Flood estimation report: Thornborough Village

Introduction

This report template is based on a supporting document to the Environment Agency's flood estimation guidelines. It provides a record of the hydrological context, the method statement, the calculations and decisions made during flood estimation and the results.

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Revision History

Revision reference	Date issued	Amendments	Issued to
01	19/5/22	First draft	Andrew Waugh

Abbreviations

AMAX .... Annual Maximum
AREA .... Catchment area (km^2)
BFI .... Base Flow Index
BFIHOST .... Base Flow Index derived using the HOST soil classification
CPRE........................... Council for the Protection of Rural England
FARL .... FEH index of flood attenuation due to reservoirs and lakes
FEH .... Flood Estimation Handbook
HOST .... Hydrology of Soil Types
NRFA .... National River Flow Archive
POT .... Peaks Over a Threshold
QMED.......................... Median Annual Flood (with return period 2 years)
ReFH........................... Revitalised Flood Hydrograph method
SAAR .... Standard Average Annual Rainfall (mm)
Tp(0) .... Time to peak of the instantaneous unit hydrograph
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

Note on flood probability

This document quotes the probability of a flood magnitude in terms of a return period based on analysis of annual maximum (AMAX) floods. The return period of a flood on the AMAX scale is the average interval between AMAX floods of that magnitude or greater. The inverse of the AMAX return period is the annual exceedance probability (AEP).

Return periods are output by the Flood Estimation Handbook (FEH) software and can be expressed more succinctly than AEP. AEP can be helpful when presenting results to non-specialists who may associate the concept of return period with a regular rather than an average interval.

Return period can also be measured on the peaks-over-threshold (POT) scale as the average interval between floods of that magnitude or greater. The difference between AMAX and POT return periods is only important for short return periods (under 10 years).

The table below is provided to enable quick conversion between these different measures.

AMAX return period (years)	n/a	2	5	10	20	30	50	75	100	200	1,000
AEP (%)	n/a	50	20	10	5	3.33	2	1.33	1	0.5	0.1
POT return period (years)	1	1.5	4.5	9.5	20	30	50	75	100	200	1,000

1 Method statement

1.1 Requirements for flood estimates

<table>
<tr>
<td>Overview</td>
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Buckinghamshire County Council have commissioned JBA to undertake a Section 19 flood investigation of the 23rd December 2020 storm event that caused flooding in the village of Thornborough.

The rainfall event started at about 7:30am on the 23rd of December and continued until about 2.30am on the 24th December. Figure 1-1 shows the rainfall data from both the closest raingauge (at Foxcote) and the HYRAD radar data and shows a multi-peaked event. A total of 34mm of rainfall fell in 18 hours. The FEH13 rainfall model[1] indicates that the storm event had a return period of 2 years. Further discussion regarding event rainfall is included in Section 6.

Based on observations made during the event, the three key watercourses draining the catchment (Cowerde Brook, Thorn Brook, Tonne Brook) all overtopped their banks at at least one location during the event. In addition, there were reports of flooding from surface water and groundwater.
In total three properties in the village were flooded internally during the event, and several others experienced flooding to gardens and outbuildings. Observations made during the event indicate that flooding occurred between 4pm and 12pm on the 23rd December.

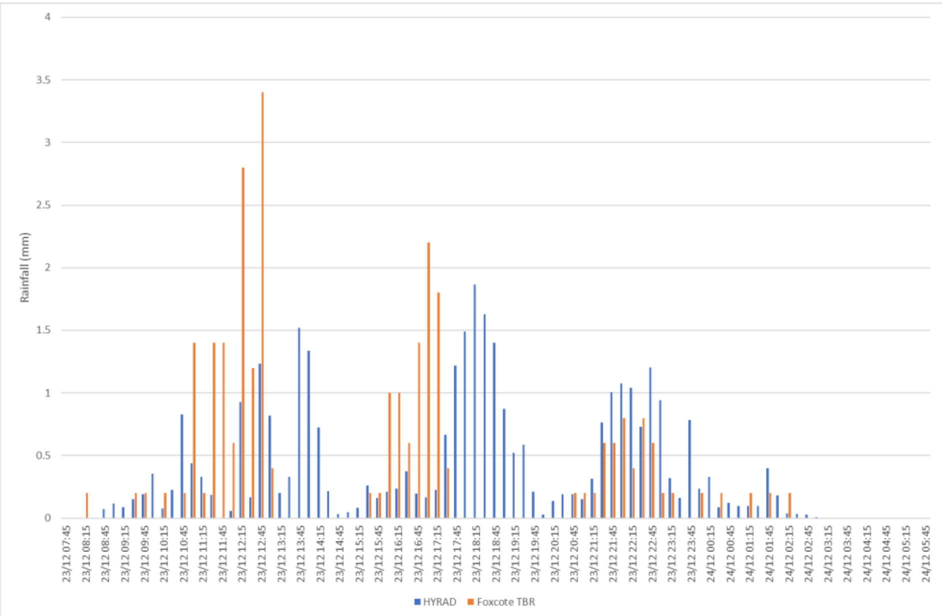

Figure 1-1 Event rainfall based on HYRAD radar and Foxcote TBR raingauge data

Aim of the hydrological assessment
The aim of this hydrological assessment is to estimate potential flood flows within Cowerde Brook, Thorn Brook and Tonne Brook. The estimates for Cowerde Brook will be used in an assessment of the flow return period of the December 2020 event (summarised in Section 6). The flow estimates for Thorn Brook and Tonne Brook will be used in a
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[1] https://fehweb.ceh.ac.uk/

	subsequent assessment of possible Natural Flood Risk Management (NFRM) measures (not included in this study). A variety of design event annual exceedance probabilities will be generated to inform the assessment of flow return period.

1.2 The catchment

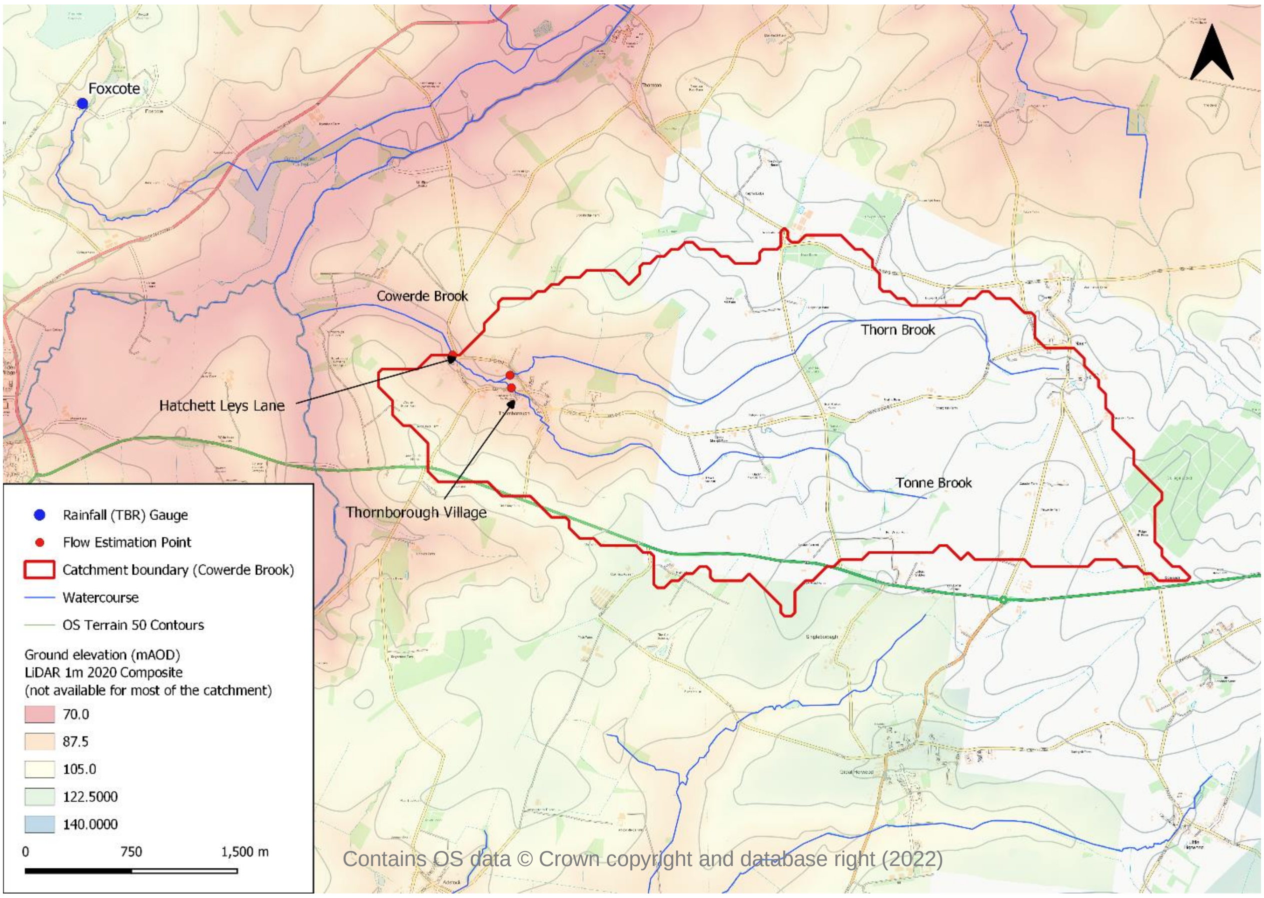
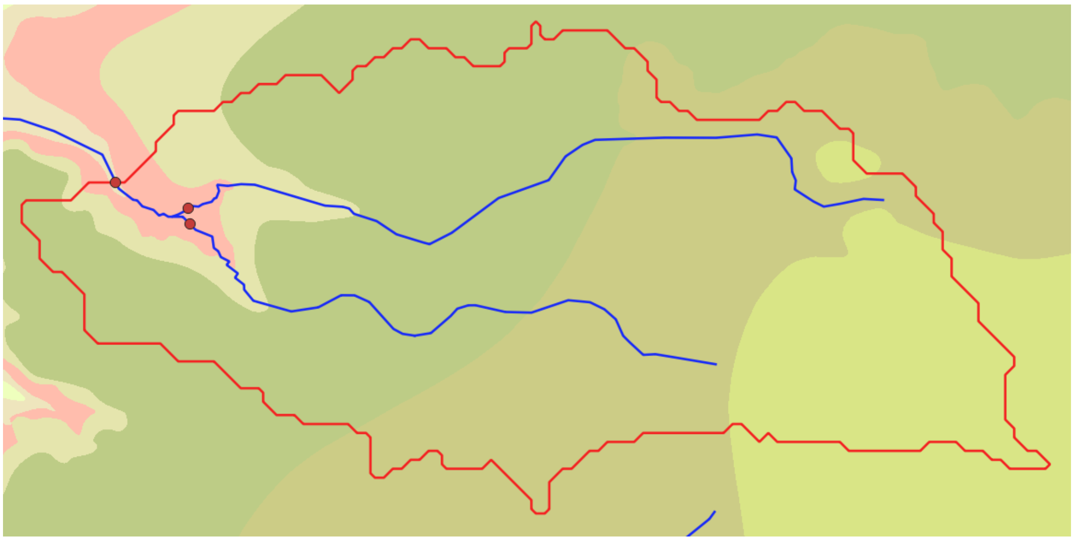
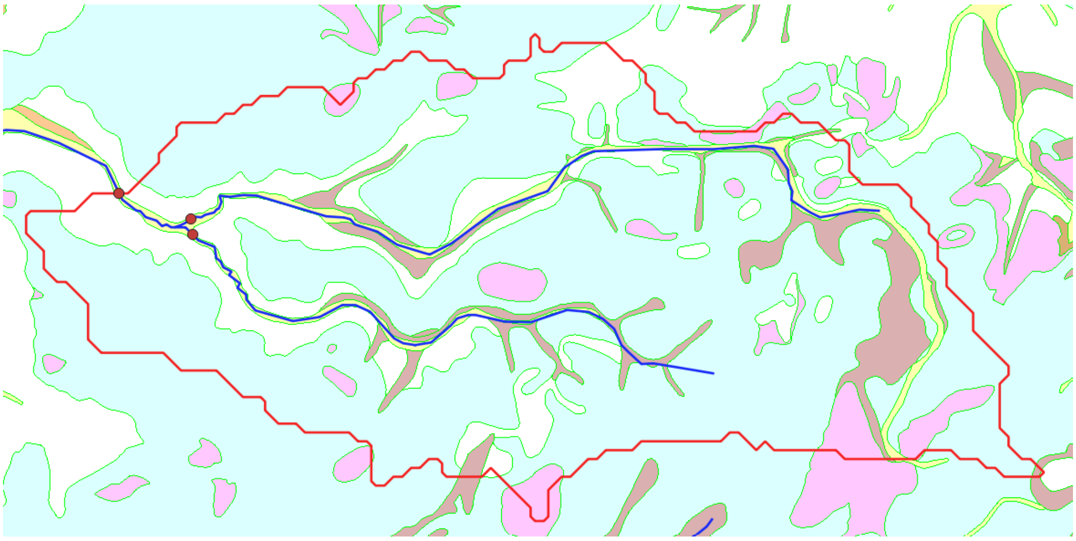


Figure 1-2 Thornborough catchment



Forest Marble Formation – limestone and mudstone, interbedded
Cornbrash Formation – limestone
Kellaways Formation – sandstone, siltstone and mudstone
Peterborough Member – mudstone
Stewartby Member – mudstone
Weymouth Member – mudstone

Figure 1-3 Bedrock Geology



River Terrace Deposits – Sand and Gravel
Alluvium – Clay, Silt, Sand and Gravel
Glaciofluvial Deposits – Sand and Gravel
Till – Diamicton
Head – Clay, Silt, Sand and Gravel

Figure 1-4 Superficial geology

Description	The catchment is drained by two watercourses, the Tonne Brook and the Thorn Brook. These rise in the east of the catchment and flow westwards, joining just west of the main village centre of Thornborough. Once combined, they become the Cowerde Brook which then continues westwards for approximately 1.5km whereby it joins the Padbury Brook. The Padbury Brook flows northwards and after approximately 300m it joins the Great Ouse. Ground levels vary from approximately 145mAOD in the east of the catchment to about 80mAOD in Thornborough, gradually decreasing westwards to about 70mAOD at the Padbury Brook/Cowerde Brook confluence. BGS mapping[2] shows that the upper two-thirds of the catchment is underlain by less permeable mudstones. The lower third of the catchment is underlain by mixed geology comprising limestone, mudstone, sandstone and siltstone. A significant area of the catchment is also covered with a mixture of superficial deposits, the majority of which is diamicton till. Hydrogeology mapping indicates that geology of the upper catchment holds essentially no groundwater whereas the lower part, underlain by limestone, is a moderately productive aquifer. Mapping by Soilscapes[3] indicates that soils of the Thornborough catchment are lime-rich loamy and clayey soils with impeded drainage. Standard average annual rainfall (1961-90) for the catchment is 637 mm/year. In terms of land use, the majority of the catchment is covered by arable agricultural fields. The village of Thornborough is the only significant urban area within the catchment. There are no significant attenuation features within the catchment.

1.3 Source of flood peak data

Source	NRFA peak flows dataset, Version 10, released August 2021. This contains data up to water year 2019-20.

1.4 Gauging stations (flow or level)

There are no flow or level gauges at or close to the site.

[2] https://www.bgs.ac.uk/
[3] http://www.landis.org.uk/soilscapes/

1.5 Other data available and how it has been obtained

Type of data	Data relevant to this study?	Data available?	Source of data	Details
Check flow gaugings	n/a	n/a	n/a	No check flow gaugings available.
Historic flood data	Yes	Yes	Buckingham County Council (BCC)	See separate table below.
			JBA Chronology of flash floods[4]	September 1935 – surface water flooding. Specific location unknown.
			CBHE[5]	No entries found.
			Environment Agency Historic Flood Map[6]	Online recorded flood outline from the EA shows no records for Thornborough.
			Environment Agency Flood Map for Planning[7]	The majority of Thornborough is located within Flood Zone 1 (low probability of flooding). Narrow strips of land immediately adjacent to the watercourse are located within Flood Zone 3 (high probability of flooding).
			Internet search	No further information in addition to that given above.
Flow or river level data for events	Yes	No		
Rainfall data for events	Yes	Yes	EA	Foxcote TBR HYRAD
Potential evaporation data	Yes	No		
Results from previous studies	Yes	No		There are no known previous studies of the Thornborough catchment.
Other data or information (e.g. groundwater, tides, channel widths, low flow statistics)	Yes	Yes	BCC/JBA	Risk from groundwater flooding map – this shows that 100-year groundwater levels are at or very close to the surface in the central part of Thornborough village.

[4] https://www.jbatrust.org/how-we-help/publications-resources/rivers-and-coasts/uk-chronology-of-flash-floods-1/
[5] https://www.cbhe.hydrology.org.uk/
[6] https://data.gov.uk/dataset/76292bec-7d8b-43e8-9c98-02734fd89c81/historic-flood-map
[7] https://flood-map-for-planning.service.gov.uk/

Flood History Summary

Date	Source of flooding	Description of impacts
September 1935	Surface water, from a storm referred to as "The Great Northampton shire hailstorm" (From JBA Chronology of flash floods)	"Making its way to the water streamed into the front windows of the New Inn and out the back; it swept up the three steps of the General shop nearby and poured into the windows and doorway. Many homes were invaded at Lower End. The water entered 17 or 18 houses in all."
1947	Unknown	Anecdotally, floodwater on High street and Back street flooded the green to 6ft
1998	Surface water runoff following prolonged heavy rainfall.	Heavy rainfall during April 1998 led to the highest river levels seen in the River Great Ouse since 1947. Road flooding seen in Thornborough at the ford on Back street with water levels anecdotally reaching above 6ft.
2007	Surface water runoff, blocked drains and watercourse overtopping after extreme rainfall event.	Approximately 10 properties flooded internally and externally.

1.6 Hydrological understanding of catchment

Hydrological interpretation	This is a small, rural catchment draining via two small watercourses (both on the FEH Web Service) which rise in steeper ground and flow down on to flatter ground within Thornborough village and beyond. The upper part is underlain by lower permeability mudstones and, as such, heavy rainfall falling on a saturated catchment should drain relatively quickly to the watercourse. Thornborough village itself and downstream is underlain by more permeable geology, including limestone. Under saturated conditions, this area may experience groundwater emergence from the underlying aquifer which may cause or exacerbate flooding.
Plots of flood peak data	The catchment is ungauged.

Conceptual model	The main site of interest is the village of Thornborough. Observations from the December 2020 event indicate that the flooding was caused by surface water, overtopping from the Tonne, Thorn and Cowerde Brooks and groundwater emergence. It is likely that extreme rainfall led to increased flows within the drainage network and rapid surface runoff from the more impermeable and steeper upper catchment. This, combined with high groundwater levels and groundwater emergence in the lower parts of the catchment, caused the

	flooding observed in the village.
Unusual catchment features	Limestone geology underlies the lower catchment. This potentially could impact the amount of water draining into the catchment. However, no further details are available to confirm this.

1.7 Initial choice of approach

Is FEH appropriate?	FEH methods, both FEH statistical and ReFH2, are appropriate for use in this study.
Initial choice of method(s)	Both FEH statistical and ReFH2 flow estimates will be generated for comparison purposes as there is no gauging at/near the site. Lumped flow estimates will be generated to: i) Downstream extent of the Tonne Brook ii) Downstream extent of the Thorn Brook iii) A location on the Cowerde Brook, just downstream of Hatchett Leys Lane, just downstream of Thornborough Village These are required for informing an analysis into the use of Natural Flood Risk Management in the upper part of the Thornborough catchment (not covered as part of this study). The flow estimates will be compared with an approximate estimate of channel capacity, as derived from LiDAR/site photographs. Observed rainfall data will be used to simulate the event using ReFH2.3. A summary of the event and analysis of return period is given in Section 6.
Software to be used	FEH Web Service[8] / WINFAP-FEH v3.0.003[9] / ReFH2.3

[8] CEH 2015. The Flood Estimation Handbook (FEH) Online Service, Centre for Ecology & Hydrology, Wallingford, Oxon, UK.
[9] WINFAP-FEH v3 © Wallingford HydroSolutions Limited and NERC (CEH) 2009.

2 Locations where flood estimates required

The table below lists the locations of subject sites. The site codes listed below are used in all subsequent tables to save space.

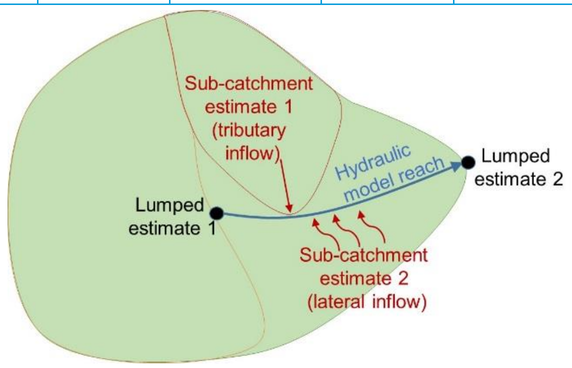
2.1 Summary of subject sites

Site code	Type of estimate L: lumped catchment S: Sub-catchment	Watercourse	Name or description of site	Easting	Northing	AREA on FEH* (km^2)	Revised AREA if altered
ThB	Lumped	Thorn Brook	Downstream extent of Thorn Brook	474300	233850	5.13	n/a
ToB	Lumped	Tonne Brook	Downstream extent of Tonne Brook	474350	233750	3.55	n/a
CoB	Lumped	Cowerde Brook	Location just downstream of Hatchett Leys Lane, Thornborough	473900	233950	9.30	n/a

Note: Lumped catchments (L) are complete catchments draining to points at which design flows are required.

Sub-catchments (S) are catchments or intervening areas that are being used as inputs to a semi-distributed model of the river system. There is no need to report any design flows for sub-catchments, as they are not relevant: the relevant result is the hydrograph that the sub-catchment is expected to contribute to a design flood event at a point further downstream in the river system. This will be recorded within the hydraulic model output files. However, catchment descriptors and ReFH model parameters should be recorded for sub-catchments so that the results can be reproduced.

The schematic diagram illustrates the distinction between lumped and sub-catchment estimates.



*FEH webservice[8]

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

Site code	FARL	PROPWET	BFIHOST 19	DPLBAR (km)	DPSBAR (m/km)	SAAR (mm)	URBEXT 2000	FPEXT
ThB	1.0	0.32	0.331	3.10	30.2	638	0.003	0.054
ToB	1.0	0.32	0.338	2.53	30.6	637	0.004	0.052
CoB	1.0	0.32	0.339	3.18	30.8	637	0.004	0.054

2.3 Checking catchment descriptors

Record how catchment boundary was checked and describe any changes (add maps if needed)	LiDAR data is not available for the majority of the catchment boundary. OS Terrain 50 contours and OS 50k mapping were used to verify the catchment boundaries. No edits were required.

Record how other catchment descriptors were checked and describe any changes. Include before/after table if necessary.	No significant flood storage areas/reservoirs in the catchment. FARL not changed. BFIHOST19 value for Cowerde catchment were queried as this was the same as that for the Thorn and Tonne Brook catchments, despite having more permeable area at the downstream end. However, this area (pink on the geology map above) is only a very small part of the Cowerde catchment so is not likely to have a significant impact. In general, values for BFIHOST19 seem reasonable for mixed geology.
Version of URBEXT	URBEXT2000
Method for updating of URBEXT	URBAN50K
Source of BFIHOST	BFIHOST19 has been used in the ReFH2 calculations, since the current release (ReFH2.3) was calibrated using BFIHOST19, and also in the FEH Statistical method, since this has been found to improve the results[10].

[10] Griffin, A., Young, A. and Stewart, E. (2019). Revising the BFIHOST catchment descriptor to improve UK flood frequency estimates. Hydrology Research.

3 Statistical method

3.1 Overview of estimation of QMED at each subject site

Site code	Initial QMED rural (m^3/s) (from catchment descriptors)	Final method	Data transfer: NRFA numbers for donor sites used (see 3.3)	Data transfer: Distance between centroids d_{ij} (km)	Data transfer: Moderated QMED adjustment factor, $(A/B)^a$	Data transfer: If more than one donor: Weight	Data transfer: If more than one donor: Weighted ave. adjustment	Urban adjust-ment factor (UAF)	Final QMED estimate (m^3/s)
ThB	1.3	AM	33018	19.54		0.5	1.027	n/a	1.30
			33030	20.77		0.5			
ToB	0.9	AM	33018	19.80		0.5	1.027	n/a	0.93
			33030	21.10		0.5			
CoB	2.1	AM	33018	19.53		0.5	1.027	n/a	2.11
			33030	21.06		0.5			

Are the values of QMED spatially consistent?	Yes
Method used for urban adjustment for subject and donor sites	n/a

Notes

Methods: AM – Annual maxima; POT – Peaks over threshold; DT – Data transfer (with urban adjustment); CD – Catchment descriptors alone (with urban adjustment); BCW – Catchment descriptors and bankfull channel width (add details); LF – Low flow statistics (add details).

The QMED adjustment factor A/B for each donor site is given in Table 3.2. 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: $(A/B)^a \times QMED_{initial} \times UAF$

Important note on urban adjustment

The method used to adjust QMED for urbanisation published in Kjeldsen (2010)[11] in which PRUAF is calculated from BFIHOST is not correctly applied in WINFAP-FEH v3.0.003. Significant differences occur only on urban catchments that are highly permeable.

[11] Kjeldsen, T. R. (2010). Modelling the impact of urbanization on flood frequency relationships in the UK. Hydrol. Res. **41**. 391-405.

3.2 Search for donor sites for QMED

Four donors have been assessed for their suitability in the adjustment of QMED. This was done using the Cowerde catchment with the final option being applied to the Thorn and Tonne Brook catchments. Table 3-1 and Figure 3-1 below show the key characteristics of the Cowerde Brooke catchment and each donor and the resulting flood frequency curves at Cowerde Brook (using the same pooling group in each case, as outlined in sections 3.4 and 3.5). These show a varied result, reflecting the mixed nature of the relationship between QMED from gauge data and QMED from catchment descriptors between the donor sites. Research (SC090031[12] and SC050050[13]) indicates donors should be chosen based on proximity to the subject catchment (using centroid distance). In this study, the closest donor is Thornborough Mill. This catchment is significantly larger than the subject site and the QMED adjustment is the lowest of all the donors considered, resulting in the red line on the graph below. The Broughton gauge is the next closest and shows a very different picture compared with Thornborough Mill, that is, a significant increase in QMED. However, Broughton is classed as an urbanised catchment (URBEXT2000>0.03) and SC050050 recommends not using such catchments due to artificial influences, though it could be argued that this catchment only just crosses this urbanised threshold. Cappenham Bridge and Clipstone donors are similar distances to the subject site and not that much further away from the subject site compared with Broughton. The Cappenham Bridge catchment is significantly larger than the subject catchment. There seems to be a west-east split between the trend in QMED adjustment factors. Those gauges on the west, and closer to the subject site, show an adjustment of <1 and those to the east show an adjustment of >1. This could reflect a number of different catchment characteristics, such as a difference in response by the larger catchments of Thornborough Mill and Cappenham Bridge, but may also indicate a geographical trend and, as such, a QMED adjustment of <1 would be more appropriate for the subject site. However, the FEH statistical flows are significantly lower than the ReFH2 estimates, and both are lower than estimated flows observed during the event. As there is no clear preferred option, a weighted adjustment based on 50/50 Cappenham Bridge and Clipstone has been adopted to derive the final FEH Statistical estimates (light blue curve in Figure 3-1).

Table 3-1 Key catchment descriptors

	Subject Site	Thornborough Mill (33005)	Cappenham Bridge (33018)	Broughton (33031)	Clipstone (33030)
Catchment Centroid Distance (km)	-	9.2	19.5	17.8	21.0
Area (km2)	9.3	387.7	132.6	70.1	40.4
BFIHOST	0.339	0.480	0.368	0.482	0.362
SAAR	637	655	661	629	640
URBEXT2000	0.004	0.014	0.016	0.038	0.016
FARL	1.00	0.98	0.99	0.97	0.98

[12] Science Report SC090031/R0: Estimating flood peaks and hydrographs for small catchments (Phase 2) (2019). A summary of an important research project, giving recommendations for practitioners
[13] Kjeldsen, T.R., Jones, D. A. and Bayliss, A.C. (2008). Improving the FEH statistical procedures for flood frequency estimation. Science Report SC050050, Environment Agency

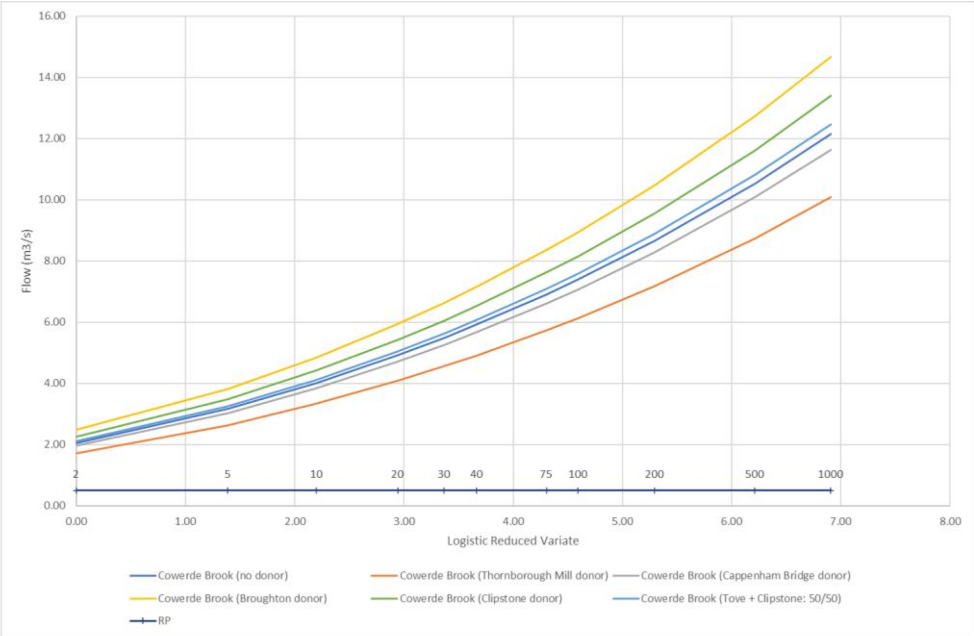


Figure 3-1 Flood frequency curves

3.3 Donor sites chosen and QMED adjustment factors

NRFA no.	Reasons for choosing	Method (AM or POT)	Adjust-ment for climatic variation?	QMED from flow data (A)	QMED from catchment descriptors (B)	Adjust-ment ratio (A/B)
33018	Proximity and reasonable approximation of QMED trend in the area	AM	n/a	17.0	19.6	0.87
33030	Proximity and reasonable approximation of QMED trend in the area	AM	n/a	8.8	6.3	1.38

3.4 Derivation of pooling groups

Several subject sites may use the same pooling group.

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	Weighted average L-moments, L-CV and L-skew, (before urban adjustment)
Cowerde	CoB	No	Site 7011 (Black Burn @ Pluscarden Abbey) – removed due to short record (7 years)	L-CV: 0.291 L-SKEW: 0.272
Note: Pooling groups were derived using the procedures from Science Report SC050050 (2008).				

3.5 Derivation of flood growth curves at subject sites

Site code	Method (SS, P, ESS, J)	If P, ESS or J, name of pooling group (Error! Reference source not found.)	Distribution used and reason for choice	Note any urban adjustment or permeable adjustment	Parameters of distribution (location, scale and shape after adjustments)	Growth factor for 100-year return period
CoB	P	Cowerde	GEV (Best fit: GEV Z-value = 0.2172, GL Z-value = 1.1555)	n/a	Location: 1.00 Scale: 0.412 Shape: -0.154	3.60
ThB	P	Cowerde				
ToB	P	Cowerde				

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 are all carried out using the method of Kjeldsen (2010).

Growth curves were derived using the procedures from Science Report SC050050 (2008).

3.6 Flood estimates from the statistical method

Site code	Flood peak (m^3/s) for the following return periods (in years)									
	2	5	10	20	30	50	75	100	500	1000
CoB	2.1	3.2	4.1	5.1	5.6	6.4	7.1	7.6	10.8	12.5
ThB	1.3	2.0	2.5	3.1	3.5	4.0	4.4	4.7	6.7	7.7
ToB	0.9	1.4	1.8	2.2	2.5	2.8	3.1	3.4	4.8	5.5

4 Revitalised flood hydrograph 2 (ReFH2) method

4.1 Parameters for ReFH2 model

In accordance with research findings, all catchments with URBEXT2000 up to 0.30 were modelled as if they were rural. Research on flood estimation in small catchments[14] found that flood frequency estimates on such catchments were more accurate if the catchment was treated as rural. This reflects the difficulty of generalising the complex and locally-specific effects that urban development has on flood flows.

All catchments					Only extremely heavily urbanised catchments
Site code	**Method**	**C_{max} (mm)**	**Tp_{rural} (hours)**	**BL (hours)**	**Area of catchment modelled as urban (km²)**
CoB	CD	272	4.58	34.9	n/a
ThB	CD	267	4.55	34.2	n/a
ToB	CD	272	4.03	33.1	n/a
Link to details of any lag or flood event analysis		See Section 6			
Version of the ReFH2 model applied		ReFH2.3 using the water balance option. This treats BR (baseflow recharge) as a state variable rather than a parameter, setting it automatically in order to conserve volume. The values of BR vary with return period and so are not reported here.			
Methods: OPT: Optimisation from fitting to observed flow data, BR: Baseflow recession fitting, CD: Catchment descriptors, DT: Data transfer (give details)					

4.2 Design events for ReFH2 method: Lumped catchments

Site code	Urban or rural	Season of design event (summer or winter)	Storm duration (hours)
CoB	Rural	Winter	7.5
ThB	Rural	Winter	7.5
ToB	Rural	Winter	6.5

4.3 Flood estimates from the ReFH2 method

Site code	Flood peak (m³/s) for the following return periods (in years)									
	2	**5**	**10**	**20**	**30**	**50**	**75**	**100**	**500**	**1000**
CoB	3.1	4.3	5.1	6.0	6.6	7.3	8.0	8.5	10.0	12.5
ThB	0.4	2.5	3.0	3.5	3.8	4.2	4.6	4.9	5.8	7.2
ToB	0.3	1.8	2.2	2.6	2.8	3.1	3.4	3.6	4.3	5.3

[14] Stewart, Lisa, Duncan Faulkner, Giuseppe Formetta, Adam Griffin, Tracey Haxton, Ilaria Prosdocimi, Gianni Vesuviano and Andy Young (2021). Estimating flood peaks and hydrographs for small catchments (Phase 2). Report – SC090031/R0, Environment Agency.

5 Discussion and summary of results

5.1 Comparison of results from different methods

Site code	Ratio of peak flow to FEH Statistical peak	
	Return period 2 years	Return period 100 years
	ReFH	ReFH
CoB	1.48	1.12
ThB	1.38	1.05
ToB	1.41	1.09

5.2 Final choice of method

Choice of method and reasons	The Thornborough catchment is small with mixed permeability between the upper and lower parts of the catchment. Both the FEH Statistical and ReFH2 methods are appropriate. In this case, as there is no gauge data against which to compare, observations from the event have been used to assess which flow estimates are deemed to be more appropriate. This is discussed in more detail in Section 6. Results discussed in Section 6, indicate that the flow estimated here are too low. However, given the limited data available, it is recommended that the ReFH2 estimates, being higher, be used in the subsequent study into NFRM measures. Suitability of these estimates for the NFRM assessment should be reviewed as part of the study.
How will the flows be applied to a hydraulic model?	n/a

5.3 Assumptions, limitations and uncertainty

Key assumptions	The drainage catchment is defined by the topography. This may not be the case where limestone geology exists as groundwater may drain into the catchment from adjacent topographic catchments. However, there is no information available to confirm whether the area draining into the catchment is different to that defined by the surface topography.
Limitations	Gauged flow data is not available so methods rely heavily on catchment descriptors.
Uncertainty	It is not possible to directly quantify the uncertainty for the ReFH2 method. The uncertainty of the FEH Statistical method will depend on many factors, for example, how unusual the study catchment is relative to the pooling group, and the uncertainty in flow measurement at other gauges. The FEH Local project (Environment Agency funded consortium of JBA, CEH and others) established that the

<table>
<tr><td></td><td>following range of a 95% confidence interval is to be expected per design flood for a rural site (numbers quoted are multipliers):
<table>
<tr><td>AEP</td><td>No donor</td><td>1 donor</td></tr>
<tr><td>50%</td><td>0.48 – 2.10</td><td>0.50 – 2.02</td></tr>
<tr><td>1%</td><td>0.45 – 2.23</td><td>0.47 – 2.12</td></tr>
</table></td></tr>
<tr><td>Comment on the suitability of the results for future studies</td><td>These flow estimates were derived for the current study and to inform subsequent work regarding NFRM features within the Thornborough catchment.

Use of these estimates in other studies should include a review of their suitability.</td></tr>
<tr><td>Give any other comments on the study</td><td>There is a lack of hydrometric river flow data within the catchment. Confidence in flow estimates and understanding of catchment response could be improved with local hydrometric data collection. The study would be improved by undertaking a hydrogeological study to identify the influence of groundwater on flood flows in the catchment.</td></tr>
</table>

5.4 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?	There is no flow gauging available at or close to the site. Discussion regarding possible flow return period of the December 2020 event is given in Section 6.
What is the range of 100-year growth factors? Is this realistic?	The 1% AEP growth factor range for the methods is: • FEH Statistical: 3.60 • ReFH2: 2.73 The typical range is 2.1 to 4.0 (based on FSR regional growth curves). The growth factors for both methods are within this range.
If 1000-year flows have been derived, what is the range of ratios for 1000-year flow over 100-year flow?	1.64-1.72
How do the results compare with those of other studies? Explain any differences and conclude which results should be preferred.	No previous studies available.
Are the results compatible with the longer-term flood history?	See section 6.
Describe any other checks on the results	Verifying the results is difficult due to a lack of gauged data. However, a comparison has been made with a channel capacity calculation at Hatchett Leys Lane, known to flood during the event. This indicates that the flow estimates produced here are too low.

5.5 Final results

Results from both methods for Cowerde Brook have been provided to inform the discussion about the event (Section 6).

Site code	Method	Flood peak (m^3/s) for the following return periods (in years)								
		2	**5**	**10**	**20**	**30**	**50**	**75**	**100**	**500**
CoB	FEH Stats	2.1	3.2	4.1	5.1	5.6	6.4	7.1	7.6	10.8
CoB	ReFH2	3.1	4.3	5.1	6.0	6.6	7.3	8.0	8.5	10.0
ThB	ReFH2	0.4	2.5	3.0	3.5	3.8	4.2	4.6	4.9	5.8
ToB	ReFH2	0.3	1.8	2.2	2.6	2.8	3.1	3.4	3.6	4.3

If flood hydrographs are needed for the next stage of the study, where are they provided? (e.g. give filename of spreadsheet, hydraulic model, or reference to table below)	Thornborough_REFH2_hydrographs.xlsx

5.6 Confidence limits

This table reports the flows derived from the uncertainty analysis detailed in Section 5.3. The 'true' value is more likely to be near the estimate reported in Section 0 than the bounds. However, it is possible that the 'true' value could still lie outside these bounds.

95 % confidence	Flood peak (m^3/s) for the following return periods (in years)					
	2		**50**		**100**	
Site code	**Lower**	**Upper**	**Lower**	**Upper**	**Lower**	**Upper**
CoB (FEH Stats)	1.06	4.26	3.09	14.21	3.57	16.10
ThB (FEH Stats)	0.65	2.62	1.90	8.75	2.20	9.91
ToB (FEH Stats)	0.47	1.88	1.36	6.28	1.58	7.11
CoB (ReFH2)	1.56	6.31	3.52	16.22	4.01	18.07
ThB (ReFH2)	0.90	3.63	2.03	9.33	2.31	10.41
ToB (ReFH2)	0.66	2.65	1.50	6.92	1.71	7.72

Note: The above confidence limits are based on results from DEFRA's research report SC130009/R[15]. These are for the FEH statistical method. It is more difficult to assess uncertainty for the ReFH2 method. However, work undertaken by Wallingford HydroSolutions indicates the factorial standard errors for ReFH2 are similar to those of the FEH statistical method for ungauged catchments. The same confidence intervals have therefore been applied to the ReFH2 estimates derived here.

[15] Dixon H, et al. (2017): Making better use of local data in flood frequency estimation, DEFRA report SC130009/R

6 December 2020 Event

6.1 Event Rainfall

Both 15-minute raingauge (TBR) data and radar catchment average data were used to derive hyetographs for the 23rd December 2020 event. Figure 6-1 shows the rainfall from both sources of data and the corresponding hydrographs from ReFH2. Foxcote TBR is the closest raingauge, lying approximately 5.3km north of the Thornton catchment. Other available raingauges are either too far from the catchment to be appropriate or do not provide sufficient data to assess the pattern of the rainfall. Catchment average rainfall was also derived from the Met Office's radar dataset.

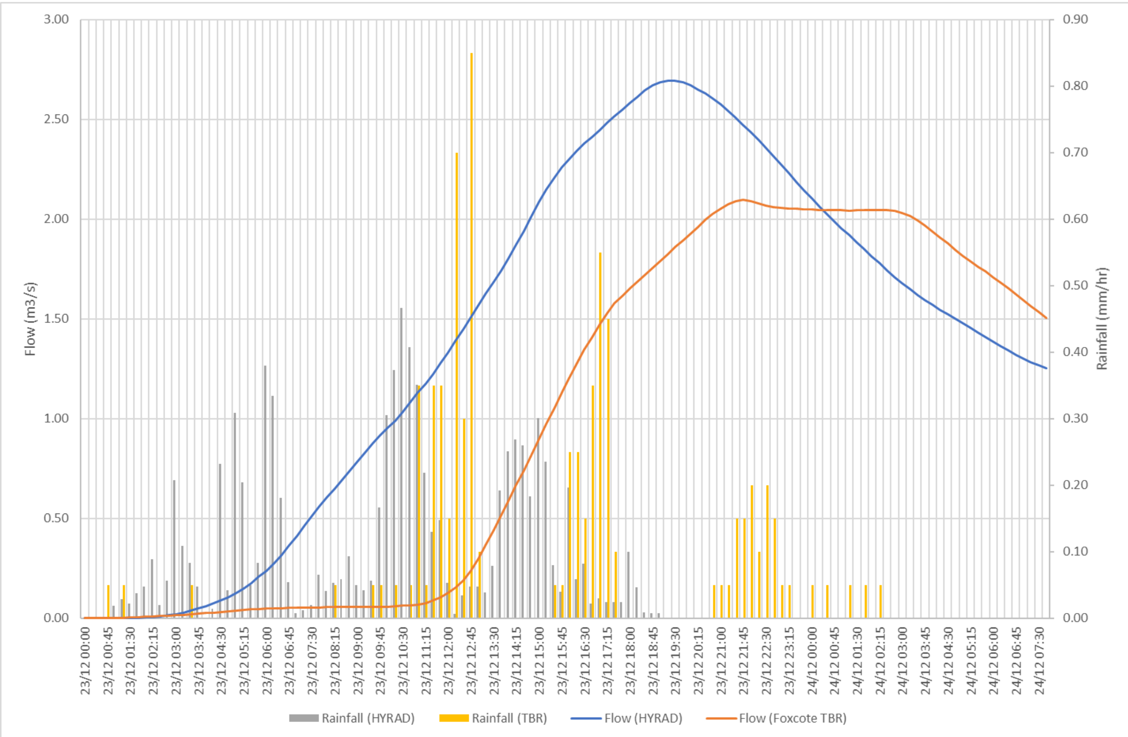


Figure 6-1 Event rainfall and corresponding ReFH hydrographs (Note: HYRAD refers to Met Office radar data)

In terms of total rainfall for the event, both Foxcote and radar sources give similar results of 28mm and 34mm respectively. The FEH13 DDF model, available via the FEH Webservice[16], estimates that, for the Thornton catchment, this rainfall depth has a return period of approximately 2 years.

6.2 Catchment response

Observed rainfall for the event was run through the ReFH2 model. Daily antecedent rainfall for the preceding 3 months, for TBR, and 12 months, for radar was used, based on available data. 15 minute rainfall was used for both TBR and radar datasets for the event itself.

Observations from the event indicate that the onset of the flooding occurred at approximately 4pm on 23rd December and subsided at around 11pm (23rd) -12am (24th). The ReFH2 hydrographs above show that, based on Foxcote TBR data, a peak of flow of 2.10m^3/s

[16] https://fehweb.ceh.ac.uk/

occurred at about 9.45pm (23rd). Based on radar data, this peak flow is estimated to be 2.69m^3/s and to occur at about 7.30pm (23th). Given that the flooding was observed to subside at about 11pm this would suggest that the timing of the hydrograph based on HYRAD data is a better representation of the event, as flows do not fall significantly until about 2.30am on the 24th, based on Foxcote TBR data.

Observations from the event state there were a number of places where water from the watercourse overtopped the banks and flowed onto adjacent areas. This occurred for all three key watercourses outlined above. One such location was at Hatchett Leys Lane where event photographs show the Cowerde Brook river level to be above bankfull, both upstream and downstream of the Hatchett Leys Lane bridge (see main Section 19 Technical Report for further details). Ground survey information of this structure or the Cowerde Brook channel at this point are not available but an estimation of the river channel approximately 10 metres upstream of Hatchett Leys Lane bridge has been made based on LiDAR data (Figure 6-2). The LiDAR data indicates the channel is approximately 6m wide by about 1m deep, which is a reasonable approximation based on site photographs.

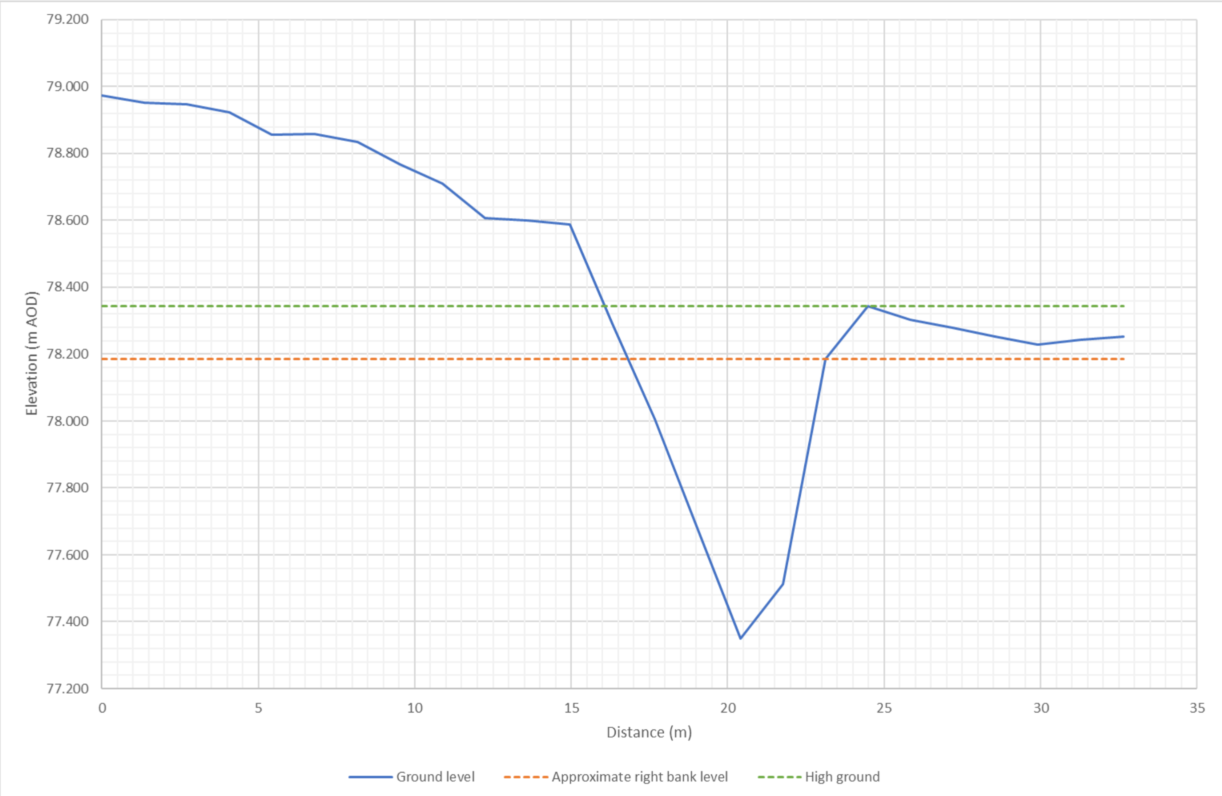


Figure 6-2 LiDAR cross-section of Cowerde Brook

Using Flood Modeller 4.5, an estimate of channel capacity has been determined, based on the Manning's n equation. The bed slope has been derived using LiDAR data and, though this data is not able to measure bed levels under water well, a channel slope has been estimated based on LiDAR bed and floodplain levels, and site photographs. This method indicates that at a right bank level of 78.186m AOD, the channel capacity is 3.15m^3/s and up to the high ground point on the right flood plain (88.343m AOD), which also flooded in the event, the channel capacity is 4.73m^3/s. This provides an approximation of what the flow was at this point, though site observations show that the flood level rose above this point so peak flood flow is likely to be greater than this.

As mentioned above, the return period for the storm event is deemed to be approximately 2-years. Based on this, a return period for the flood event of up to 50-years is reasonable, though up to 100-years is considered possible on very wet catchments. The underlying aquifer is likely to be contributing to the flood flows through Thornborough such that a higher flood flow is observed, compared with the storm event. Unfortunately, it is very difficult to assess such an influence without an in-depth hydrogeological study.

Table 6-1 shows the peak flows generated by this study. ReFH2 peak flow using observed rainfall data, 2.10m^3/s based on TBR data and 2.69m^3/s based on radar data, indicates the event has a flow return period of less than 2 years. This is based on the ReFH2 flood frequency estimates (as per guidance in the Flow Estimation Guidelines[17]). Given that this area has only experienced flooding approximately 3-4 times in the past 70 years, a return period of 2 years is not considered reasonable and it is likely that ReFH2 is underestimating flow.

Based on the channel capacity calculations, the flow return period is at least 10-20 years, based on FEH statistical estimates, and 5-10 years, based on ReFH2 estimates. This is a more reasonable approximation based on the limited flood history.

Table 6-1 Peak flow estimates for Cowerde Brook, from the current study

Site code	Method	Flood peak (m^3/s) for the following return periods (in years)									
		2	5	10	20	30	50	75	100	500	1000
CoB	FEH Stats	2.1	3.2	4.1	5.1	5.6	6.4	7.1	7.6	10.8	12.5
CoB	ReFH2	3.1	4.3	5.1	6.0	6.6	7.3	8.0	8.5	10.0	12.5

Based on the information available, an approximate return period of 5-20 years is estimated for the flow in Cowerde Brook. It should be noted that estimating flow return period is an inherently difficult task. This is due to the many sources of uncertainty involved, such as the estimation of rainfall and antecedent conditions, plus the impact of groundwater and any possible blockages within the watercourse. In ungauged catchments, such as Thornborough, there is no data available to calibrate or verify the flow estimates derived. Therefore, any flow return period estimated should be considered to be an approximate guide to what happened during the event.

[17] Environment Agency (2020) Flood Estimation Guidelines, Technical guidance 197_08

7 Annex

7.1 Pooling Group

Station Number	Watercourse	Location	Years
27051	Crimple	Burn Bridge	47
26016	Gypsey Race	Kirby Grindalythe	22
25019	Leven	Easby	41
49005	Bolingey Stream	Bolingey Cocks Bridge	9
27010	Hodge Beck	Bransdale Weir	41
45816	Haddeo	Upton	26
44008	South Winterbourne	Winterbourne Steepleton	40
36010	Bumpstead Brook	Broad Green	52
28033	Dove	Hollinsclough	44
47022	Tory Brook	Newnham Park	25
25011	Langdon Beck	Langdon	33
26014	Water Forlornes	Driffield	21
41020	Bevern Stream	Clappers Bridge	50
27032	Hebden Beck	Hebden	53

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