considered necessary to adjust the other catchment descriptors to reflect this change Environment Agency's Devon Hydrology Strategy (DHS) node ref. 2146
Culm6173	FEH catchment at 302700, 108900 plus FEH catchment at 303700, 109300 Environment Agency's DHS node ref. 858
NK0889	FEH catchment at 302900, 107400 plus FEH catchment at 305550, 108550 Environment Agency's DHS node ref. 2240
Sp3922	FEH catchment at 302600, 108900 plus FEH catchment at 302650, 108950 Environment Agency's DHS node ref. 2167
Heron0540	FEH catchment at 302500, 108800 – no changes required. Environment Agency's DHS node ref. 2963
SA0935	FEH catchment at 302350, 107750 - no changes required. Environment Agency's DHS node ref. – N/A
Crow2496	FEH catchment at 300600, 107350 - no changes required Environment Agency's DHS node ref. – N/A
Cole1750	FEH catchment at 301400, 106500 - no changes required Environment Agency's DHS node ref. 2131 (minus ref. 2132)
SCole744	FEH catchment at 302050, 105950 minus FEH catchment at Cole1750 Environment Agency's DHS node ref. 2123 (minus refs. 2131 – 2132)
Inter01	FEH catchment at 302850, 107650 minus FEH catchment at 303700, 109300 Environment Agency's DHS node ref. 857 minus ref. 848
Inter02	FEH catchment at node 302750, 107600 minus the following FEH catchments: RullLeat Sp3922 Heron0540 302700, 108900 Environment Agency's DHS node ref. 2156 minus ref. 2163
Inter03	FEH catchment at 302400, 106700 minus SA0935 Environment Agency's DHS node ref. – N/A

FEP	Comments
Inter04	FEH catchment at node 301650, 104900 minus the following FEH catchments: 302850, 107350 302050, 105950 302350, 106700 302400, 106700 302700, 106650 Also removed a small area (0.36 km^2) draining to the Crow Green Stream; adjusted AREA, DPLBAR and DPSBAR accordingly but not the other catchment descriptors – this is not considered to have a significant effect on results Environment Agency's DHS node ref. – N/A
RullLeat (St. Georges Well Stream)	FEH catchment at 302500, 108250 - no changes required Environment Agency's DHS node ref. – N/A

APPENDIX C

Rain Gauge Data Details

APPENDIX D

AMAX Data – Culm at Woodmill

Woodmill AMAX Q (supplied by the Environment Agency in November 2016)

Date	Time	Q (m^3/s)
30.09.1962	18:00:00	18.047
14.02.1963	23:00:00	80.289
18.11.1963	04:00:00	30.861
20.01.1965	14:00:00	59.445
29.11.1965	13:00:00	72.077
17.02.1967	07:00:00	74.262
11.07.1968	05:00:00	201.215
29.07.1969	14:00:00	119.98
14.01.1970	20:00:00	57.101
21.01.1971	07:00:00	66.458
02.02.1972	19:00:00	53.892
06.12.1972	13:00:00	84.818
27.09.1974	20:00:00	78.785
20.01.1975	14:00:00	57.986
02.12.01975	05:00:00	21.343
30.11.1976	23:00:00	71.929
24.02.1978	01:00:00	76.528
01.02.1979	19:00:00	53.013
28.12.1979	02:00:00	100.395
17.11.1980	18:45:00	96.174
30.12.1981	17:15:00	94.178
12.11.1982	14:00:00	67.997
27.01.1984	13:15:00	92.131
21.01.1985	16:45:00	32.24
26.12.1985	14:00:00	102.384

Cullompton Eastern Distributor Road

Date	Time	Q (m^3/s)
04.04.1987	04:45:00	63.274
29.01.1988	17:45:00	42.527
24.02.1989	17:15:00	64.745
21.12.1989	02:30:00	69.081
10.01.1991	08:30:00	26.673
09.01.1992	08:15:00	31.388
30.11.1992	20:00:00	96.793
20.12.1993	16:00:00	90.035
09.11.1994	07:00:00	73.975
22.12.1995	14:30:00	50.30
06.08.1997	19:15:00	54.233
03.01.1998	17:00:00	53.40
20.01.1999	07:15:00	72.849
19.12.1999	06:00:00	75.044
08.12.2000	*01:15:00*	*138.34*
26.01.2002	21:45:00	40.531
14.11.2002	05:00:00	120.71
12.01.2004	14:45:00	70.561
19.12.2004	10:15:00	57.120
02.12.2005	09:15:00	65.177
05.03.2007	00:00:00	60.686
30.05.2008	05:00:00	77.754
30.10.2008	*08:45:00*	*137.01*
16.01.2010	15:30:00	49.396
17.11.2010	20:15:00	65.549
30.04.2012	12:15:00	100.21
21.11.2012	*12:15:00*	*192.32*

Cullompton Eastern Distributor Road

Date	Time	Q (m^3/s)
24.12.2013	00:15:00	89.96
12.11.2014	05:30:00	56.49
06.02.2016	21.45:00	97.026

Italicised years indicate effects of the most recent (November 2016) revision to the upper limb of the rating.

APPENDIX E

Final Pooling Group Composition

Cullompton Eastern Distributor Road

Culm6173

	Station	Distance	Years of d	QMED AM	L-CV	L-SKEW	Discordancy
	76011 (Coal Burn @ Coalburn)	0.703	35	1.84	0.169	0.333	1.32
	45816 (Haddeo @ Upton)	1.795	19	3.456	0.324	0.434	0.8
	27051 (Crimple @ Burn Bridge)	1.979	40	4.539	0.222	0.149	0.799
	28033 (Dove @ Hollinsclough)	2.063	33	4.666	0.266	0.415	0.611
	25011 (Langdon Beck @ Langdon)	2.74	26	15.878	0.241	0.326	1.669
	47022 (Tory Brook @ Newnham Park)	2.785	19	7.331	0.257	0.071	1.103
	54022 (Severn @ Plynlimon Flume)	2.787	37	15.031	0.155	0.168	1.315
	25003 (Trout Beck @ Moor House)	2.805	39	15.164	0.176	0.291	0.871
	25019 (Leven @ Easby)	2.835	34	5.538	0.347	0.394	1.051
	26802 (Gypsey Race @ Kirby Grindalythe)	2.924	13	0.109	0.261	0.199	0.325
	206006 (Annalong @ Recorder)	2.929	48	15.33	0.189	0.052	1.532
	27073 (Brompton Beck @ Snainton Ings)	3.113	32	0.813	0.197	-0.022	1.577
	27010 (Hodge Beck @ Bransdale Weir)	3.144	41	9.42	0.224	0.293	0.178
	44008 (South Winterbourne @ Winterbourne Steepleton)	3.239	33	0.42	0.395	0.332	1.984
	22003 (Usway Burn @ Shillmoor)	3.361	26	19.22	0.303	0.303	0.693
	45003 (Culm @ Wood Mill)	6.641	54	71.245	0.232	0.202	0.172
	Total		529				
	Weighted means				0.244	0.245	

SP3922

Station	Distance	Years of d	QMED AM	L-CV	L-SKEW	Discordancy
76019 (Roe Beck @ Stockdalewath)	0.198	13	43.521	0.213	0.365	1.685
41022 (Lod @ Halfway Bridge)	0.421	39	16.044	0.287	0.214	1.475
42011 (Hamble @ Frogmill)	0.457	40	8.028	0.159	0.013	0.782
43806 (Wylye @ Brixton Deverill)	0.509	21	1.914	0.383	0.222	2.798
53023 (Sherston Avon @ Fosseway)	0.531	36	7.281	0.206	0.121	0.295
42006 (Meon @ Mislingford)	0.58	53	2.889	0.254	0.21	0.486
51001 (Doniford Stream @ Swill Bridge)	0.626	46	11.434	0.325	0.396	2.089
205008 (Lagan @ Drumiller)	0.626	38	28.775	0.156	-0.073	1.45
27059 (Laver @ Ripon)	0.63	35	21.878	0.239	0.363	1.073
41020 (Bevern Stream @ Clappers Bridge)	0.642	43	13.49	0.214	0.208	0.325
205005 (Ravernet @ Ravernet)	0.645	40	14.355	0.218	0.33	0.78
203043 (Oonawater @ Shanmoy)	0.685	26	30.461	0.169	0.059	0.5
84009 (Nethan @ Kirkmuirhill)	0.751	36	31.157	0.241	0.155	0.09
45003 (Culm @ Wood Mill)	1.987	54	71.245	0.232	0.202	0.17
Total		520				
Weighted means				0.235	0.197	

KS1417

	Station	Distance	Years of d	QMED AM	L-CV	L-SKEW	Discordancy
	27051 (Crimple @ Burn Bridge)	0.266	40	4.539	0.222	0.149	1.041
	45816 (Haddeo @ Upton)	0.581	19	3.456	0.324	0.434	0.939
	28033 (Dove @ Hollinsclough)	0.77	33	4.666	0.266	0.415	0.959
	25019 (Leven @ Easby)	1.03	34	5.538	0.347	0.394	1.021
	26802 (Gypsey Race @ Kirby Grindalythe)	1.159	13	0.109	0.261	0.199	0.362
	47022 (Tory Brook @ Newnham Park)	1.19	19	7.331	0.257	0.071	1.748
	25011 (Langdon Beck @ Langdon)	1.193	26	15.878	0.241	0.326	1.706
	27010 (Hodge Beck @ Bransdale Weir)	1.324	41	9.42	0.224	0.293	0.257
	44008 (South Winterbourne @ Winterbourne Steepletor	1.425	33	0.42	0.395	0.332	1.678
	206006 (Annalong @ Recorder)	1.488	48	15.33	0.189	0.052	1.634
	22003 (Usway Burn @ Shillmoor)	1.548	26	19.22	0.303	0.303	0.54
	25003 (Trout Beck @ Moor House)	1.579	39	15.164	0.176	0.291	1.033
	51002 (Horner Water @ West Luccombe)	1.692	31	8.354	0.382	0.326	1.422
	203046 (Rathmore Burn @ Rathmore Bridge)	1.731	30	10.934	0.136	0.091	0.973
	27032 (Hebden Beck @ Hebden)	1.769	46	4.082	0.211	0.258	0.316
	54022 (Severn @ Plynlimon Flume)	1.932	37	15.031	0.155	0.168	1.184
	45003 (Culm @ Wood Mill)	4.835	54	71.245	0.232	0.202	0.187
	Total		569				
	Weighted means				0.255	0.251	

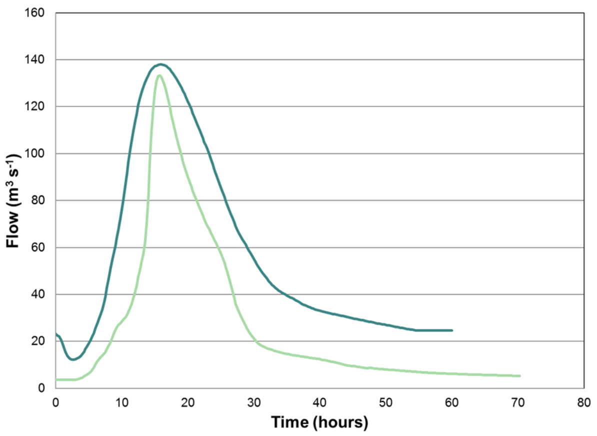
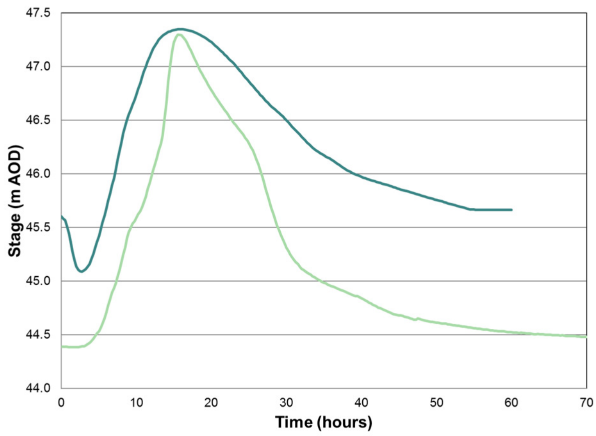
Cullompton Eastern Distributor Road

COLE1750

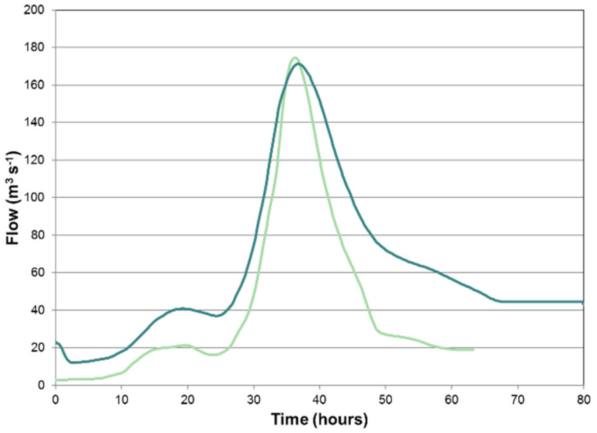
Station	Distance	Years of	QMED AM	L-CV	L-SKEW	Discordancy
76011 (Coal Burn @ Coalburn)	0.703	35	1.84	0.169	0.333	1.32
45816 (Haddeo @ Upton)	1.795	19	3.456	0.324	0.434	0.8
27051 (Crimple @ Burn Bridge)	1.979	40	4.539	0.222	0.149	0.799
28033 (Dove @ Hollinsclough)	2.063	33	4.666	0.266	0.415	0.611
25011 (Langdon Beck @ Langdon)	2.74	26	15.878	0.241	0.326	1.669
47022 (Tory Brook @ Newnham Park)	2.785	19	7.331	0.257	0.071	1.103
54022 (Severn @ Plynlimon Flume)	2.787	37	15.031	0.155	0.168	1.315
25003 (Trout Beck @ Moor House)	2.805	39	15.164	0.176	0.291	0.871
25019 (Leven @ Easby)	2.835	34	5.538	0.347	0.394	1.051
26802 (Gypsey Race @ Kirby Grindalythe)	2.924	13	0.109	0.261	0.199	0.325
206006 (Annalong @ Recorder)	2.929	48	15.33	0.189	0.052	1.532
27073 (Brompton Beck @ Snainton Ings)	3.113	32	0.813	0.197	-0.022	1.577
27010 (Hodge Beck @ Bransdale Weir)	3.144	41	9.42	0.224	0.293	0.178
44008 (South Winterbourne @ Winterbourne Steep	3.239	33	0.42	0.395	0.332	1.984
22003 (Usway Burn @ Shillmoor)	3.361	26	19.22	0.303	0.303	0.693
45003 (Culm @ Wood Mill)	6.641	54	71.245	0.232	0.202	0.172
Total		529				
Weighted means				0.244	0.245	

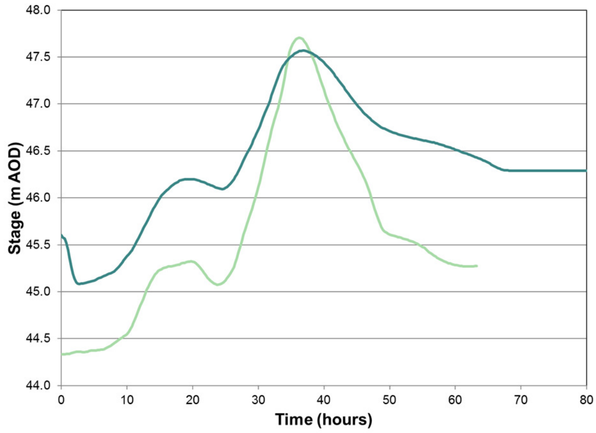
APPENDIX F

2016 Model Calibration Hydrographs

Flow	Stage
	

30-Oct-08





21-Nov-12

Legend

Observed Modelled

APPENDIX G

Drawing

4002-UA005763-UU41D-02 - 50 Wrack Nov12 Comparison

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