Flood estimation report: Thornborough Mill

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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Approval

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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><td>
Buckinghamshire County Council have commissioned JBA to undertake a Section 19 flood investigation of the 23rd December 2020 storm event that caused flooding at Thornborough Mill.

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 raingauges (weighted average of Brackley and Foxcote tipping bucket raingauges (TBR)) and the radar data from the Met Office. This shows a multi-peaked storm event with the corresponding rise in gauged river level at Thornborough Mill, peaking at approximately 9:15am on the 24th. A total of 39mm of rainfall fell in 18 hours. The FEH13 rainfall model[1] indicates that the storm event had a return period of 5 years. Further discussion regarding event rainfall is included in Section 6.

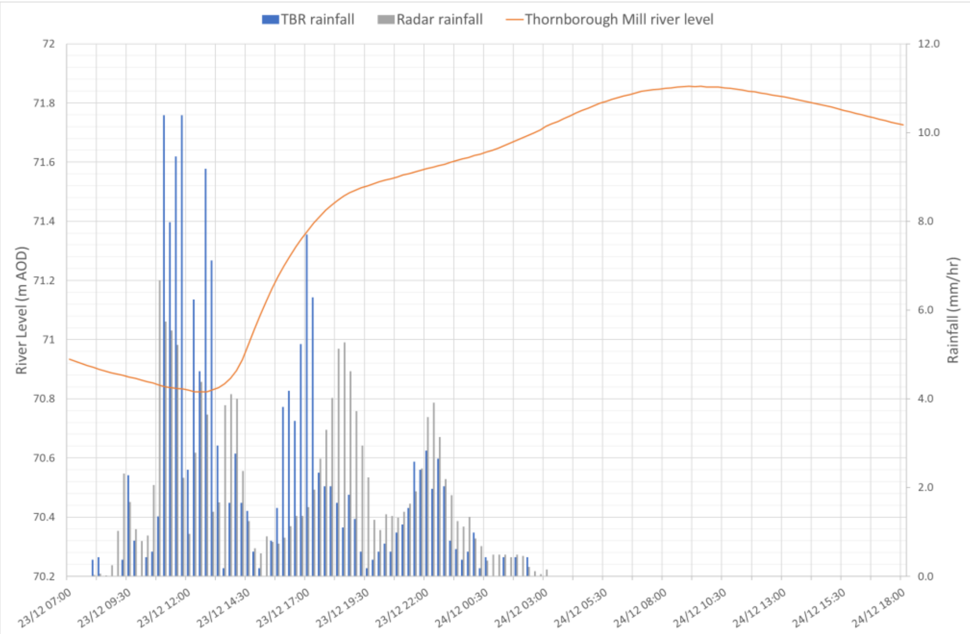

Figure 1-1 Event rainfall and river level

Based on observations made during the event, flooding at Thornborough Mill started at 3am on the 24th December and was caused by water from the Great Ouse watercourse overtopping the right bank at this location.

Aim of the hydrological assessment
The aim of this hydrological assessment is to estimate potential flood flows within the Great Ouse at Thornborough Mill. This estimate will be used in an assessment of the flow return period of the December 2020 event (summarised in Section 6).
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</table>

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

1.2 The catchment

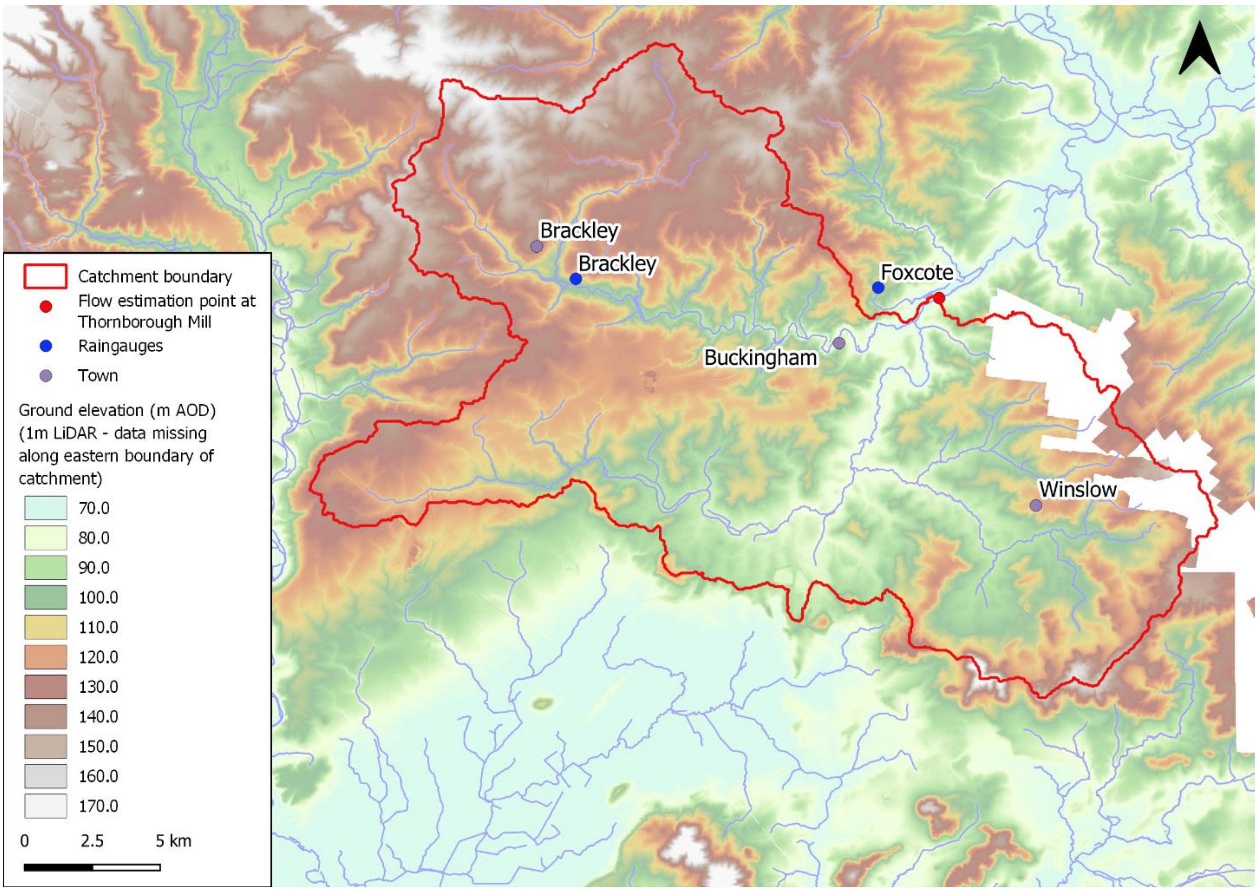


Figure 1-2 Thornborough Mill catchment

Figure 1-3 1:625,000 bedrock geology[2]

Main bedrock geology types within the catchment:

Great Oolite Group – sandstones, limestones, argillaceous

Kellaways/Oxford Clay Formations – mudstone, siltstone, sandstone

Lias Group – mudstone, siltstone, limestone and sandstone

West Walton/Ampthill/ Kimmeridge Formations - clay

Main superficial geology types within the catchment:

Till

Alluvium

Glacial sand and gravel

Description	Thornborough Mill is located on the southern bank of the Great Ouse, approximately 2km north-east of Buckingham and the catchment to this point is relatively large with an area of 388km^2. The Great Ouse rises

[2] https://www.bgs.ac.uk/

	at Radstone, flows initially south to Brackley before following an easterly direction, through Buckingham. Downstream of Buckingham the Great Ouse follows a generally north-easterly direction, passing to the north of Milton Keynes and through Bedford, until it joins the sea to the north of Kings Lynn. Approximately 1.3km upstream of Thornborough Mill, the Padbury Brook tributary joins the main watercourse of the Great Ouse. Ground levels range from approximately 71m AOD at the catchment outlet at Thornborough Mill up to about 172m AOD in the north-western tip of the catchment. There is also higher ground in the very south-eastern part of the catchment (up to about 162m AOD). BGS[2] mapping shows there is an approximate north-west/south-east divide in terms of geology. The south-eastern half of the catchment, drained by the Padbury Brook, is underlain by less permeable mudstones/siltstones/sandstones, characterised as rocks with essentially no groundwater. The north-western half of the catchment, drained by the main watercourse of the Great Ouse, is underlain by more permeable limestones, characterised as a moderately productive aquifer. This divide is also reflected in the soil types which show mainly slowly permeable loamy and clayey soils in the south-eastern half of the catchment and more freely draining lime-rich and loamy soils in the north-western half of the catchment[3]. Standard average annual rainfall (1961-90) for the catchment is 655 mm/year. In terms of land use, the majority of the catchment is covered by arable agricultural fields and grassland. The towns of Buckingham, Brackley and Winslow are the only significant urban areas within this predominantly rural catchment. There are a few small lakes in the catchment, notably The Lake at Stowe, in the northern part of the catchment, and Grebe Lakes, in the southern part of the catchment. Online information indicates all such lakes are ornamental/recreational and, as such, would offer little in terms of flow attenuation.

[3] http://www.landis.org.uk/soilscapes/

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)

(at or very near to the sites of flood estimates)

Water-course	Station name	Gauging authority number	NRFA number	Catchment area (km²)	Type (rated / ultrasonic / level…)	Start of record and end if station closed
Great Ouse	Thornborough Mill	033005	33005	388.5	Rated	Flow: 11/9/1950 – 1/10/1978 Level: 11/9/1950 - present
Great Ouse	Thornborough Mill (downstream)	033005_DS	n/a	388.5	Level	Unknown - present

1.5 Data available at each flow gauging station in Table 1.4

Station name	Start and end of NRFA flood peak record	Update for this study?	OK for QMED?	OK for pooling?	Data quality check needed?
Thornborough Mill	1950-1978	No	Yes	Yes	No
Tabulate any updated or revised flood peak series in the Annex. Give link/reference to any further data quality checks carried out.					n/a

1.5.1 Comments about Thornborough Mill flow gauging station

Information from the NRFA:

The Thornborough Mill gauging station is a flat V crump weir (10.2m wide) with two sluice gates (3.6m broad). Before 1976, the weir was a broad-crested weir with a central V-notch. In 1979, peak flow recordings changed to digital but only upstream stage was recorded, not gate opening or downstream level. Therefore, peak flows after 1979 have been deemed unreliable and excluded from the data classed as 'OK for QMED/OK for pooling'.

A bypass channel exists (flowing to the south of the main watercourse and Thornborough Mill) but operation of the gates has ensured the highest flows have been recorded. One rating has been applied and this assumes the gates are shut below 0.572m and open above it.

As mentioned above, the NRFA information states that downstream level has not been recorded. However, downstream level data has been received from the Environment Agency for the period September-December 2020, in addition to the river level data upstream of the weir. This data is discussed further in Section 0.

1.6 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	No	No	n/a	
Historic flood data	Yes	No	Internet search	No results found for historical flooding at Thornborough Mill.
			CBHE[4]	
			British Chronology of Flash Floods[5]	
			Local knowledge	Unconfirmed flooding of Thornborough Mill property in 2007
Flow or river level data for events	Yes	Level only	Environment Agency	See section 0
Rainfall data for events	Yes	Yes	Environment Agency	Foxcote and Brackley TBRs Met Office radar observed rain-rate (H17)
Potential evaporation data	Yes	No	n/a	
Results from previous studies	Yes	No	2019	Upper Ouse Model Report – Strategic Model Update*
Other data or information	No	No	n/a	

*Report written by Jacobs CH2M but redacted by the Environment Agency as study could not replicate the flooding history.

1.7 Hydrological understanding of catchment

Plots of flow data	Figure 1-4 and Figure 1-5 below show annual hydrographs at the Thornborough Mill flow gauge for 1977 and 1976 respectively. As can be seen from Figure 1-7, these represent the years with the highest and lowest AMAX from the flow record. In 1977, baseflow can be seen to increase between October and February with the highest peak flows occurring during December to February. From March to September, baseflow decreases though there are notable high peaks for the time

[4] https://www.cbhe.hydrology.org.uk/

[5] https://www.jbatrust.org/how-we-help/publications-resources/rivers-and-coasts/uk-chronology-of-flash-floods-1/

of year in June and August.

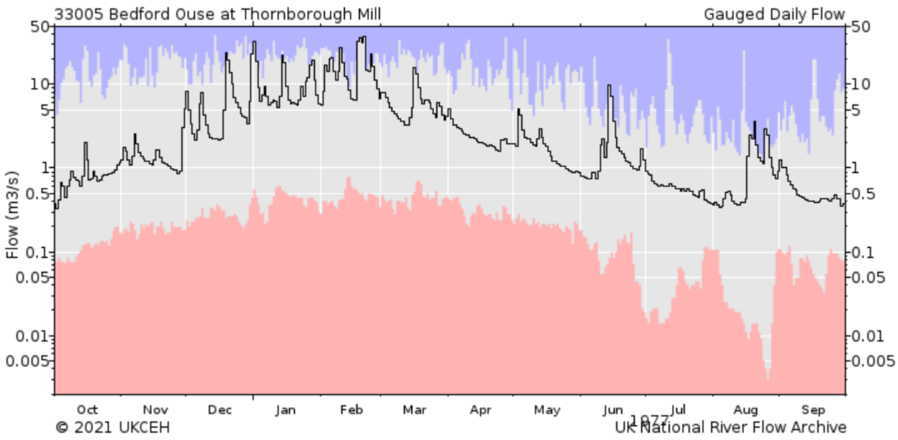


*Figure 1-4 Annual hydrograph at Thornborough Mill – 1977**

In 1976, the lowest AMAX on record, the annual hydrograph shows a steady baseflow between October and April, decreasing to very low flows in August, before increasing quickly to winter levels in September.

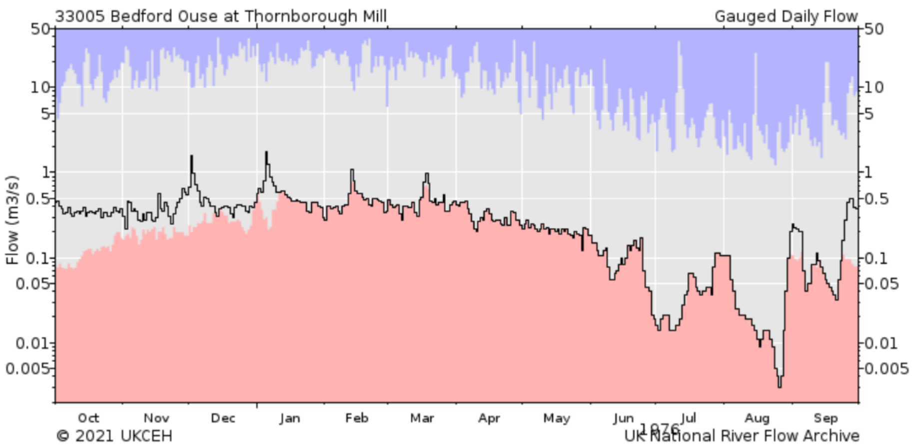
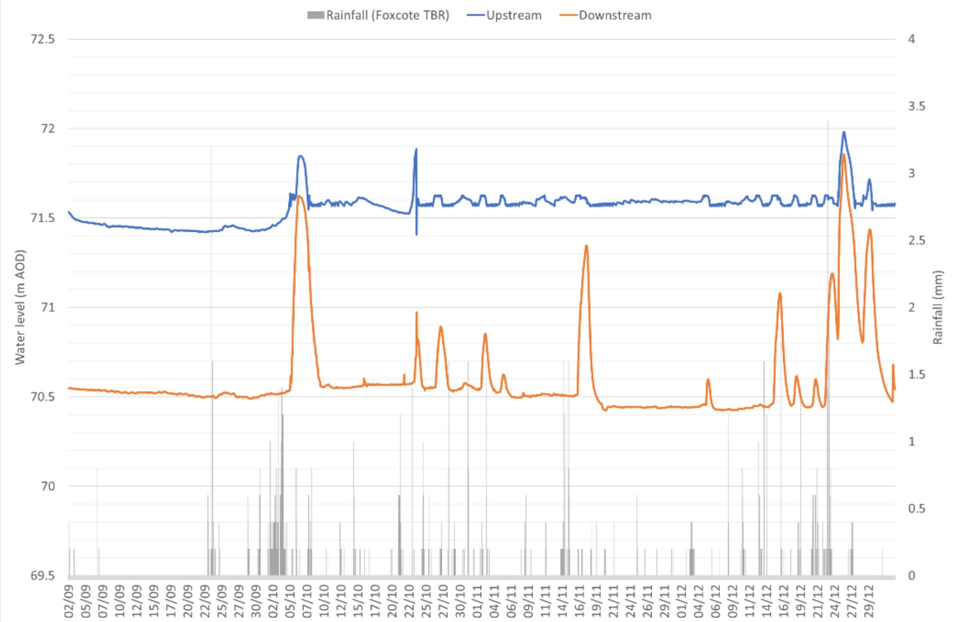


*Figure 1-5 Annual hydrographs at Thornborough Mill – 1976**

*Data taken from the NRFA[6]. Red and blue envelopes represent the lowest and highest flows on each day over the period of record.

[6] https://nrfa.ceh.ac.uk/

	 *Figure 1-6 Thornborough Mill river levels for September to December 2020.* Figure 1-6 shows river levels for the Thornborough Mill upstream and downstream river gauges. The operation of the sluice gates can be seen to moderate water levels upstream at approximately 71.6m AOD. Gate operation does not impact on water levels at the downstream gauge. Both gauges show an increase in water level in response to particularly intense rainfall, such as during Storm Alex, at the beginning of October, and during the event in question on 23rd December.
Hydrological interpretation	A lag analysis was undertaken as part of the study based on the September-December 2020 downstream level gauge data and Brackley raingauge data (see section 7.1 for details). Based on this period, the average lag time between peak level and the centroid of the rainfall is 25 hours.

Plots of flood peak data

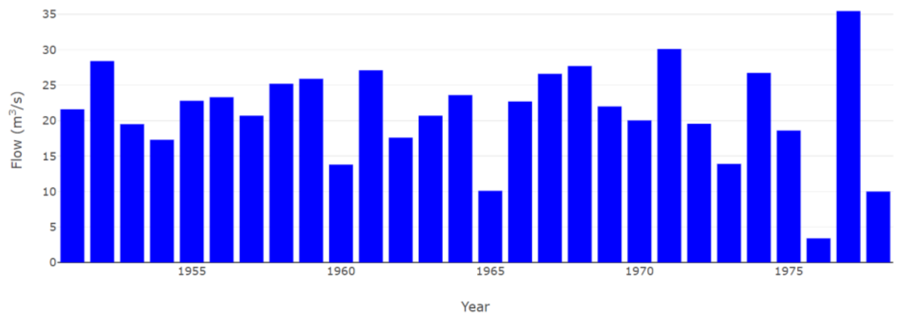


Figure 1-7 AMAX series for Thornborough Mill[6]

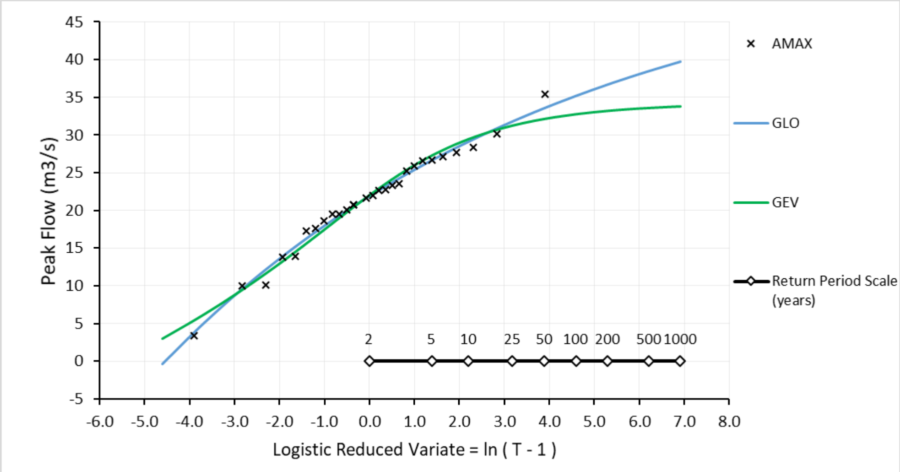


Figure 1-8 Thornborough Mill flood frequency curves

*Table 1-1 Flow frequency analysis for Thornborough Mill**

RP (Years)	Growth Factor	Flood Frequency (m^3/s)
2	1.00	21.8
5	1.22	26.5
10	1.33	29.0
20	1.42	31.1
30	1.47	32.1
50	1.53	33.4
75	1.58	34.4
100	1.61	35.1
200	1.68	36.5
1000	1.81	39.5

*Generalised logistic (GLO) distribution

Hydrological interpretation

Figure 1-7 shows the AMAX series for Thornborough Mill flow gauge from NRFA. As mentioned above, the data spans from 1950-1978, a record length of 28 years. A Mann-Kendall test of the AMAX data indicates that there is no significant trend in the data. The 1976 AMAX is notably low compared with the rest of the data. 1976 experienced very little rainfall and the neighbouring flow gauges on NRFA show a similar pattern for this year.

Figure 1-8 and Table 1-1 show results from a flood frequency analysis carried out using the Thornborough Mill flow AMAX data. Based on FSR regional growth curves, the 100-year growth factor 1.61 is lower than

	the typical range (2.1-4.0) indicating that growth curve and corresponding flow estimates are flatter and lower than would be expected. Such an analysis is only appropriate where the record length is atleast twice as long as the return period, which in this case is up to a return period of 14 years. Estimates for return periods above this should be treated with caution. However, lower estimates at higher return periods could be a reflection of the more permeable geology within the catchment. This has the potential to impact on the flow estimates derived using generalised FEH methods as the catchment is behaving atypically.

Outline of the conceptual model	Observations from the 23 December 2020 event state that flooding from the Great Ouse caused flooding at Thornborough Mill. This is likely to have been caused by intense rainfall over a prolonged period generating high flows within the watercourse, which subsequently overwhelmed the right bank of the river at this location.
Any unusual catchment features to take into account?	There are significant areas of limestone within the catchment and, as such, the catchment draining to the watercourse could differ to the topographic catchment. Without a detailed hydrogeological study, it is difficult to determine the nature of this impact and its significance on flows. A hydrogeological study is beyond the scope of the current study.

1.8 Initial choice of approach

Is FEH appropriate?	Yes, both FEH statistical and ReFH2.
Initial choice of method(s)	As there is a flow gauge at the site (Thornborough Mill), ReFH2 and Enhanced Single Site (ESS) analyses will be undertaken and results compared. Data from this gauge is not available for the December 2020 event so observed rainfall data will be applied to ReFH2 to determine an estimate for flow during the event. Results are discussed in Section 6.
Software to be used (with version numbers)	FEH Web Service[7] / WINFAP-FEH v3.0.003[8] / ReFH2.3 /

[7] CEH 2015. The Flood Estimation Handbook (FEH) Online Service, Centre for Ecology & Hydrology, Wallingford, Oxon, UK.
[8] 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.

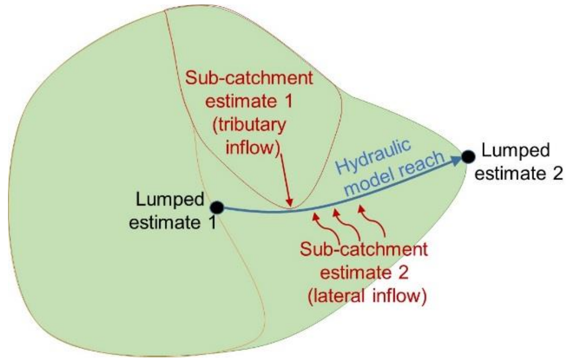
2.1 Summary of subject sites

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
TM	L	Great Ouse	Thornborough Mill	473500	235350	388	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[7]

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
TM	0.983	0.31	0.466	22.37	27.4	655	0.014	0.111

2.3 Checking catchment descriptors

Record how catchment boundary was checked and describe any changes	Catchment boundary checked against 1m LiDAR data[9]. No changes required.
Record how other catchment descriptors were checked and describe any changes.	FARL and BFIHOST19 values checked against OS and BGS mapping. Values seem reasonable. No changes required.
Version of URBEXT	URBEXT2000
Method for updating of URBEXT	CPRE formula from 2006 CEH report on URBEXT2000
Source of BFIHOST	BFIHOST19 was 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].

[9] https://environment.data.gov.uk/DefraDataDownload/?Mode=survey
[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					Urban adjust-ment factor (UAF)	Final QMED estimate (m^3/s)
			NRFA numbers for donor sites used (see 3.3)	Distance between centroids d_{ij} (km)	Moderated QMED adjustment factor, $(A/B)^a$	If more than one donor			
						Weight	Weighted ave. adjustment		
TM	35.2	AM	033005	0	0.609			n/a	21.8

Are the values of QMED spatially consistent?	n/a
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.

3.2 Search for donor sites for QMED (if applicable)

Comment on potential donor sites Include a map if necessary. Note that donor catchments should usually be rural.	No donor required as site is gauged.

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

3.3 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)
TM (ESS)	TM	Yes	None	L-CV: 0.239 L-SKEW: 0.185
TM (UG)*	TM	No	Thornborough Mill (033005) removed. Ugie@Inverugie (10002) added to complete 500 year record.	L-CV: 0.256 L-SKEW: 0.253
Note: Pooling groups were derived using the procedures from Science Report SC050050 (2008).				

*UG – treated as ungauged

3.4 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
TM	ESS	TM(ESS)	GL Lowest Z-value (-2.5)	n/a	Location: 1.00 Scale: 0.243 Shape: -0.185	2.76
TM	P	TM (UG)	GL Lowest Z-value (-1.62)	n/a	Location: 1.00 Scale: 0.256 Shape: -0.253	3.23

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).

The GL distribution fitted to the enhanced pooling group (ie including Thornborough Mill gauge) was not deemed to be an acceptable fit (the absolute Z-value of 2.5 is greater than acceptable range of 0 to 1.64). With the Thornborough Mill gauge removed, this fit improves, reflecting the differing behaviour of the Thornborough Mill catchment compared with the rest in the pooling group. This can be seen in Figure 3-1 which shows the flood frequency curves based on different inputs. The blue curve treats Thornborough Mill as ungauged and, as such, is based on catchments descriptors only for both QMED (unadjusted) and pooling group. The red curve shows the results from the enhanced single site analysis using QMED based on AMAX data (21.8m3/s) and a pooling group including Thornborough Mill. The green curve is the same as the red but with Thornborough Mill removed from the pooling group (and Ugie added, see section 3.3), showing that Thornborough Mill has the effect of reducing the growth factors and corresponding flow estimates, more markedly at higher return periods. Given the gauge at the site is classified as suitable for QMED and pooling on NRFA, the preferred estimates are those based on gauge AMAX data and the red curve shown below.

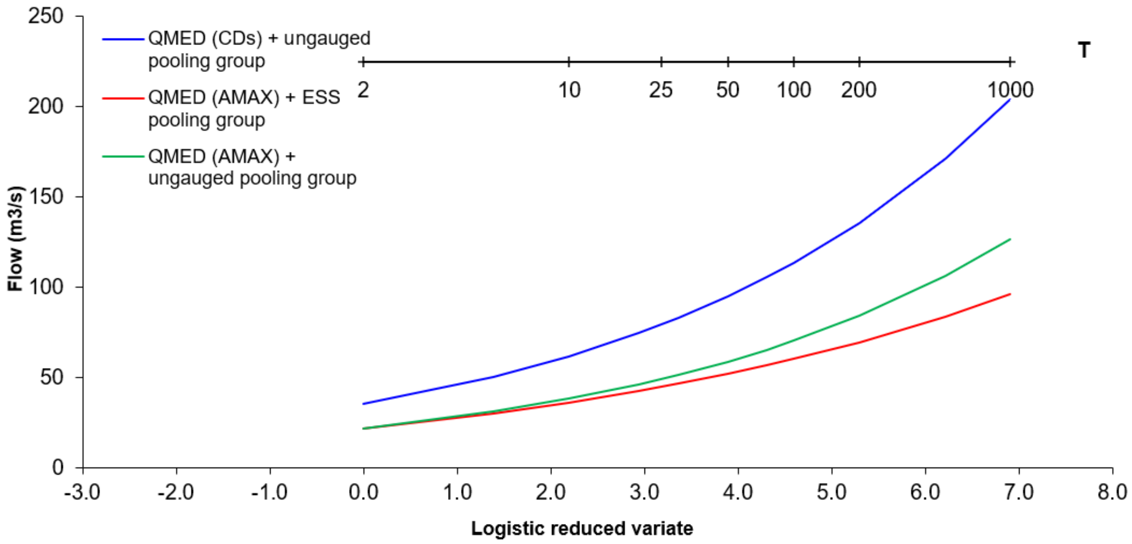


Figure 3-1 FEH statistical flood frequency curves

3.5 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**	**200**	**1000**
TM*	21.8	30.2	36.2	42.6	46.6	52.0	56.7	60.2	69.5	96.0

*Based on Thornborough Mill AMAX data for QMED and enhanced single site pooling group

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[12] 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)**
TM	CD	381.92	15.06	65.65	n/a
Link to details of any lag or flood event analysis		The Tp(0) in ReFH2 was adjusted using a scaling factor between the Tp(0) from the lag analysis and the Tp(0) from FEH Volume 4 (as per guidance in the Flood Estimation Guidelines[13]). Further details about the lag analysis are given in Section 7.			
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)
TM	Rural	Winter	26.25

4.3 Flood estimates from the ReFH2 method

Note: This table is for recording results for lumped catchments. There is no need to record peak flows from sub-catchments or intervening areas that are being used as inputs to a semi-distributed model of the river system.

Site code	Flood peak (m³/s) for the following return periods (in years)									
	2	**5**	**10**	**20**	**30**	**50**	**75**	**100**	**200**	**1000**
TM	40.3	52.5	61.1	70.0	75.6	83.2	89.9	95.0	108.9	150.7

[12] 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.

[13] Flood Estimation Guidelines, Technical guidance 197_08. Environment Agency, June 2020.

5 Discussion and summary of results

5.1 Comparison of results from different methods

This table compares peak flows from various methods with those from the FEH Statistical method at example sites for two key return periods. Given the 2 year estimate for the FEH statistical method is based on gauge data, the 2 year estimate for ReFH is considered to be too high.

Site code	Ratio of peak flow to FEH Statistical peak	
	Return period 2 years	Return period 100 years
	ReFH	ReFH
TM	1.85	1.58

5.2 Final choice of method

Choice of method and reasons	The Thornborough catchment is large with mixed geology, with notable differences between the less permeable eastern part of the catchment and the more permeable western/northern parts of the catchment. Gauge data and the FEH statistical analysis indicate that the catchment is responding differently than a generalised FEH approach would suggest. Further study is required to ascertain why this is, though the varying permeability of the catchment is one possible cause. As catchment descriptors appear to generate a higher flood frequency curve compared with gauge data, the FEH statistical method, based on QMED derived from AMAX data and an enhanced single site pooling group, is preferred in this instance. However, no flow data exists for the 20 December 2020 and results from previous modelling studies are not available at this location. Therefore, observed rainfall was applied to the ReFH model in an attempt to determine the flow return period for the event. Discussion regarding flow return period estimation for the 23 December event is provided in section 6.
How will the flows be applied to a hydraulic model?	No hydraulic modelling has been undertaken as part of the wider study.

5.3 Assumptions, limitations and uncertainty

Key assumptions	The key assumption here is that Thornborough Mill gauge is suitable for use in QMED estimation and pooling group derivation. AMAX data is only available up to 1979 and so does not account for any catchment changes since this time. Also, the existence of limestone geology within the catchment means that the area draining to Thornborough Mill could be very different to the topographic catchment.
Limitations	Gauge data indicates that the catchment to Thornborough Mill is behaving differently to what would be expected from generalised FEH methods. The ReFH2 method in this instance relies heavily on catchment descriptors (with a minor adjustment to Tp based on limited river level data) and is therefore less applicable here.

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 following range of a 95% confidence interval is to be expected per design flood for a rural site (numbers quoted are multipliers): AEP / No donor / 1 donor 50% / 0.48 – 2.10 / 0.50 – 2.02 1% / 0.45 – 2.23 / 0.47 – 2.12
Comment on the suitability of the results for future studies	The flow estimates derived here were for the sole purpose of the section 19 investigation to offer some idea of flow return period. For any other study a review of their suitability should be undertaken.
Give any other comments on the study	Further work is required to better understand the catchment and its atypical behaviour. This could include undertaking a hydrogeological study to identify the influence of groundwater on flood flows and impact of varying geology on catchment response. Previous modelling studies of the Great Ouse in 2011 by Capita Symonds[14] and 2019 by Jacobs CH2M[15] have attempted to model the upper Great Ouse, including the catchment to Thornborough Mill. However, both these studies were not able to sufficiently simulate historical flood events and were subsequently rejected by the Environment Agency.

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?	Discussion regarding possible flow return period of the December 2020 event is given in Section **Error! Reference source not found.**.
What is the range of 100-year growth factors? Is this realistic?	The 1% AEP growth factor range for the methods is: • FEH Statistical: 2.76 • ReFH2: 2.36 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. The 100-year growth factor based on gauge data is 1.61 indicating that FEH methods will overestimate flows for the catchment.
If 1000-year flows have been	1.59 (FEH statistical and ReFH2), 1.13 (gauge data)

[14] Upper River Great Ouse Flood Hazard Mapping, Capita Symonds & Scott Wilson, June 2011
[15] M+F 2016/17 Modelling 1 – Upper Ouse, Jacobs CH2M, June 2019

derived, what is the range of ratios for 1000-year flow over 100-year flow?	
How do the results compare with those of other studies? Explain any differences and conclude which results should be preferred.	Previous modelling studies were carried out in 2011 and 2019 but were rejected by the Environment Agency due to inability to simulate historical flood events.
Are the results compatible with the longer-term flood history?	See section 6.
Describe any other checks on the results	n/a

5.5 Final results

Results from gauge data and both FEH methods have been provided to inform the discussion about the event in section 6.

Site code	Flood peak (m^3/s) for the following return periods (in years)							
	2	**5**	**10**	**20**	**30**	**50**	**75**	**100**
TM (AMAX) (from Table 1-1)	21.80	26.53	28.98	31.05	32.15	33.44	34.40	35.05
TM (FEH Stats)	21.81	30.19	36.19	42.57	46.59	52.04	56.71	60.22
TM (ReFH2)	40.30	52.45	61.12	70.04	75.61	83.23	89.88	94.98

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 5.5 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**
TM (FEH Stats)	10.9	44.1	25.0	109.3	28.3	127.7
TM (ReFH2)	20.2	81.4	40.0	174.8	44.6	201.3

Note: The above confidence limits are based on results from DEFRA's research report SC130009/R[16]. 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.

[16] 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 river level from Thornborough Mill D/S gauge. Brackley and Foxcote TBRs are the closest raingauges, lying approximately 7.8km north-west and 5.8km north-east of the Thornborough Mill catchment respectively, see Figure 1-2 in section 1.2. Catchment average rainfall was calculated using these raingauges (based on area weighting) and also Met Office radar data.

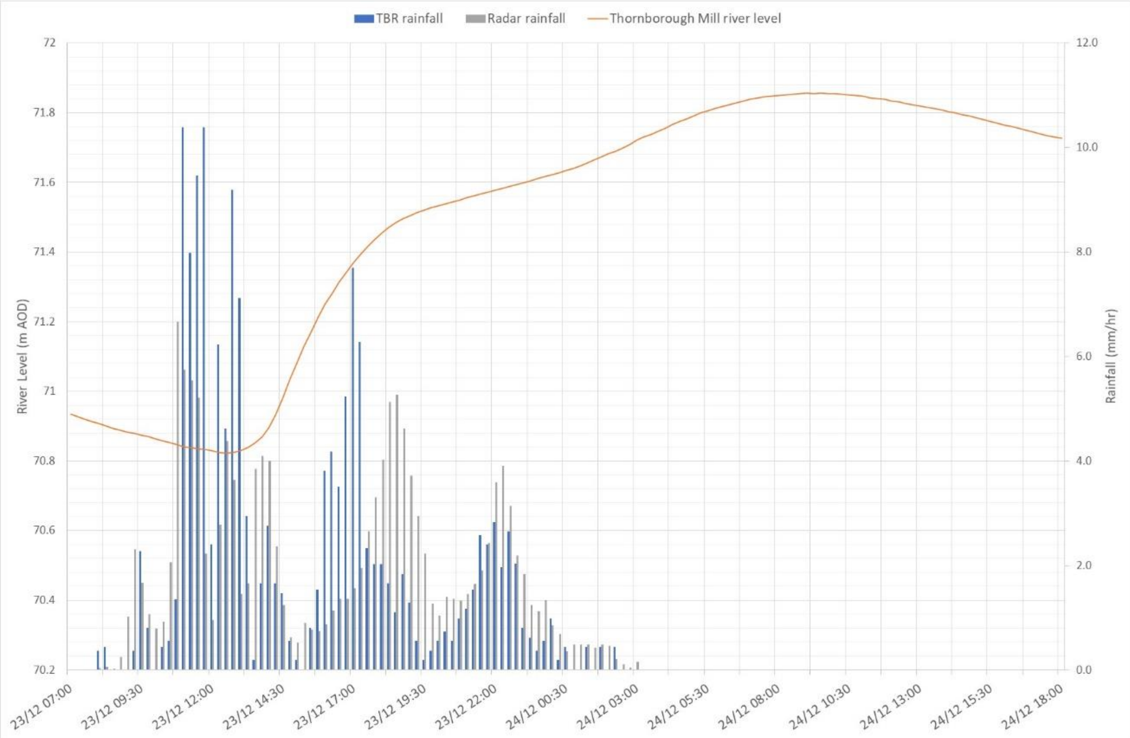


Figure 6-1 Event rainfall and Thornborough Mill D/S river level

In terms of total rainfall for the event, both TBR and radar sources give similar results of 39mm and 37mm respectively over 18 hours. The FEH13 DDF model, available via the FEH Webservice[17], estimates that, for the Thornborough Mill catchment, this rainfall depth has a return period of approximately 5 years.

6.2 Catchment response

Figure 6-1 shows the rise of the river level at Thornborough Mill (downstream of the weir) in response to the storm event a peak level of 71.86m AOD reached at 09:00 on 24 December. Gauged flow data was not available for the event and there was not sufficient level data to undertake a frequency analysis. Therefore, observed rainfall was run through the ReFH2 model to determine flow during the event. 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.

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

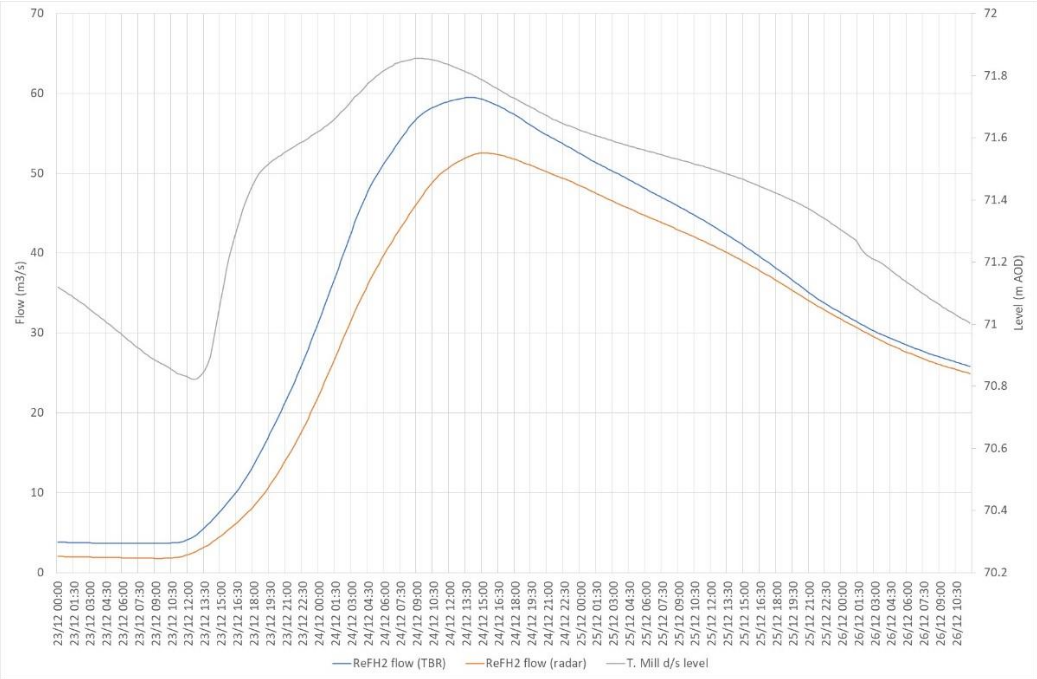


Figure 6-2 ReFH2 hydrographs and Thornborough Mill D/S river level

Figure 6-2 shows the event hydrograph shape based on ReFH2 simulated flow from TBR and radar data, and river level data from Thornborough Mill d/s gauge. This shows that the ReFH2 flow peaks at 59.5 m^3/s at 14:00 on 24 December, based on TBR data, and 52.5m^3/s at 15:15, based on radar data. Gauge data indicates that levels in the watercourse peaked at about 09:00 on 24th December.

As seen in the flow estimation analysis above, the ReFH2 model generates flows that are far greater than the enhanced single site analysis. Figure 6-3 shows the flood frequency curves for the FEH methods and single site analysis using gauged AMAX data. This shows that the AMAX and associated single site curve are significantly lower and flatter than those from FEH methods.

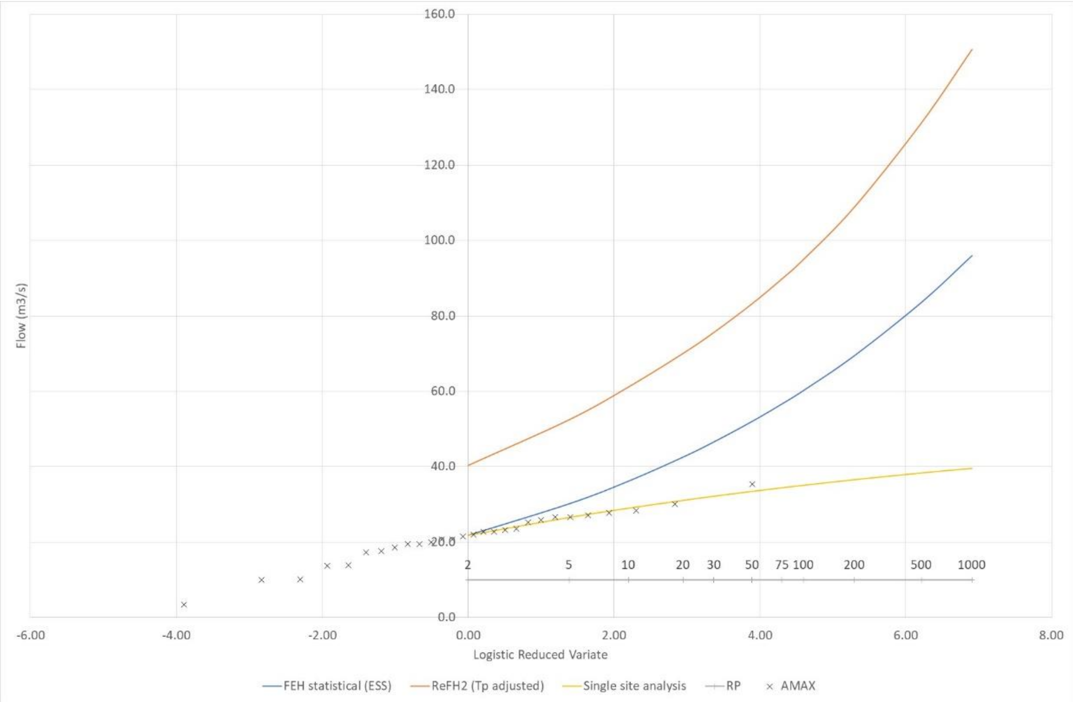


Figure 6-3 Flood frequency curves for FEH methods and Thornborough Mill flow AMAX data

QMED from the ReFH2 model is 1.85 times higher than that from the enhanced single site (ESS) analysis, though this drops to 1.58 times for the 100-year return period. Scaling down the estimated flow from ReFH2 based on observed rainfall and a factor of 1.85, gives an estimated flow of 28.4 m^3/s based on radar rainfall and 32.2 m^3/s based on TBR rainfall. This equates to a return period of approximately 10-30 years based on the single site flood frequency curve and <2 years based on the ESS method. If a lower scaling factor of 1.69 is used (based on ReFH2:ESS at 10 years) this generates an estimated flow of 31.1-35.2m^3/s, approximately a 20-100 year return period based on the singe site analysis and 5-10 years based on the ESS method.

There are no other proven instances of flooding of Thornborough Mill at property level. There is some anecdotal evidence of possible flooding during 2007, though no solid evidence to support this claim exists. The lower tier of the back garden is known to flood often (based on owner's observations since living in the property from 2015) and the upper tier is known to flood occasionally. Based on 1m LiDAR ground elevation data, the house is situated at approximately 71.5m AOD and the lower and upper tiers of the garden are located at approximately 70.5m AOD and 71.0m AOD respectively. The peak level of the Thornborough Level gauge (downstream of the weir) during the 23 September event was 71.86m AOD. Interestingly, the gauge data shows that the river level rose to 71.6m AOD on 5 October 2020 following storm Alex but there is no report of the house flooding at this time.

Based on the flooding at Thornborough Mill in 2020 and possible flooding prior to this, a flow return period for the December 2020 event of 10-30 years is reasonable and up to 100 years is possible. 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 this case, there is no flow data available for the event 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.

7 Annex

7.1 Lag analysis

	Rainfall centroid	Date of peak level	LAG	Tp(0)
1	03/10/2020 13:07	05/10/2020 00:15	35.1	25.92
2	21/10/2020 10:08	22/10/2020 09:45	23.6	17.77
3	24/10/2020 23:27	25/10/2020 22:45	23.3	17.55
4	31/10/2020 11:22	01/11/2020 11:45	24.4	18.34
5	03/11/2020 05:35	04/11/2020 04:00	22.4	16.91
6	14/11/2020 18:01	16/11/2020 09:45	39.7	29.14
7	03/12/2020 09:43	04/12/2020 08:45	23.0	17.34
8	13/12/2020 20:44	14/12/2020 23:00	26.3	19.70
9	16/12/2020 15:28	17/12/2020 09:30	18.0	13.73
10	19/12/2020 05:53	20/12/2020 04:45	22.9	17.27
11	21/12/2020 13:33	22/12/2020 16:00	26.5	19.84
12	23/12/2020 14:51	24/12/2020 09:00	18.2	13.88
			Geomean	18.52
	$Tp(0)_{CD}$ (FEHRR)	17.38		
	$Tp(0)_{Ob}$ (LAG)	18.52		
	Ratio	1.07		
	$Tp(0)_{CD}$ (ReFH2)	15.06		
	$Tp(0)_{ADJ}$ (ReFH2)	16.05		

7.2 Enhanced single site pooling group

Station Number	Watercourse	Location	Years
33005	Bedford Ouse	Thornborough Mill	28
31005	Welland	Tixover	57
28024	Wreake	Syston Mill	52
22006	Blyth	Hartford Bridge	59
14001	Eden	Kemback	39
39034	Evenlode	Cassington Mill	48
39006	Windrush	Newbridge	69
39021	Cherwell	Enslow Mill	52
53008	Avon	Great Somerford	56
43005	Avon	Amesbury	30
55021	Lugg	Butts Bridge	35

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