



Wrexham Solar Development

Baseline Flood Model Report

Novus RS Ltd

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1 Introduction

1.1 Background

This Report describes the application of a hydraulic flood model to a section of the River Clywedog near Wrexham in Wales (Figure 1-1). The modelling has been undertaken in order to appraise the site owner of the flood risk to the Site. The approximate Site boundary is shown in red.

This is v2 of the Report and responds to comments made by NRW on the v1 Report and model.

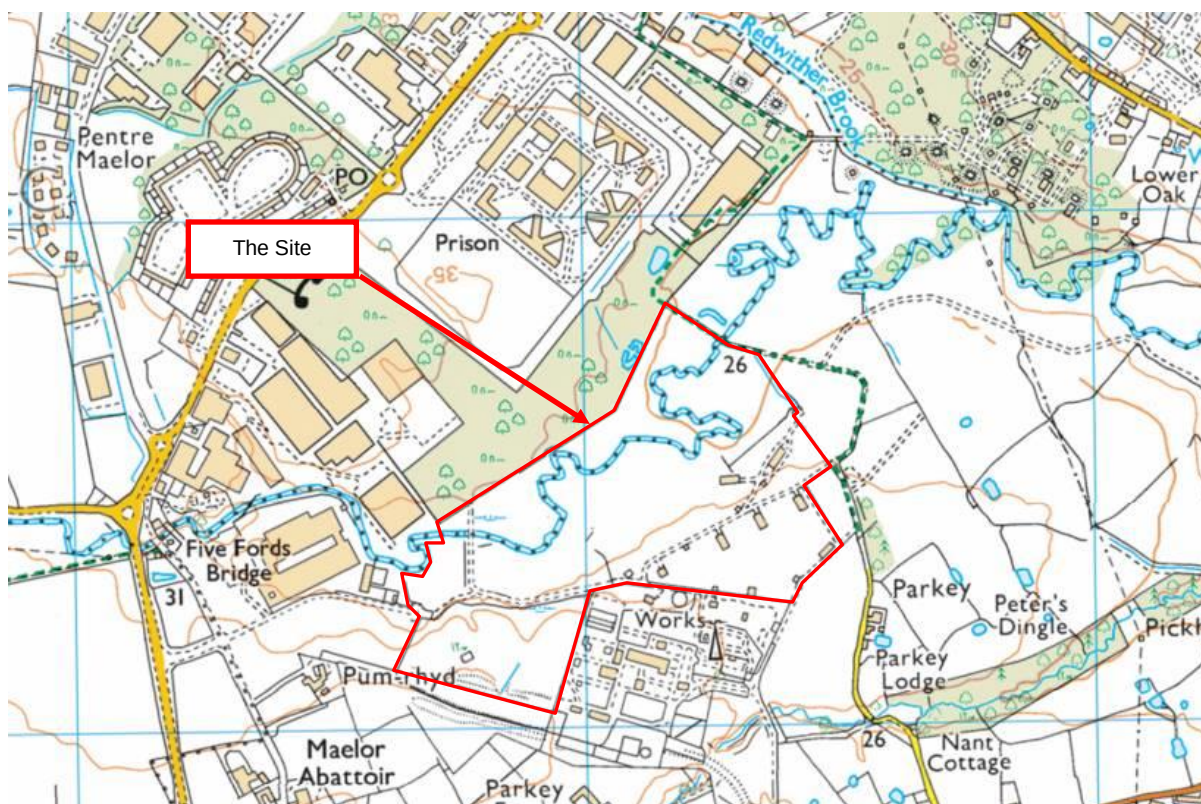


Figure 1-1: Location of Site

1.2 Engagement with NRW

The following exchanges have taken place with NRW in relation to this Site:

- In **2019** as part of a Scoping Assessment, it was confirmed by NRW that there was no detailed flood modelling available for the Site. Extracts from the NRW flood map are shown in Figure 1-2.
- Corylus sought pre-application development advice in **September 2019** on behalf of the client, with the NRW response provided in October 2019 (ref CAS-101338-S4D2).
- In **March 2020**, a notification was provided to NRW (Rhys Hughes) of the intention to undertake the modelling work that is the subject of this Report.
- In **June 2020**, the model was submitted to NRW for review
- A response was received from NRW on **14 July 2020** (Ref NRW:00944180) with modelling comments shown in Appendix C.

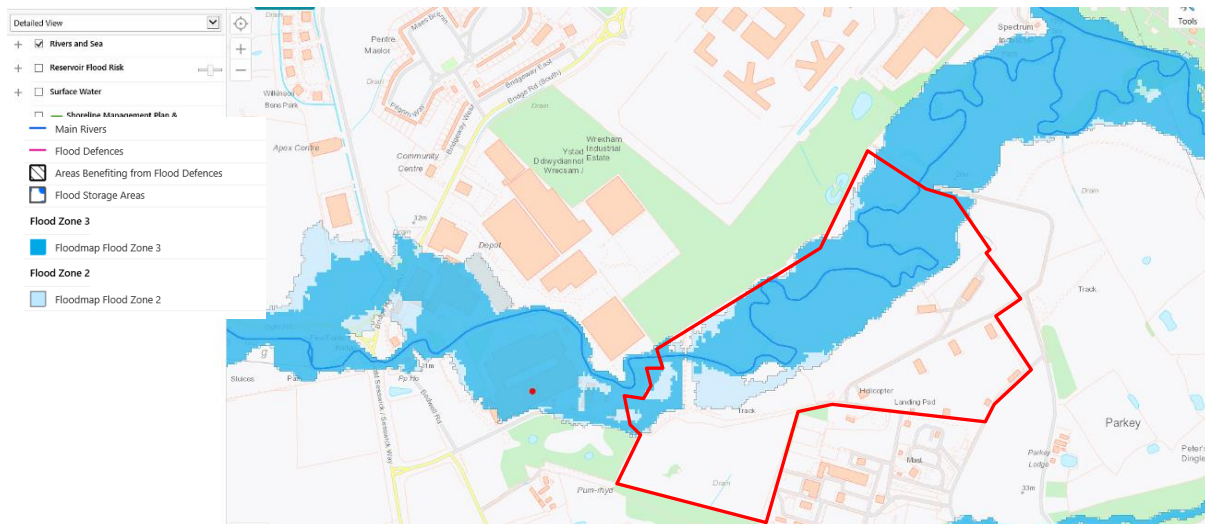


Figure 1-2: Extracts from NRW Flood Maps

1.3 Structure of Report

The Report comprises the following Sections:

This Section provides the background to the Report;

- Section 2 describes the hydrological modelling
- Section 3 describes the development of the model
- Section 4 provides flood extents and profiles and a discussion of the results
- Section 5 is a summary of the main findings.

The following Appendices are provided:

- Appendix A is the Hydrological modelling Report
- Appendix B is NRW Flood Calculation template
- Appendix C contains the comments made by NRW and the response to them
- Appendix D is the Model log

Model files will be provided when requested by NRW.

2 Hydrological Modelling

2.1 Introduction

Hydrological modelling is required to define the inflows to the model. The modelling has been undertaken by Wallingford Hydrosolutions Limited, whose report is provided in Appendix A. This has been undertaken in line with the GN008 Guidelines (NRW, 2017), with results presented in the standard template in Appendix B.

Calculations have been presented for a location downstream of the Site at a flow measurement stations known as Bowling Bank (67025). Whilst this is an official NRFA (National River Flow Archive) gauging station, the derived flows are deemed “not suitable” for use in flood estimation procedures due primarily to the backwater effects of the River Dee, located around 1 km downstream of the gauging station. Nevertheless, it provides a useful reference for calculations, subject to the comments in this Section.

The choice of Bowling Bank for flood calculations that is downstream of the captioned Site reflects the fact that the client has an interest in further sites, downstream of the captioned Site, but within the catchment area for Bowling Bank. The use of a location downstream of all sites of interest enables consistency to be brought to the analyses that will follow from this initial phase of modelling. This strategy was discussed with the NRW and agreed, in principle through email received on 13th August 2020.



Figure 2-1: Catchment Area for Bowling Bank

2.2 Review of contributing catchment areas

The extracts from the NRFA web site show the catchment area for the gauging station to be 98.6 km² (Table 2-1). We have highlighted with the NRFA an inconsistency with the areas shown on the FEH Web Services which shows a catchment area of 105.5 km² and which has been acknowledged. As confirmed in Table 1 of Appendix A, we have used the higher of these areas in flow calculations.

Table 2-1: Extracts from NRFA Web Site for Bowling Bank

67025 - Clywedog at Bowling Bank

Station info	Daily flow data	Catchment info	Photo gallery
Grid Reference:	SJ395482	Hydrometric Area:	67 - Dee (Cheshire)
Catchment Area:	98.6 km ²	Measuring Authority (local station number):	Natural Resources Wales (067025)
Station Level:	14 m AOD	Station Operating Period:	01/1976 - N/A
Station Summary Description:			
Simple Crump profile weir. Runoff influenced by groundwater abstraction/recharge.			

The Bowling Bank gauge is located downstream of the Site. The principal tributaries of the Clywedog within and downstream of the Site are the Redwither Brook (Figure 2-2) with an area of 10.82 km² and the Bedwell Brook (Figure 2-3) with a catchment area of 5.55 km². In the initial model configuration, the inflow for the entire Bowling Brook catchment has been applied at the upstream boundary. This is clearly a conservative strategy; however, the NRW have indicated that this is not appropriate for a flood map challenge. An alternative strategy has thus been used in order to derive consistent inflow hydrographs for three boundaries, these being:

- the Redwither Brook (Figure 2-2) with an area of 10.82 km² ;
- the Bedwell Brook (Figure 2-3) with a catchment area of 5.55 km²; and
- the Clywedog, upstream of its confluence with the Redwither Brook.

The revised strategy is described in Section 2.4.

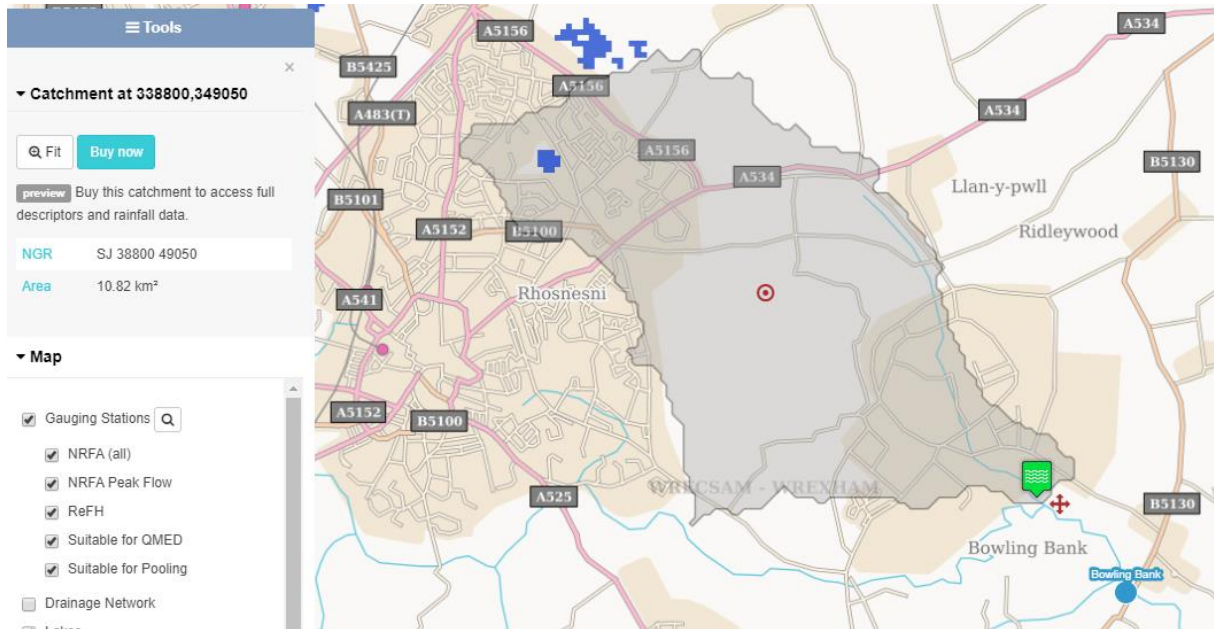


Figure 2-2: Catchment Area for Redwither Brook

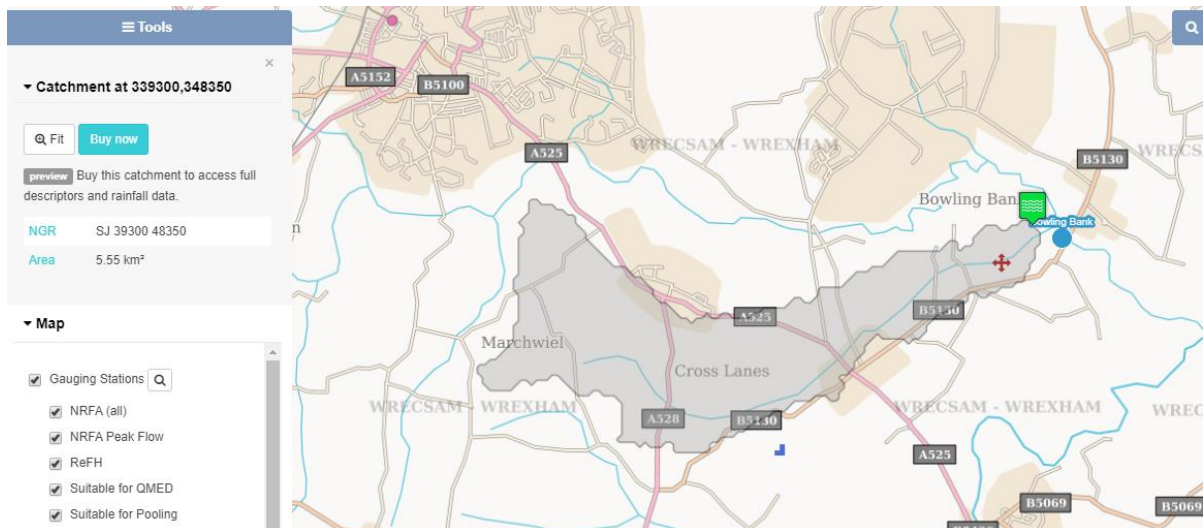


Figure 2-3: Catchment Area for Bedwell Brook

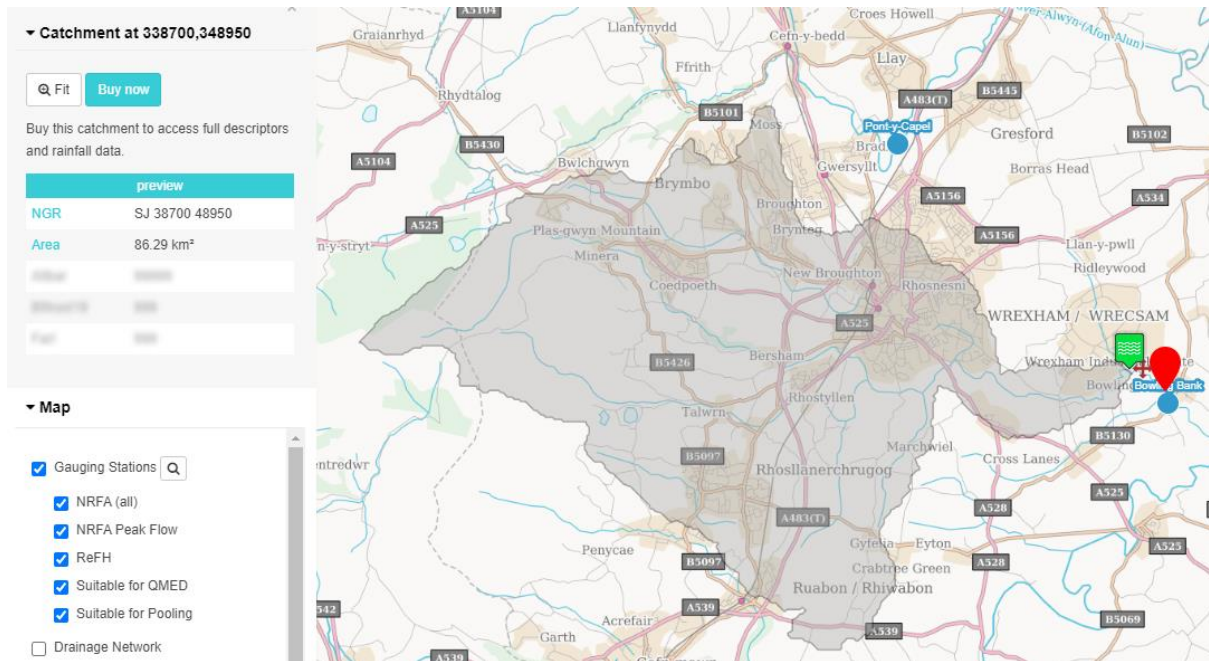


Figure 2-4: Catchment Area for Clywedog upstream of confluence with Bedwell Brook

2.3 Results for Bowling Bank

The results are shown for different return periods in Table 2-2; the Final results are largely based on the Statistical Method, save for the 0.1% AEP for which the weighting as prescribed in GN008 has been applied.

Design hydrographs have been obtained through scaling of flood peaks using the hydrographs obtained from the rainfall-runoff method and are shown in Figure 2-5.

Table 2-2: Design flood peaks for Bowling Bank

Return period (yrs.)	AEP	Statistical (m3/s)	Rainfall-runoff (m3/s)	Final (m3/s)
2	50.0%	16.63	19.7	16.63
25	4.0%	31.47	44.28	31.47
50	2.0%	36.23	52.77	36.23
100	1.0%	41.59	61.95	41.59
500	0.2%	57.03	85.8	57.6
1000	0.1%	65.26	96.79	64.98

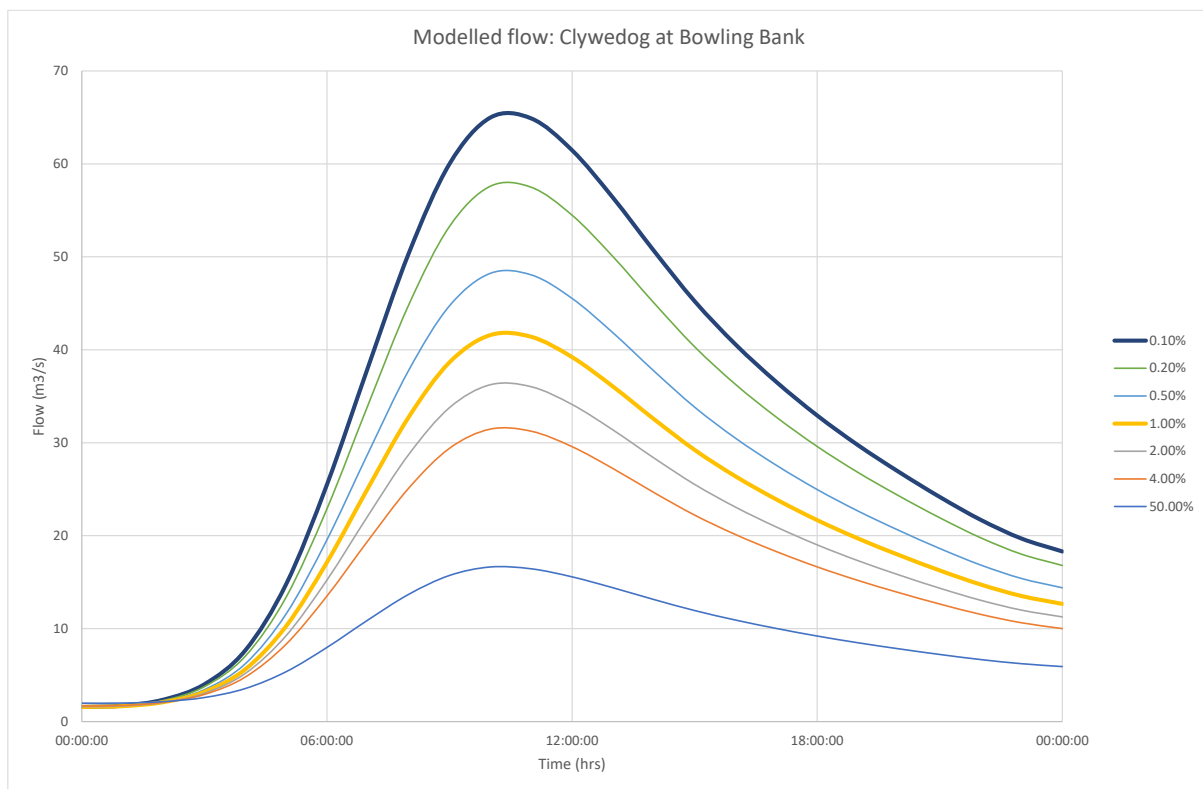


Figure 2-5: Design flood hydrographs for Bowling Bank

2.4 Derivation of inflow boundary hydrographs

In the revised model, there are three inflow boundaries:

- The River Clywedog at the upstream end of the model,
- The Redwither brook
- The Bedwell Brook

Following discussion with NRW, it was agreed that the inflow hydrographs could be scaled from the peak flows for Bowling Bank given in Section 2.3. The methodology used to do this is as follows:

1. Obtain the 1% (1 in 100) design flood hydrograph for the River Clywedog upstream of the Redwither Brook using the ReFH2 methodology – this will be used as the basis for the inflow boundary at the upstream end of the model;
2. Extract the storm parameters (duration, time step, areal reduction factor, seasonal correction factor) for this storm at this location.
3. Use ReFH2 to obtain the hydrographs **using the storm extracted for the Clywedog catchment** for both the Redwither and Bedwell Brooks.
4. Sum the hydrograph ordinates for each time step for the three hydrographs
5. Produce three dimensionless flow hydrographs, one for each inflow boundary, by dividing each ordinate by the peak of the summed hydrograph.
6. Multiply by the appropriate instantaneous peak for Bowling Bank to obtain three inflow hydrographs for each return period.

The key step here is that the hydrographs for the two tributaries are not for their respective 1% case; they are for the 1 (1 in 100) critical duration storm from the main catchment applied to the tributaries.

3.2.2 Bank levels and Flood walls Survey

Bank levels and flood walls survey data for the River Clywedog (K1041-BANK LEVELS.dwg, submitted under separate cover) were obtained by Invar Mapping Surveys in May 2020. Figure 3-2 shows the bank levels and flood walls (Red lines) collected as part of this survey. This survey data has been used to represent the bank elevation and flood defence walls in the model.

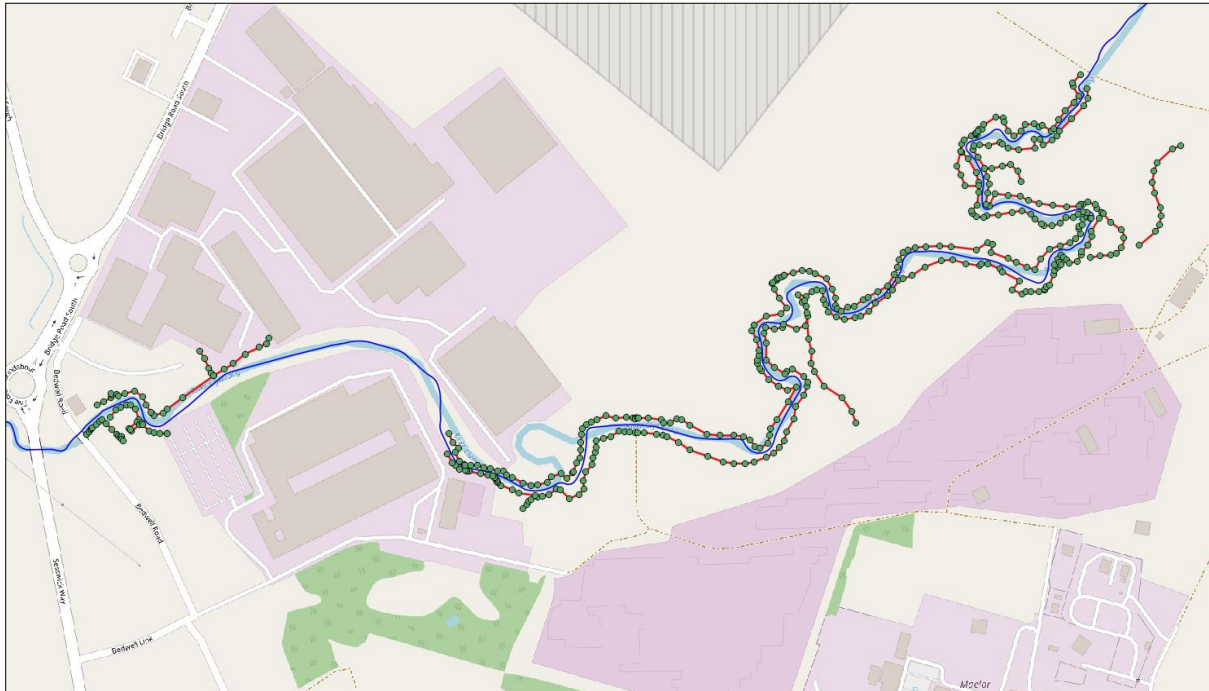


Figure 3-2: Surveyed Bank levels and Flood walls.

3.2.3 Topographic Survey

Topographic survey (K1041-TOPOGRAPHIC 2D.dwg, submitted under separate cover) has been used to create a digital terrain model (DTM). The ground levels at the site has been updated based on the DTM derived from the topographic survey. The survey used in the model was dated May 2020 and completed by Invar Mapping Surveys. The extent of the topographic survey is shown Figure 3-3.



Figure 3-3: Extent of the Topographic Survey.

3.2.4 Proposed Site Survey

Proposed industrial site Survey (WREX-259-04.dwg) was used to digitise the buildings and the PV Extension (Solar panel extensions) survey (WR-EX-258-06D STAGE 2 DESIGN LAYOUT.dwg) was used to digitise the Solar panel extensions.

3.2.5 Lidar

Digital Terrain Model (DTM) data (generated via LiDAR) at 1.0m resolution was downloaded from the lle.gov.wales website. The LiDAR data has been used to build the ground model for the 2D (TUFLOW) model. The extent of the LiDAR data is shown in Figure 3-4.

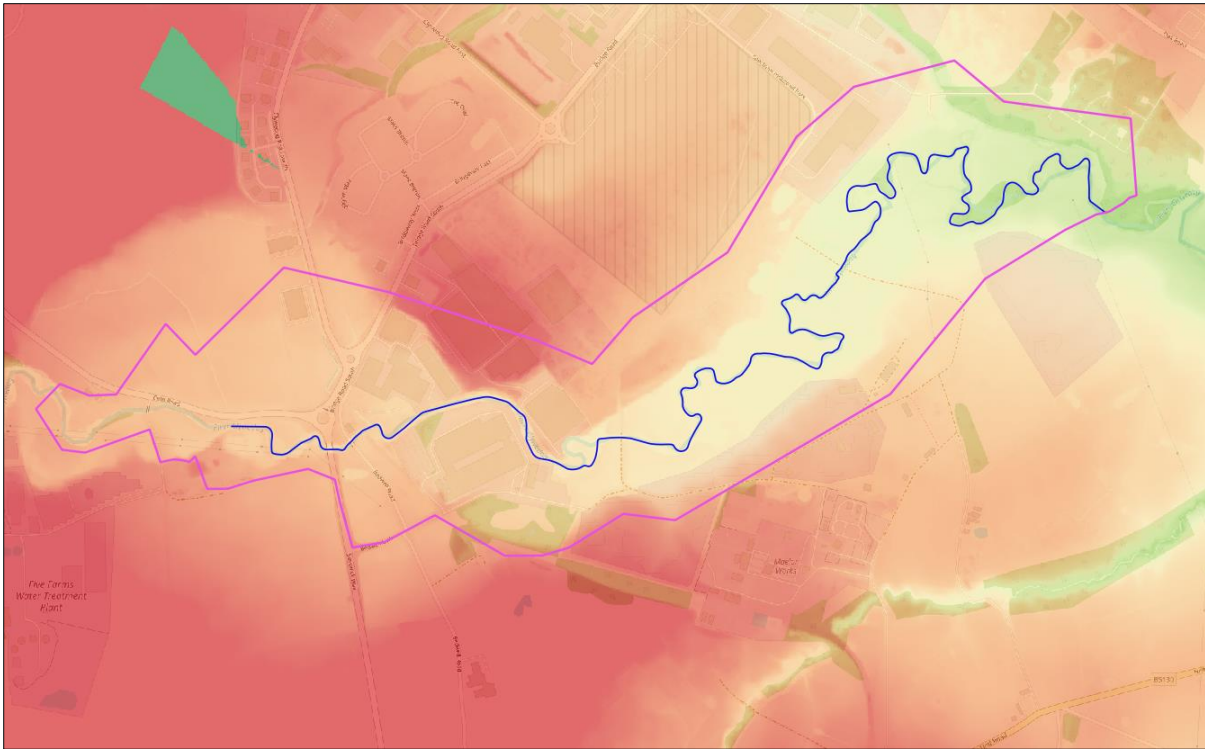


Figure 3-4: Extent of LiDAR data.

3.2.6 Comparison of LiDAR and Survey data

The surveys detailed above have enabled a comparison with the LiDAR data by way of a quality check. Comparison are presented for 4 sections; the locations are shown in Figure 3-5 and the comparison in Figure 3-6.

The comparison shows very good agreement between the two data sources which provides confidence in the use of LiDAR data for the model domain. The largest differences are for Section 1 where the surveyed data is around 0.1 m above the LiDAR DTM with a maximum difference of 0.2 m. The localised nature of these differences may reflect specific agricultural practices. In any case, the model has been based on the surveyed data, where available, which in this instance is more conservative with regard to flood levels and depths.

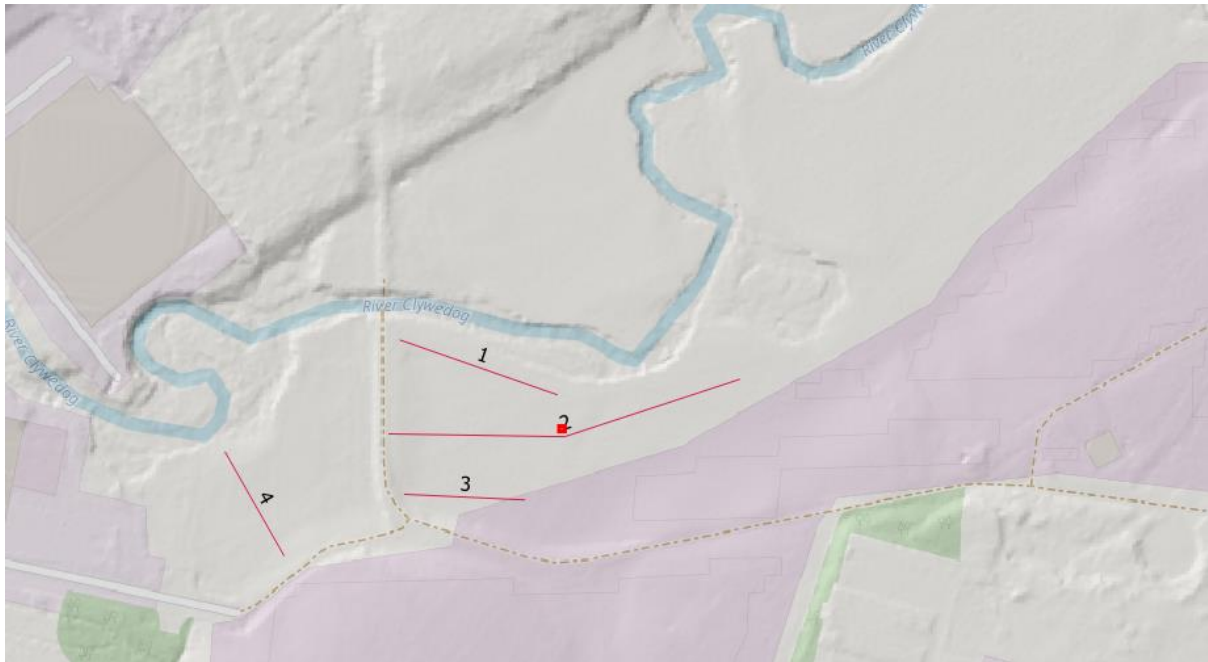


Figure 3-5: Locations where survey data have been compared LiDAR data.

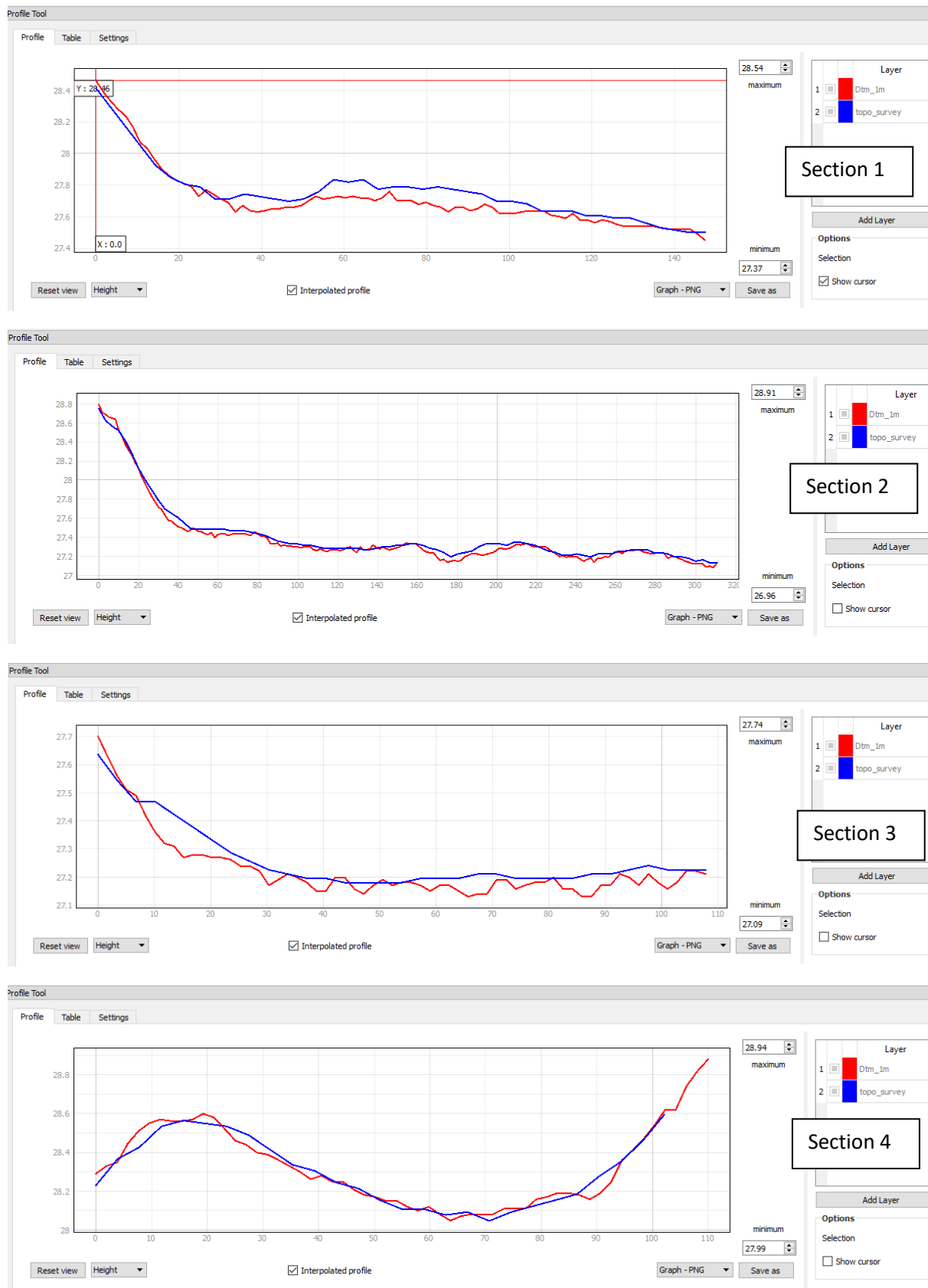


Figure 3-6: Comparison of DTM (LIDAR) and topographic survey

3.3 Hydraulic Model

3.3.1 Model Extent

The extent of the linked River Clywedog modelled in ESTRY (blue polyline) and the floodplain modelling in TUFLOW (pink polygon) and can be seen in Figure 3-7.

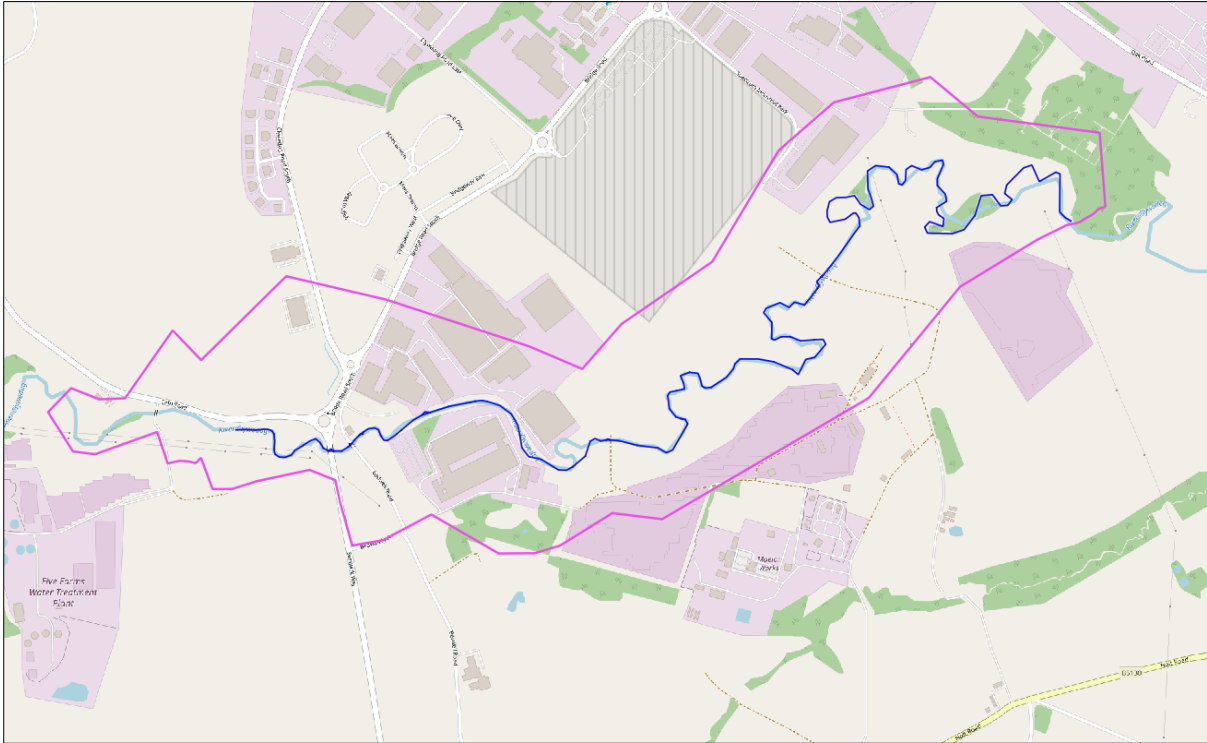


Figure 3-7: ESTRY and TUFLOW Extents.

3.3.2 1D Model Geometry

The River Clywedog were schematised in 1D ESTRY, with the channel geometry taken from the channel survey conducted as a part of the current study. The 1D channel was schematised to mesh with the 2D model domain by fixing the 1D channel widths to the 2D model cells 'nulled' from the model.

Where surveyed river sections extended into the floodplain (which is to be represented within the 2D TUFLOW domain), the 1D channel sections were truncated. This ensured there was no duplication of conveyance between the 1D and 2D domains. The location of the model cross sections (red line) is shown in Figure 3-8.

Interpolated cross-sections have been added where necessary to improve model stability.

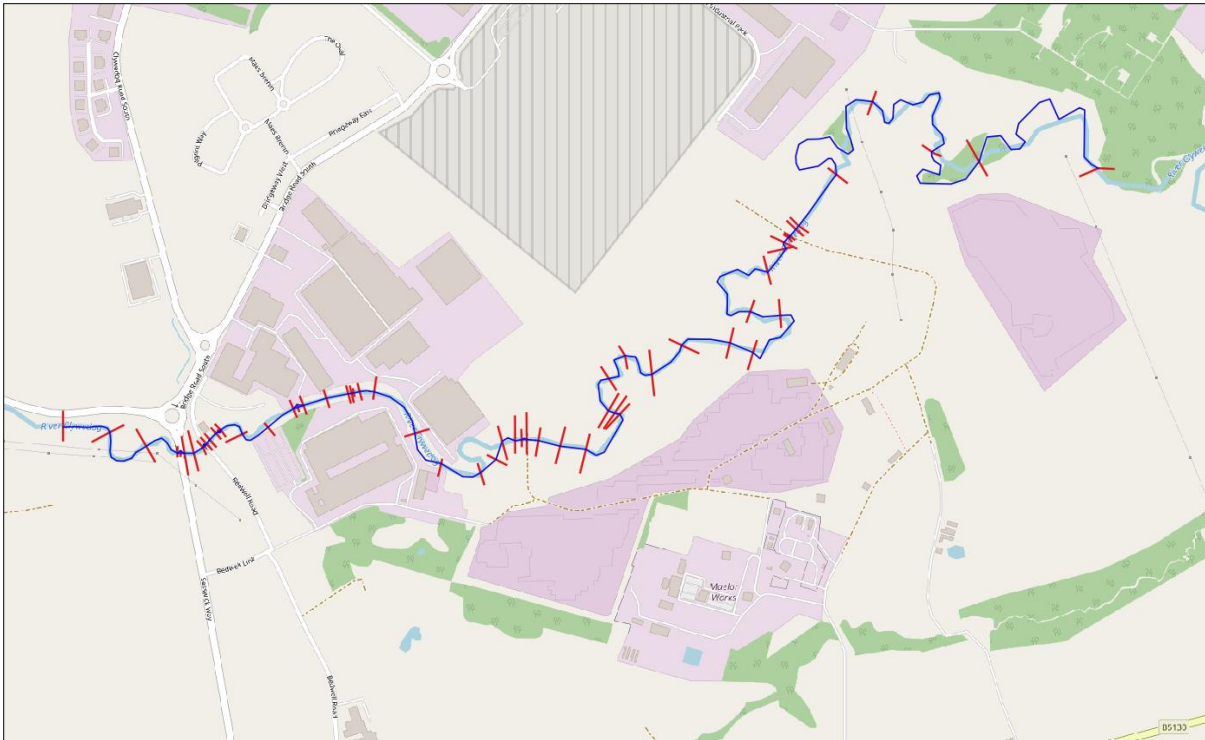


Figure 3-8: Location of the ESTRY model cross sections.

Hydraulic structures in the model were represented using standard structure units in the 1D ESTRY software such as the weir, bridge, and channel types. Structure dimensions and inverts were extracted from the channel survey. Other energy loss coefficients were based on the values recommended in the TUFLOW User Manual.

The model includes six bridges and one weir structures which have a significant impact on the flows. Details of the schematisation of the structures in the ESTRY model are shown in Table 3-1.

Table 3-1: List of modelled structures.

Structure	Survey Reference	Model Node	Model Unit
Sesswick Way Road Bridge	CLYW3724	CLYW3724B with Weir (CLYW3724W) modelled in 1D.	ESTRY Bridge (BB) and a weir representing overtopping of the road deck (W). The Form_Loss attribute is set to 0.1, so that the BB Bridges automatically creates the LC table.
Bedwell Road Bridge	CLYW3667	CLYW3667B with Weir (CLYW3667W) modelled in 1D.	ESTRY Bridge (BB) and a weir representing overtopping of the road deck (W). The Form_Loss attribute is set to 0.1, so that the BB Bridges automatically creates the LC table.
Foot Bridge immediately	CLYW3633	CLYW3633B with Weir (CLYW3633W) modelled in 1D.	ESTRY Bridge (BB) and a weir representing overtopping of

downstream of Bedwell Road			the road deck (W). The Form_Loss attribute is set to 0.1, so that the BB Bridges automatically creates the LC table.
Foot Bridge near Mill cottage	CLYW3444	CLYW3444B with Weir (CLYW3444W) modelled in 1D.	ESTRY Bridge (BB) and a weir representing overtopping of the road deck (W). The Form_Loss attribute is set to 0.1, so that the BB Bridges automatically creates the LC table.
Weir upstream of Industrial Estate	CLYW3330	CLYW3330W	ESTRY weir (W)
Foot bridge downstream of Mainetti Ltd	CLYW2865	CLYW2865B with Weir (CLYW2865W) modelled in 1D.	ESTRY Bridge (BB) and a weir representing overtopping of the road deck (W). The Form_Loss attribute is set to 0.1, so that the BB Bridges automatically creates the LC table.
Foot bridge near cube consulting & resourcing Ltd	CLYW1622	CLYW1622B with Weir (CLYW1622W) modelled in 1D.	ESTRY Bridge (BB) and a weir representing overtopping of the road deck (W). The Form_Loss attribute is set to 0.1, so that the BB Bridges automatically creates the LC table.
		CLYW3691W1, CLYW3667W1, 3650W1, CLYW3633W1, CLYW3566W, CLYW2881W1, CLYW2617W, CLYW2586W1, CLYW1634W1, CLYW1611W1,	Inline ESTRY weirs (W) included in the model to represent bed level changes in the channel (to improve stability).

The downstream bridge (CLYW1615, near the cube consulting & resourcing Ltd) has not been included in the model in order to improve model stability. However, the channel constriction is represented in the upstream bridge (CLYW1622) and it will not have any noticeable impact on modelled outputs.

Channel roughness values are represented in hydraulic models using the Manning's 'n' coefficient. These have been applied throughout the models with reference to a survey of the reach of the watercourse. Selected values are supported by photographs of the model reach that were provided with the topographical survey. All information was used with reference to Chow's industry standard reference guide to roughness coefficients (1959)¹. Figure 3-9 gives some example photos and their corresponding roughness values.

Cross Section	Photo	Left Bank Roughness	In Channel Roughness	Right Bank Roughness
CLYW 4022		0.05 Light brush and trees in summer	0.04 clean, winding, some pools and shoals	0.05 Scattered brush, heavy weeds
CLYW 3927		0.05 Light brush and trees in summer	0.045 Clean winding channel with some weeds and stones	0.04 Scattered brush, heavy weeds
CLYW 3736		0.03 Short grass	0.04 clean, winding, some pools and shoals	0.04 Scattered brush, heavy weeds
CLYW 3691		0.05 Light brush and trees in summer	0.05 Clean winding channel with some weeds and more stones	0.04 Scattered brush, heavy weeds
CLYW 3681		0.05 Light brush and trees in summer	0.05 Clean winding channel with some weeds and more stones	0.05 Scattered brush, heavy weeds
CLYW 3504		0.06 Light brush and trees in summer	0.05 Clean winding channel with some weeds and more stones	0.05 Scattered brush, heavy weeds

Figure 3-9: Channel Roughness Values.

3.3.3 2D Model Geometry

The 2d model domain covers a total area 1.09 km² (Figure 3-7), with a grid size of 2 m. The 2D elevation data was read into the model directly from the LiDAR ASCII data file (1 m resolution LiDAR data were downloaded from the website *lle.gov.wales.uk* with ground levels at the site updated using a DTM of the topographic survey obtained from the Invar Mapping Surveys (K1041-TOPOGRAPHIC 2D.dwg).

The bank levels of the channel were represented in the TUFLOW model using Z line and Z point layer (obtained from K1041-BANK LEVELS.dwg).

Z shapes have been used to smooth areas of poor LiDAR filtering using the surrounding ground levels.

The culvert under the Bridge Road is represented in 2D domain as circular culvert and the dimensions were obtained from the survey drawing (K1041-BANK LEVELS.dwg).

Floodplain roughness has been represented in the model through incorporation of an appropriate Manning's 'n' value. These values were determined from assessment of the land use types included in the Ordnance survey digital data GIS files. The data contains different layers of land use type in the form of lines and polygons, which can be transferred to a material layer. Each type of land use was assigned an ID which was then linked to the Manning's 'n' values in the material files. The list of Manning's 'n' values used in the model is presented in Table 3-2.

Table 3-2: Floodplain Roughness Values.

Roughness Code	Description	Manning's n
1	General Surface	0.04
2	Buildings	0.5
3	Water	0.035
4	Roads tracks and paths	0.025
5	Woodlands	0.1

3.4 Model Boundaries

3.4.1 Inflows

The design inflows generated (as outlined in Appendix A) for the River Clywedog were applied as a QT (flow versus time). The peak inflows used in the model for 1%AEP and 0.1%AEP events are showed in Table 3-3.

Table 3-3: Peak inflows (m³/s)

Node Label	1%AEP	0.1%AEP
Clywedog	35.05	54.76
Redwither	3.78	5.90

3.4.2 Downstream Boundary

The 1D downstream boundary comprises of a head flow boundary (rating curve), with a stage discharge relationship generated were calculated using the node “CLYW0000” and the slope of the channel.

The 2D downstream boundary comprises a normal-depth boundary (note TUFLOW refers to this boundary as HQ). This HQ boundary uses a user-specified gradient to calculate a stage discharge relationship for flow out of the model domain. A value of 0.006 (1 in 166) has been used on the right bank and a value of 0.0052 (1 in 192) has been used on the left bank based on the ground slope.

The location of the model boundaries is shown in Figure 3-10.

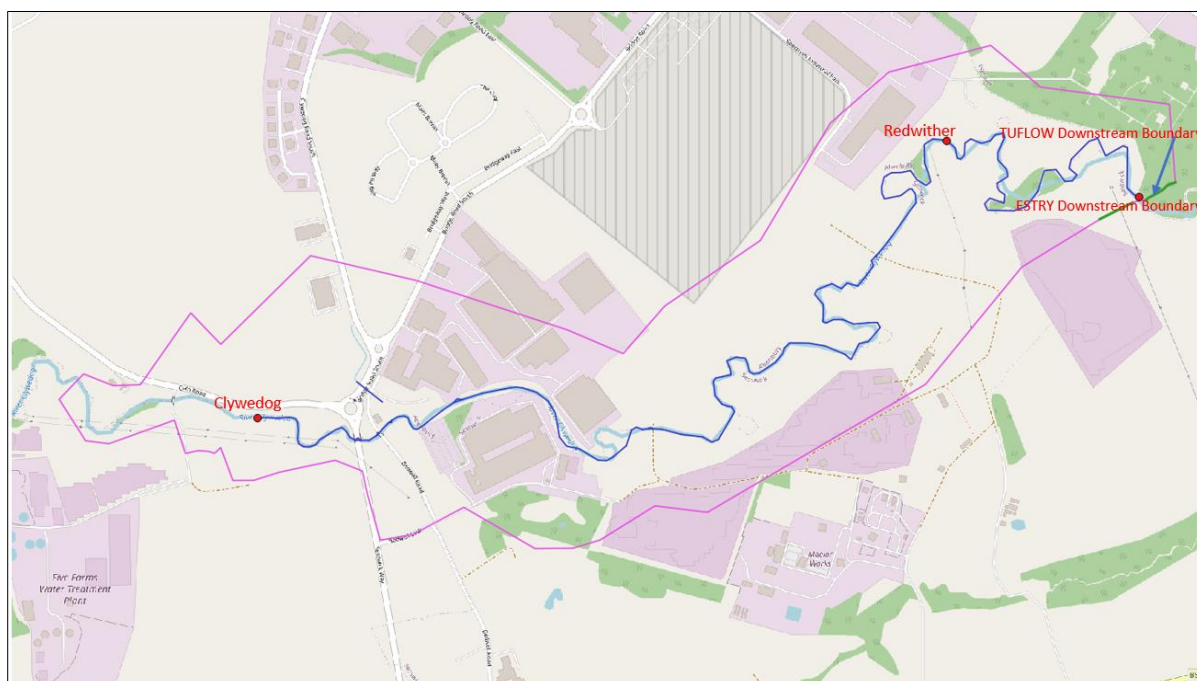


Figure 3-10: Location of model boundaries.

Links between the 1d ESTRY channel and the 2d TUFLOW domain have been schematised using HX lines digitised along the channel bank tops. The elevation of the HX cell in the TUFLOW model should match, or be close to, the elevation of the bank in the cross section used by ESTRY to accurately model the spilling between the 1d and 2d models. Therefore, surveyed bank levels were applied to the 2D domain along the HX lines using ZP points in the 2d_bc layer.

3.5 Model Performance

3.5.1 Run Configuration

All simulations were run using TUFLOW build TUFLOW.2020-01-AB-IDP-w64. The model was run to simulate 50 hours which allowed substantial time for the hydrograph to pass through the catchment.

A fixed time-step of 0.5 seconds was applied to the 1D element of the model and a time-step of 1.0 second was applied to the 2D element of the model. These time-steps were chosen as they provided model stability and are appropriate given the 2-m cell size of the 2D grid.

All the 1D run parameters remained as default.

3.5.2 ESTRY TUFLOW Model Performance

Numerical convergence in a 1D and 2D models has been checked through examination of the mass balance time series within the MB1D and MB2D csv results. Numerical convergence is considered good, if the mass balance errors is within +/- 1%.

The ESTRY (1D) mass balance output for the 1 in 100 (1% AEP) event is shown in Figure 3-11. The model simulation shows that the mass balance slightly exceeds the expected model tolerance at the start of the simulation (around 1.08hrs). The peak occurs around 11 hrs when the mass balance is well with tolerance. This spike is not expected to affect the final results.

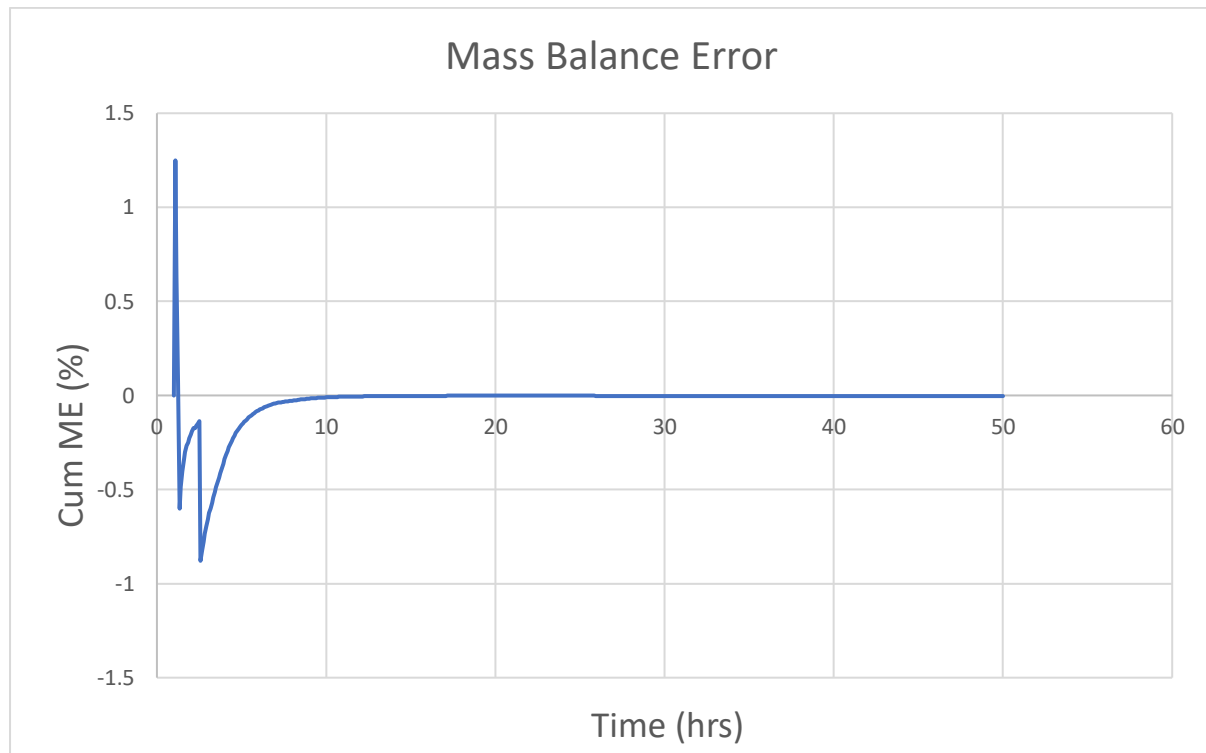


Figure 3-11: 1D Mass balance.

The TUFLOW (2D) mass balance output for the 1 in 100 (1% AEP) event is shown in Figure 3-12. Results show that the mass error exceeds the target model tolerance for a short period at approximately 6.16 hours into the simulation for all design events. During this early part of the event, maximum mass balance errors are approximately 2.82%.

The mass balance graph shows the initial spike in poorer mass balance followed by rapid improvement to within target tolerances. The peak occurs around 11 hours when the mass balance is well within tolerances.

Mass balance grid outputs confirm that poorer convergence occurs predominantly as a result of water ponding on the 2D domain near the industrial estate which is shown in Figure 3-13. To improve mass balance at industrial estate, the DTM could be smoothed. We do not recommend this smoothing, as there is greater benefit in retention of the topography than would be gained through improvement in mass balance during the early period of the event.

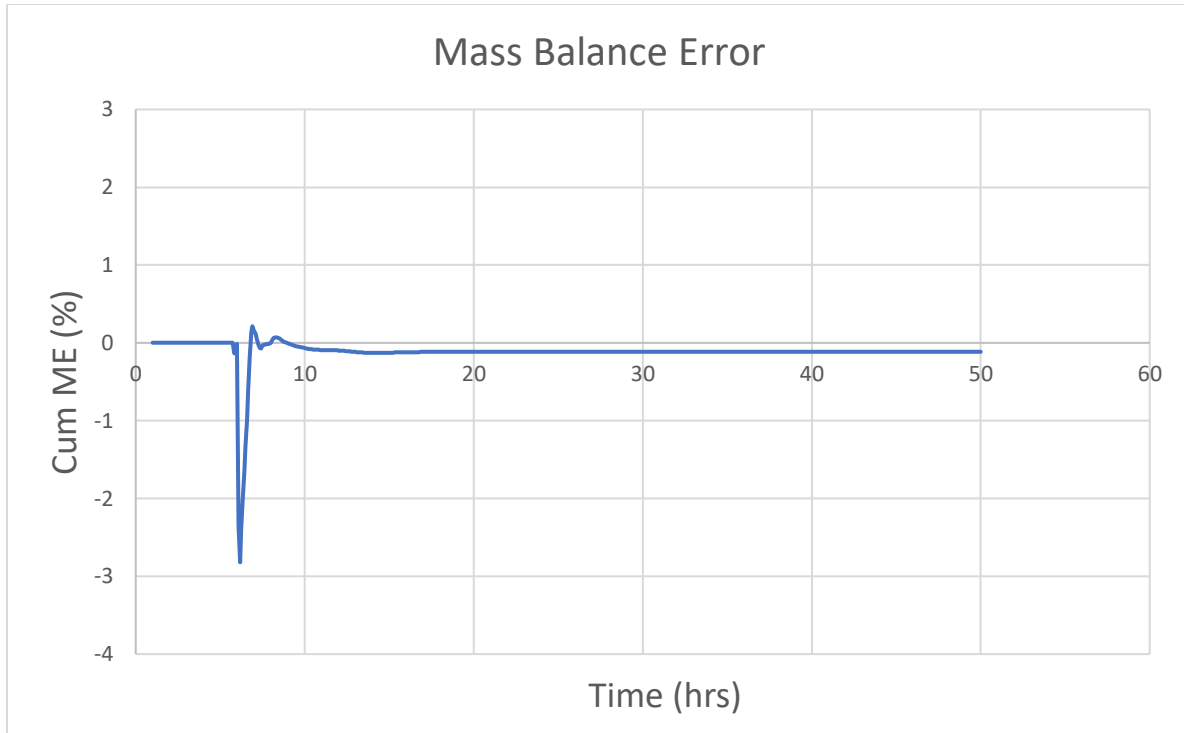


Figure 3-12: 2D Mass balance.

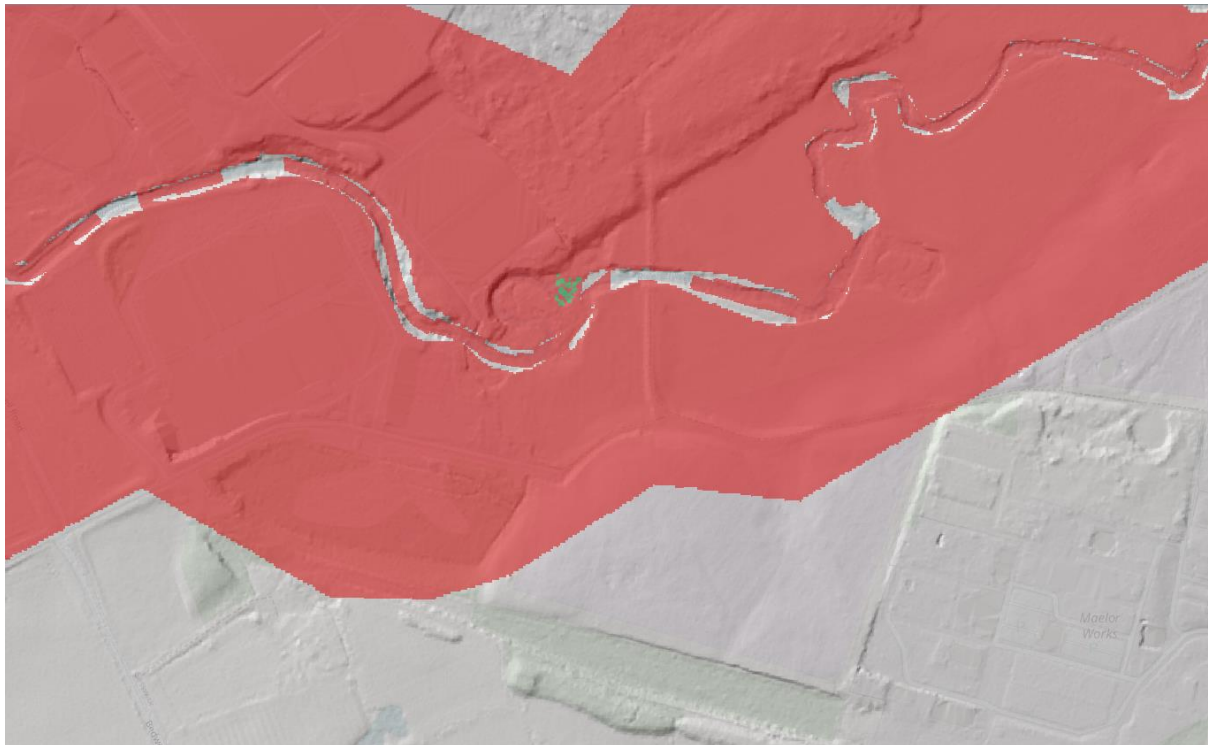


Figure 3-13: Location of poorer mass balance.

Negative depth warning message indicates the 1D and 2D model stability. Negative depth warnings are issued if the depth in a 1D node or 2D cells falls below -0.1 m. The 1% AEP TUFLOW simulation summary (Figure 3-14) shows that the total 1D negative depths is one and 2D negative depths are zero.

The one 1D negative depths occurs at node CLYW3736.1 at 1.13hours simulation. These 1D negative depths are occurring due to sudden change in the flow area. Since the negative depths occur at isolated location and for very limited timesteps, they do not affect the quality of the results.

The model simulation summary shows that there are 39 warning occurred prior to simulation.

Warning 1100 - These warning will be issued where a 1D structure's invert/bed lies below the bed of the primary upstream and/or downstream channel. Survey shows that for some structures the invert levels are below the channel bed levels. For example

The survey section CLYW3330 shows that the bed level upstream of the weir (CLYW3330) is 27.443 and the weir crest (CLYW3330W) crest level is 27.438. So the below error message issued.

WARNING 1100 - Structure CLYW3330W crest/invert (27.438) is below bed (27.443) of primary upstream channel CLYW3336.

Warning 1317- This warning will be issued when the WLL line does not cross the 1D channel.

Warning 2073 - This warning will be issued when GIS software will add the null objects to the layer to indicate deleted objects (particularly if using the shapefile format).

None of the above warning messages will affect the quality of the model results.

Simulation FINISHED				
Classic 1D Negative Depths: 1				
Classic 2D Negative Depths: 0				
WARNINGS prior to simulation: 39 [0 not in _messages layer]				
WARNINGS during simulation: 1 [0 not in _messages layer]				
CHECKS prior to simulation: 11 [0 not in _messages layer]				
CHECKS during simulation: 1 [0 not in _messages layer]				
Peak Flow In (m3/s): 39.6 at Time 11.00				
Peak Flow Out (m3/s): 41.5 at Time 12.89				
Volume at Start (m3): 0				
Volume at End (m3): 49447				
Total Volume In (m3): 2471576				
Total Volume Out (m3): 2543360				
Volume Error (m3): 121231 or 2.4% of Volume In + Out				
Final Cumulative ME: 2.42%				
	Whole Simulation		Qi+Qo > 5%	
Peak +ve dV (m3):	8.5	at 1.22h	7.0	at 8.12h
Peak -ve dV (m3):	-12.1	at 1.25h	-10.4	at 25.91h
Peak ddV over one timestep:	-13.6	at 1.25h	10.4	at 25.88h
Peak ddV as a % of peak dV:	112.0%		100.2%	
Peak Cumulative ME:	78.83%	at 1.00h	4.13%	at 17.75h

Figure 3-14: Baseline simulation summary for 1%AEP.

4 Model Results

4.1 Flood Extents

The ESTRY TUFLOW model has been run for 1% and 0.1% AEP events. Outputs from the TUFLOW models have been extracted in ASCII format to provide an estimate of the maximum water level, depth and velocity across the model extent.

The modelled flood extents for the 1% and 0.1% AEP events are shown in Figure 4-1 and Figure 4-2 respectively. The peak water levels at each of the model nodes for 1% and 0.1% AEP events are presented in Table 4-1.

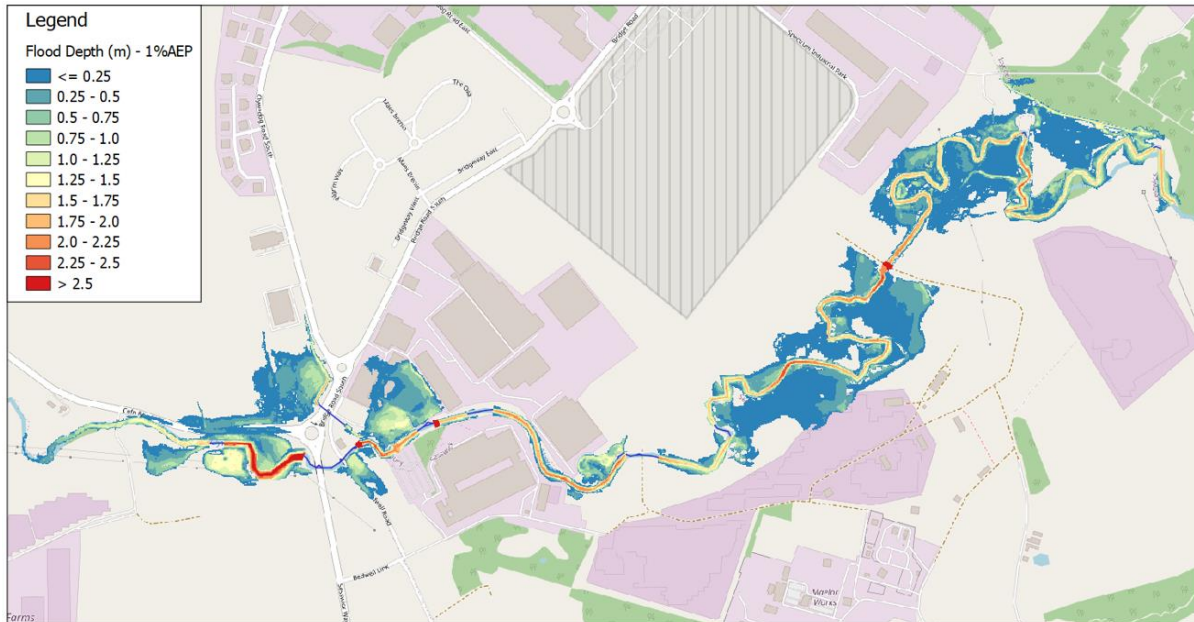


Figure 4-1: Flood depth for 1% AEP

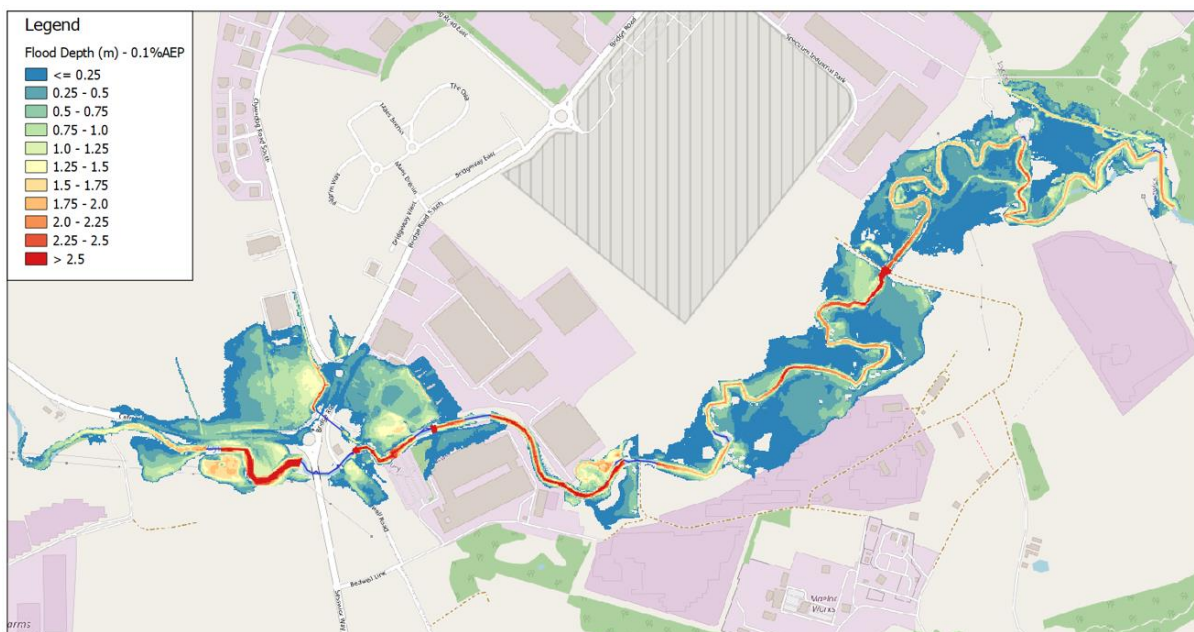


Figure 4-2: Flood depth for 0.1% AEP

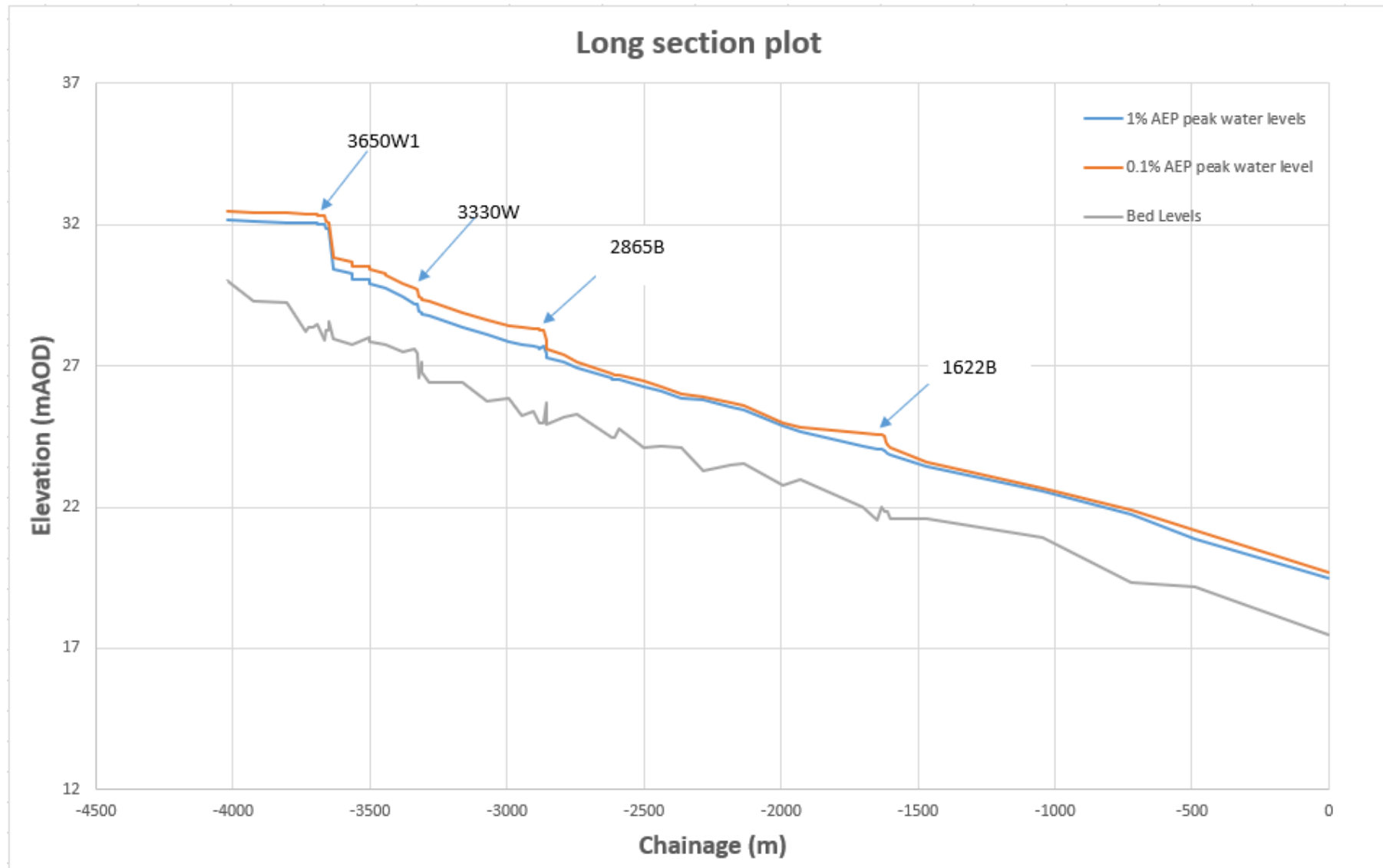


Figure 4-3: Long Section

Table 4-1: Peak water levels

Node Label	Peak water levels (m)	
	1%AEP	0.1%AEP
CLYW4022.1	32.176	32.467
CLYW3927.1	32.094	32.412
CLYW3805.1	32.079	32.403
CLYW3736.1	32.070	32.393
CLYW3724B.1	32.066	32.389
CLYW3710.1	32.054	32.365
CLYW3691.1	32.047	32.357
CLYW3691.2	32.039	32.348
CLY3667W1.1	32.037	32.344
CLY3667W1.2	32.032	32.338
CLYW3661.1	31.849	32.099
CLYW3650.1	31.841	32.091
3650W1.1	31.831	32.080
3650W1.2	31.822	32.069
CLYW3633B.1	30.498	30.919
CLYW3633B.2	30.436	30.822
CLYW3566.1	30.254	30.673
CLYW3566.2	30.071	30.534
CLYW3504.1	30.059	30.520
CLYW3504.2	29.929	30.413
CLYW3444B.1	29.757	30.247
CLYW3444B.2	29.740	30.204
CLYW3378.1	29.426	29.927
CLYW3336.1	29.206	29.747
CLYW3330W.1	29.177	29.724
CLYW3320.1	28.936	29.429
CLYW3314.1	28.901	29.391
CLYW3314.2	28.831	29.329
CLYW3287.1	28.772	29.269
CLYW3165.1	28.392	28.898
CLYW3075.1	28.097	28.612
CLYW2993.1	27.835	28.405
CLYW2946.1	27.752	28.376
CLYW2906.1	27.697	28.344
CLYW2881.1	27.642	28.302
CLYW2881.2	27.600	28.265
CLYW2865B.1	27.695	28.243
CLYW2856.1	27.458	27.889
CLYW2794.1	27.147	27.418
CLYW2744.1	26.931	27.148
CLYW2617.1	26.559	26.719
CLYW2617.2	26.547	26.707
CLYW2606.1	26.526	26.677
CLYW2589.1	26.503	26.658

CLYW2586W1.1	27.353	27.759
CLYW2586W1.2	27.291	27.613
CLYW2504.1	26.262	26.447
CLYW2437.1	26.102	26.270
CLYW2366.1	25.880	26.027
CLYW2283.1	25.779	25.910
CLYW2185.1	25.558	25.710
CLYW2137.1	25.423	25.591
CLYW1992.1	24.904	25.001
CLYW1932.1	24.691	24.852
CLYW1704.1	24.150	24.606
CLYW1648.1	24.080	24.579
CLYW1634W1.1	24.050	24.555
CLYW1622B.1	24.018	24.503
CLYW1619.1	23.959	24.325
CLYW1611W1.1	23.884	24.220
CLYW1603.1	23.839	24.118
CLYW1469.1	23.465	23.588
CLYW1046.1	22.588	22.662
CLYW0722.1	21.755	21.897
CLYW0487.1	20.896	21.170
CLYW0487.2	19.497	19.705

4.2 Discussion

The results show a general and consistent fall in water levels across most of the model domain. However, the largest flood depths occur at the upstream end of the model and reflect constrictions at two locations as shown in Figure 4-4; the Mainetti factory and the Williams causeway.

At the Mainetti factory, the model shows that all flow is confined in the Clywedog channel. This is in contrast to the flood extents shown in the NRW flood map (Figure 4-7). The model results seem plausible given the elevated ground on which the factory has been built (Figure 4-5). There seems to be no practical opportunity for alternative flow paths around the factory to the south. Notwithstanding this, the constriction leads to extensive areas of flooding north-west of the Mainetti factory and on the Bedwell Road.

There is an abrupt fall in peak water levels at chainage 3650 m corresponding to the Williams Causeway. This is consistent with the NRW flood extents and with the elevated nature of the causeway (Figure 4-6).



Figure 4-4: Constrictions in river-floodplain system

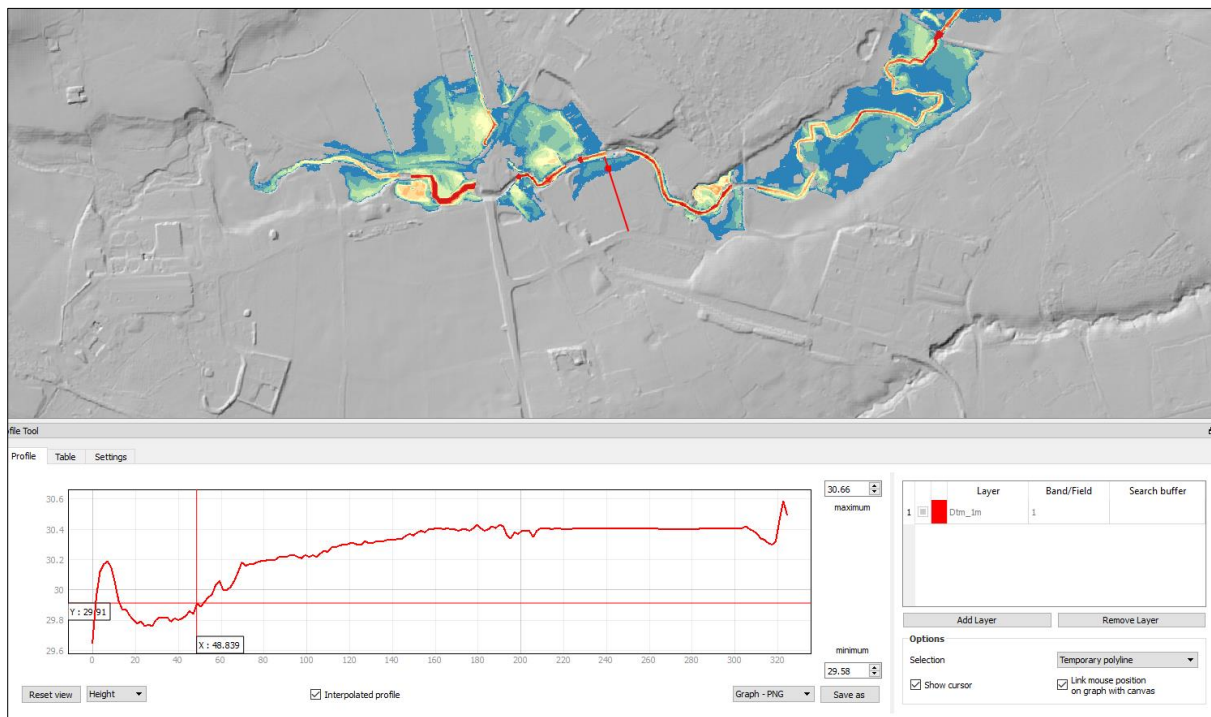


Figure 4-5: Ground levels at Mainetti factory



Figure 4-6: Williams Causeway (view towards north)

4.3 Comparison with NRW Published Flood Extents

The 0.1% AEP modelled flood extent is compared in Figure 4-7 with the NRW Published Flood Zone 2. There is broad agreement between the extents for much of the model domain. The largest differences relate to the two constrictions at the Mainetti factory and the Williams causeway and have already been described. Since the NRW published maps are based on generalised modelling, it will not have been able to capture the topographic and structural detail than has been incorporated into our hydraulic model. The observed differences are thus likely to reflect the more detailed representations in the captioned model.

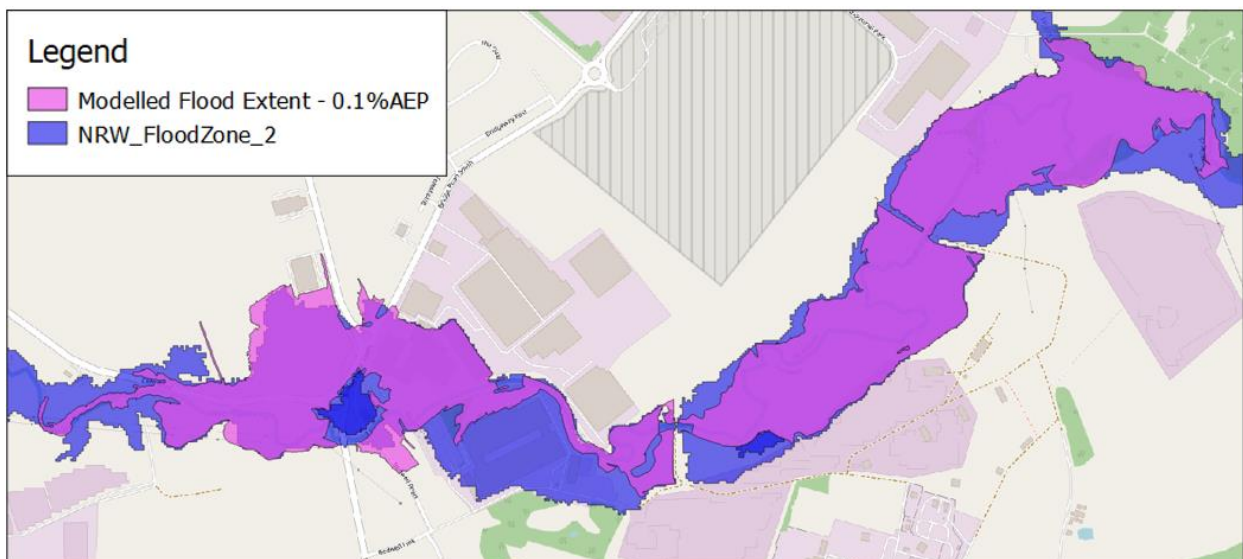


Figure 4-7: Comparison NRW and model extents (0.1% AEP)

4.4 Sensitivity

Sensitivity analysis is important in understanding modelling uncertainty and confirming the reliability of model results. Sensitivity tests on Manning's n roughness and the downstream boundary condition have been undertaken as part of the modelling assessment.

4.4.1 Roughness

Simulations were undertaken with the 1D(ESRTY) in-bank channel and 2D floodplain roughness values (Manning's n coefficient) uniformly decreased and increased by 20%. The sensitivity analysis can be used to assess the impacts of channel maintenance and vegetation growth/decline in addition to understanding modelling parameterisation uncertainty.

Increasing roughness by 20% resulted in increases the maximum water level in the channel by 0.23m at node CLYW3314.1, as shown in the Table 4-2 and the flood extent slightly increased compare to the baseline model at the development site as shown in Figure 4-8.

Table 4-2: Sensitivity Results: Increasing channel roughness by 20%

Node Label	1% AEP Peak water levels (m)		
	Baseline	Roughness plus 20%	Changes
CLYW4022.1	32.176	32.213	0.037
CLYW3927.1	32.094	32.107	0.013
CLYW3805.1	32.079	32.086	0.007
CLYW3736.1	32.070	32.073	0.004
CLYW3724B.1	32.066	32.069	0.002
CLYW3710.1	32.054	32.056	0.002
CLYW3691.1	32.047	32.047	0.000
CLYW3691.2	32.039	32.036	-0.004
CLY3667W1.1	32.037	32.033	-0.003
CLY3667W1.2	32.032	32.028	-0.004
CLYW3661.1	31.849	31.848	-0.001
CLYW3650.1	31.841	31.837	-0.004
3650W1.1	31.831	31.822	-0.009
3650W1.2	31.822	31.813	-0.009
CLYW3633B.1	30.498	30.664	0.167
CLYW3633B.2	30.436	30.604	0.168
CLYW3566.1	30.254	30.408	0.154
CLYW3566.2	30.071	30.215	0.144
CLYW3504.1	30.059	30.205	0.145
CLYW3504.2	29.929	30.069	0.141
CLYW3444B.1	29.757	29.887	0.130
CLYW3444B.2	29.740	29.870	0.130
CLYW3378.1	29.426	29.529	0.103
CLYW3336.1	29.206	29.278	0.073
CLYW3330W.1	29.177	29.244	0.067
CLYW3320.1	28.936	29.097	0.161
CLYW3314.2	28.901	28.992	0.091
CLYW3314.1	28.831	29.061	0.230
CLYW3287.1	28.772	28.932	0.160
CLYW3165.1	28.392	28.542	0.150

CLYW3075.1	28.097	28.231	0.134
CLYW2993.1	27.835	27.956	0.121
CLYW2946.1	27.752	27.880	0.127
CLYW2906.1	27.697	27.827	0.130
CLYW2881.2	27.642	27.719	0.077
CLYW2881.1	27.600	27.768	0.168
CLYW2865B.1	27.695	27.707	0.012
CLYW2856.1	27.458	27.579	0.121
CLYW2586W1.1	27.353	27.458	0.106
CLYW2586W1.2	27.291	27.405	0.114
CLYW2794.1	27.147	27.242	0.095
CLYW2744.1	26.931	27.009	0.078
CLYW2617.2	26.559	26.604	0.045
CLYW2617.1	26.547	26.617	0.069
CLYW2606.1	26.526	26.587	0.061
CLYW2589.1	26.503	26.566	0.062
CLYW2504.1	26.262	26.337	0.075
CLYW2437.1	26.102	26.169	0.067
CLYW2366.1	25.880	25.938	0.058
CLYW2283.1	25.779	25.830	0.051
CLYW2185.1	25.558	25.619	0.061
CLYW2137.1	25.423	25.496	0.073
CLYW1992.1	24.904	24.933	0.029
CLYW1932.1	24.691	24.729	0.038
CLYW1704.1	24.150	24.244	0.094
CLYW1648.1	24.080	24.181	0.102
CLYW1634W1.1	24.050	24.148	0.098
CLYW1622B.1	24.018	24.120	0.102
CLYW1619.1	23.959	24.062	0.102
CLYW1611W1.1	23.884	23.974	0.090
CLYW1603.1	23.839	23.936	0.096
CLYW1469.1	23.465	23.504	0.038
CLYW1046.1	22.588	22.606	0.018
CLYW0722.1	21.755	21.788	0.033
CLYW0487.1	20.896	21.026	0.130
CLYW0487.2	19.497	19.491	-0.007
Maximum			0.23
Minimum			-0.009
Average			0.077

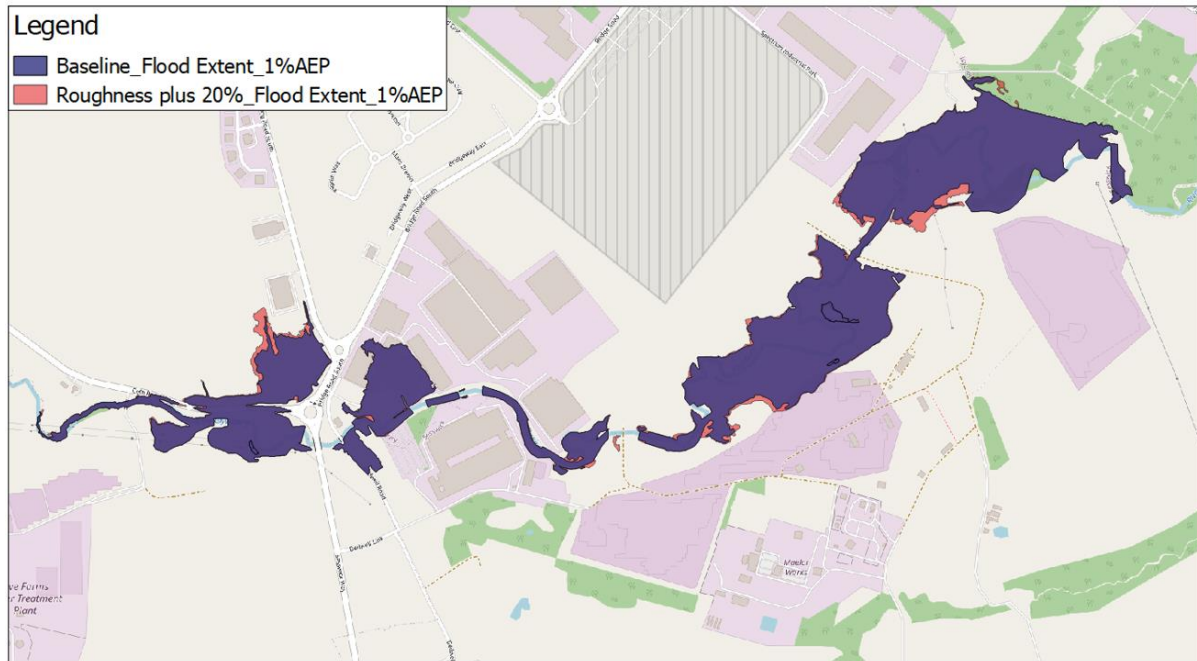


Figure 4-8: Increasing roughness by 20% compare to baseline flood extent.

Decreasing roughness by 20% resulted in decreases the maximum water level in the channel by 0.26m at node CLYW3314.2, as shown in the Table 4-3 and the flood extent slightly decreased compare to the baseline model at the development site as shown in Figure 4-9.

Table 4-3: Sensitivity Results: Decreasing channel roughness by 20%

Node Label	1% AEP Peak water levels (m)		
	Baseline	Roughness minus 20%	Changes
CLYW4022.1	32.176	32.141	-0.035
CLYW3927.1	32.094	32.083	-0.011
CLYW3805.1	32.079	32.073	-0.005
CLYW3736.1	32.070	32.067	-0.002
CLYW3724B.1	32.066	32.065	-0.001
CLYW3710.1	32.054	32.052	-0.002
CLYW3691.1	32.047	32.048	0.001
CLYW3691.2	32.039	32.043	0.004
CLY3667W1.1	32.037	32.040	0.004
CLY3667W1.2	32.032	32.035	0.004
CLYW3661.1	31.849	31.850	0.001
CLYW3650.1	31.841	31.845	0.004
3650W1.1	31.831	31.838	0.008
3650W1.2	31.822	31.830	0.008
CLYW3633B.1	30.498	30.303	-0.195
CLYW3633B.2	30.436	30.241	-0.195
CLYW3566.1	30.254	30.079	-0.175
CLYW3566.2	30.071	29.914	-0.158
CLYW3504.1	30.059	29.899	-0.160
CLYW3504.2	29.929	29.777	-0.151
CLYW3444B.1	29.757	29.623	-0.134

CLYW3444B.2	29.740	29.606	-0.134
CLYW3378.1	29.426	29.342	-0.084
CLYW3336.1	29.206	29.177	-0.029
CLYW3330W.1	29.177	29.157	-0.020
CLYW3320.1	28.936	28.745	-0.191
CLYW3314.2	28.901	28.638	-0.264
CLYW3314.1	28.831	28.711	-0.119
CLYW3287.1	28.772	28.581	-0.191
CLYW3165.1	28.392	28.209	-0.184
CLYW3075.1	28.097	27.930	-0.167
CLYW2993.1	27.835	27.685	-0.150
CLYW2946.1	27.752	27.601	-0.151
CLYW2906.1	27.697	27.545	-0.152
CLYW2881.2	27.642	27.459	-0.183
CLYW2881.1	27.600	27.495	-0.105
CLYW2865B.1	27.695	27.444	-0.250
CLYW2856.1	27.458	27.317	-0.141
CLYW2586W1.1	27.353	27.228	-0.125
CLYW2586W1.2	27.291	27.155	-0.136
CLYW2794.1	27.147	27.031	-0.116
CLYW2744.1	26.931	26.832	-0.099
CLYW2617.2	26.559	26.475	-0.084
CLYW2617.1	26.547	26.486	-0.061
CLYW2606.1	26.526	26.448	-0.078
CLYW2589.1	26.503	26.424	-0.080
CLYW2504.1	26.262	26.156	-0.106
CLYW2437.1	26.102	26.005	-0.097
CLYW2366.1	25.880	25.789	-0.091
CLYW2283.1	25.779	25.691	-0.088
CLYW2185.1	25.558	25.470	-0.089
CLYW2137.1	25.423	25.318	-0.105
CLYW1992.1	24.904	24.856	-0.048
CLYW1932.1	24.691	24.641	-0.050
CLYW1704.1	24.150	24.044	-0.106
CLYW1648.1	24.080	23.963	-0.117
CLYW1634W1.1	24.050	23.939	-0.112
CLYW1622B.1	24.018	23.899	-0.118
CLYW1619.1	23.959	23.842	-0.118
CLYW1611W1.1	23.884	23.781	-0.103
CLYW1603.1	23.839	23.726	-0.113
CLYW1469.1	23.465	23.418	-0.048
CLYW1046.1	22.588	22.552	-0.036
CLYW0722.1	21.755	21.707	-0.048
CLYW0487.1	20.896	20.764	-0.133
CLYW0487.2	19.497	19.507	0.009
Maximum			-0.264
Minimum			0.009
Average			0.094

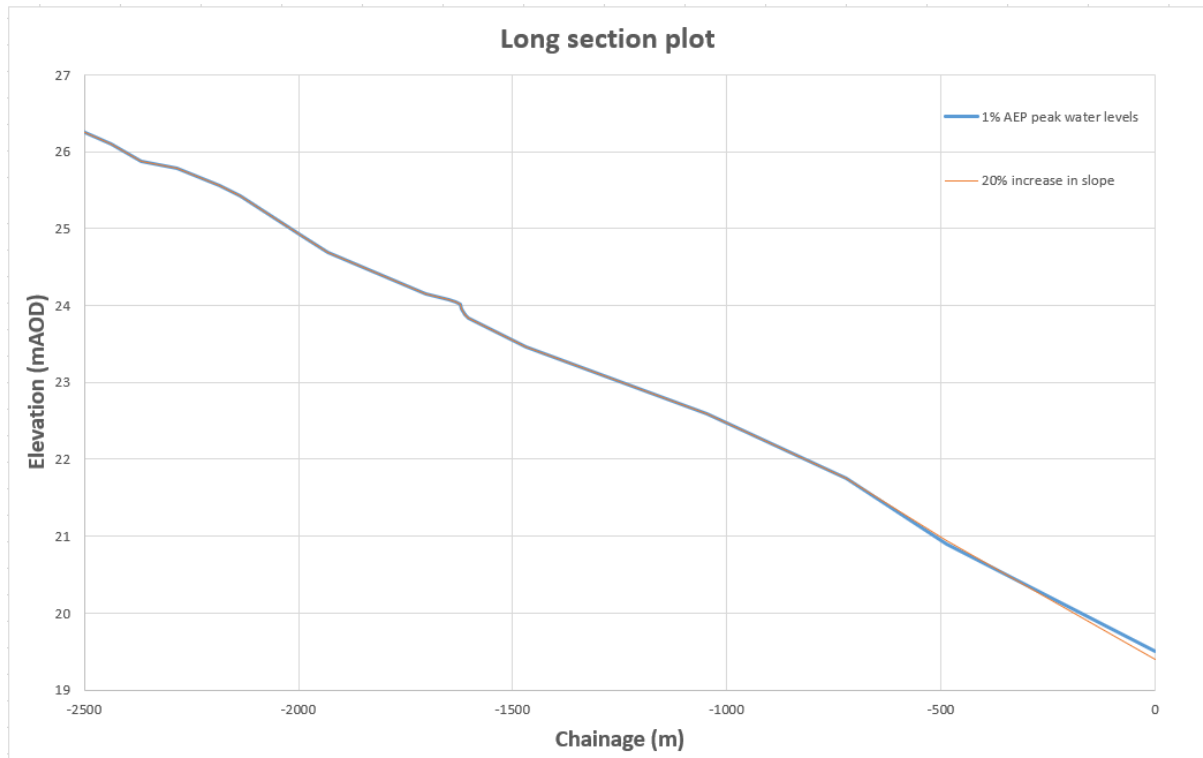


Figure 4-10: Model sensitivity to increasing the downstream boundary by 20%

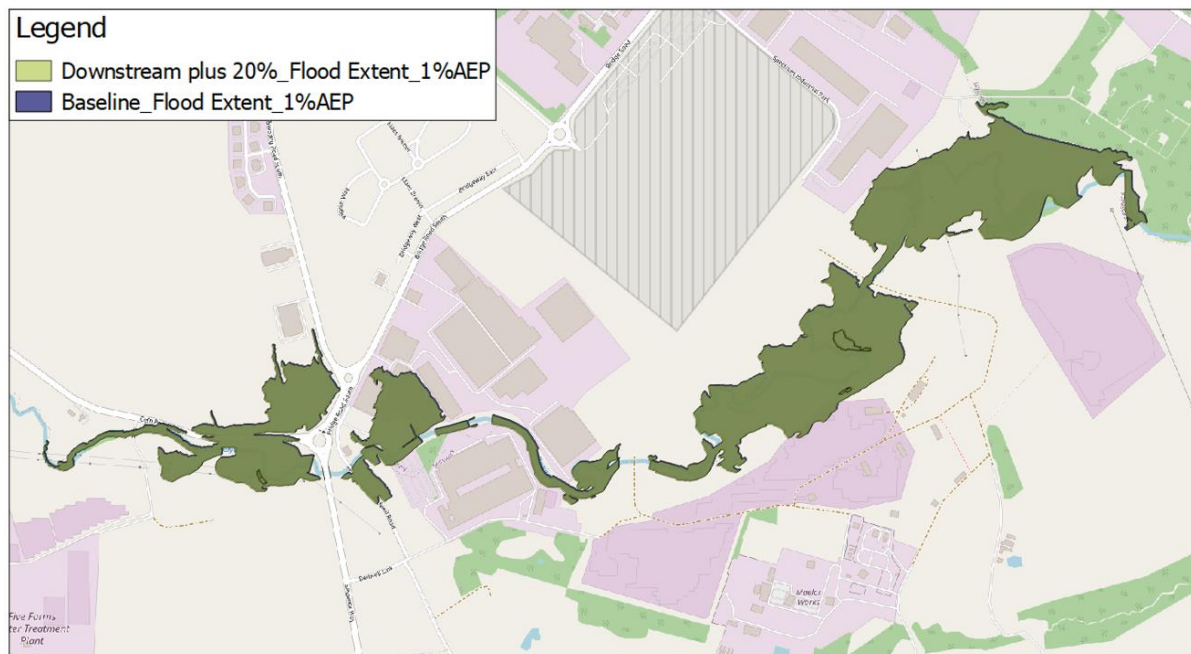


Figure 4-11: Increasing downstream slope by 20% compare to baseline flood extent.

The effect of the increasing the downstream boundary slope by 20% changes only extend approximately 487m upstream with only a maximum 0.17m variance in water level at the downstream end of the model as shown Figure 4-12. There is virtually no change in flood extent compare to the baseline model as shown in Figure 4-13.

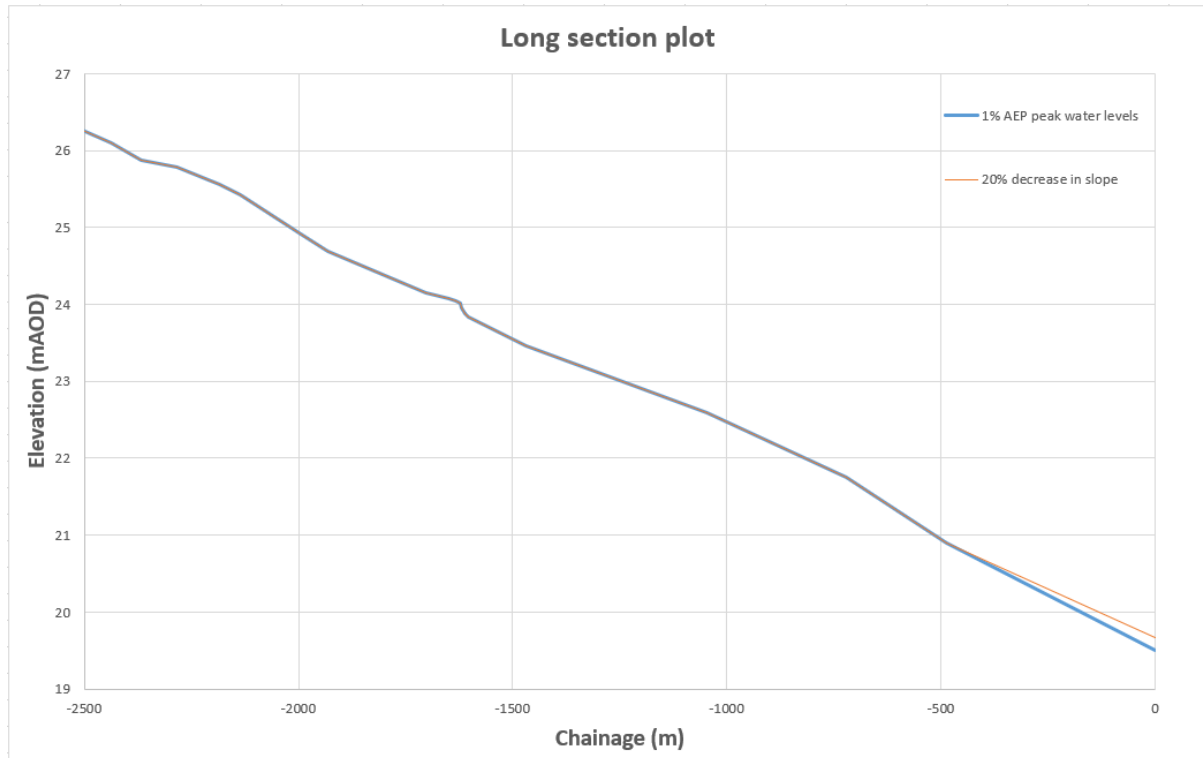


Figure 4-12: Model sensitivity to decreasing the downstream boundary by 20%

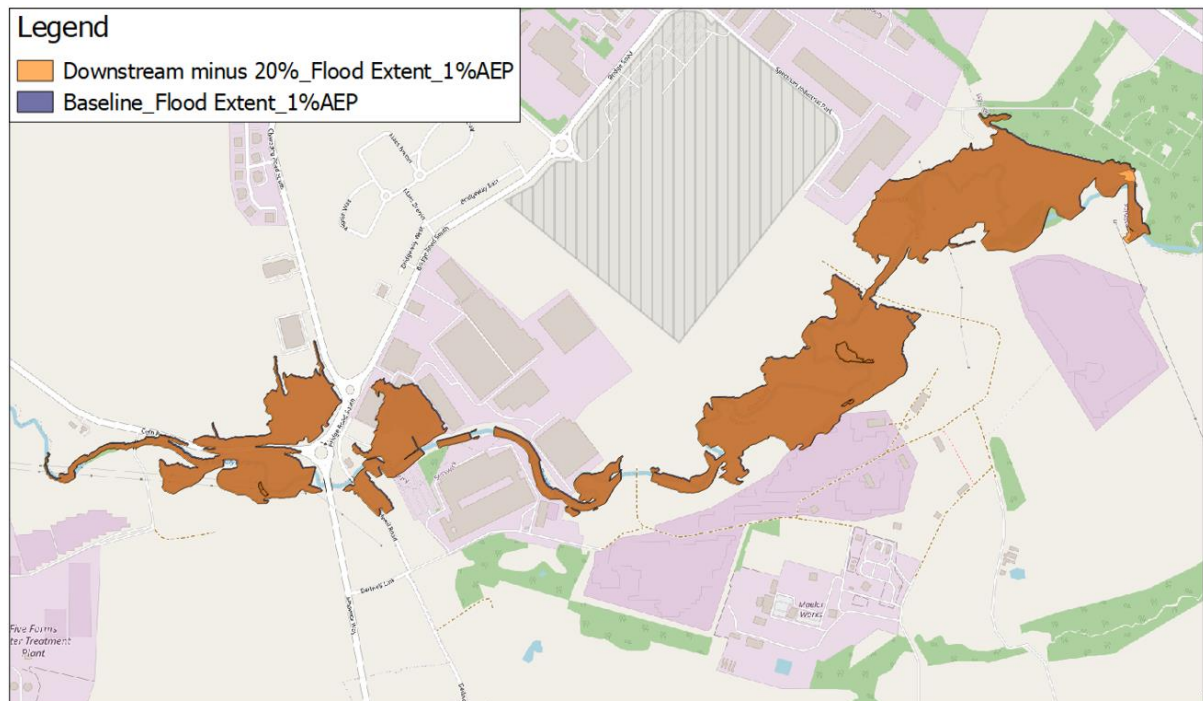


Figure 4-13: Decreasing downstream slope by 20% compare to baseline flood extent.

The results of the roughness and downstream boundary test shows that the flood risk to the proposed development site is not overly sensitive to change in roughness coefficients and downstream boundary slope.

5 Summary

This Report describes the development and application of a hydraulic model for the River Clywedog in Wales, near the Wrexham Industrial Estate. The main work undertaken was:

- Hydrological modelling to derive design flows;
- Topographic survey by Invar mapping to obtain channel cross-sections and general topography;
- Development of an ESTRY 1D hydraulic model of the River Clywedog;
- Linking of the 1D model to TUFLOW to simulate flows over the floodplain.
- Production of flood extents for the 1% and 0.1% AEP.

There is broad agreement between the flood extents published by the NRW and those produced in this Report.

It is proposed to use the model to inform development proposals and the production of a Flood Consequences Assessment (FCA) for land in the ownership of our client. This will include further model runs to address:

- The impacts of climate change
- The impacts of blockage
- The flood risk to any proposed developments
- The consequence of any developments on flooding.

These issues have been addressed in a Companion FCA for proposed Solar Development at this Site.

6 References

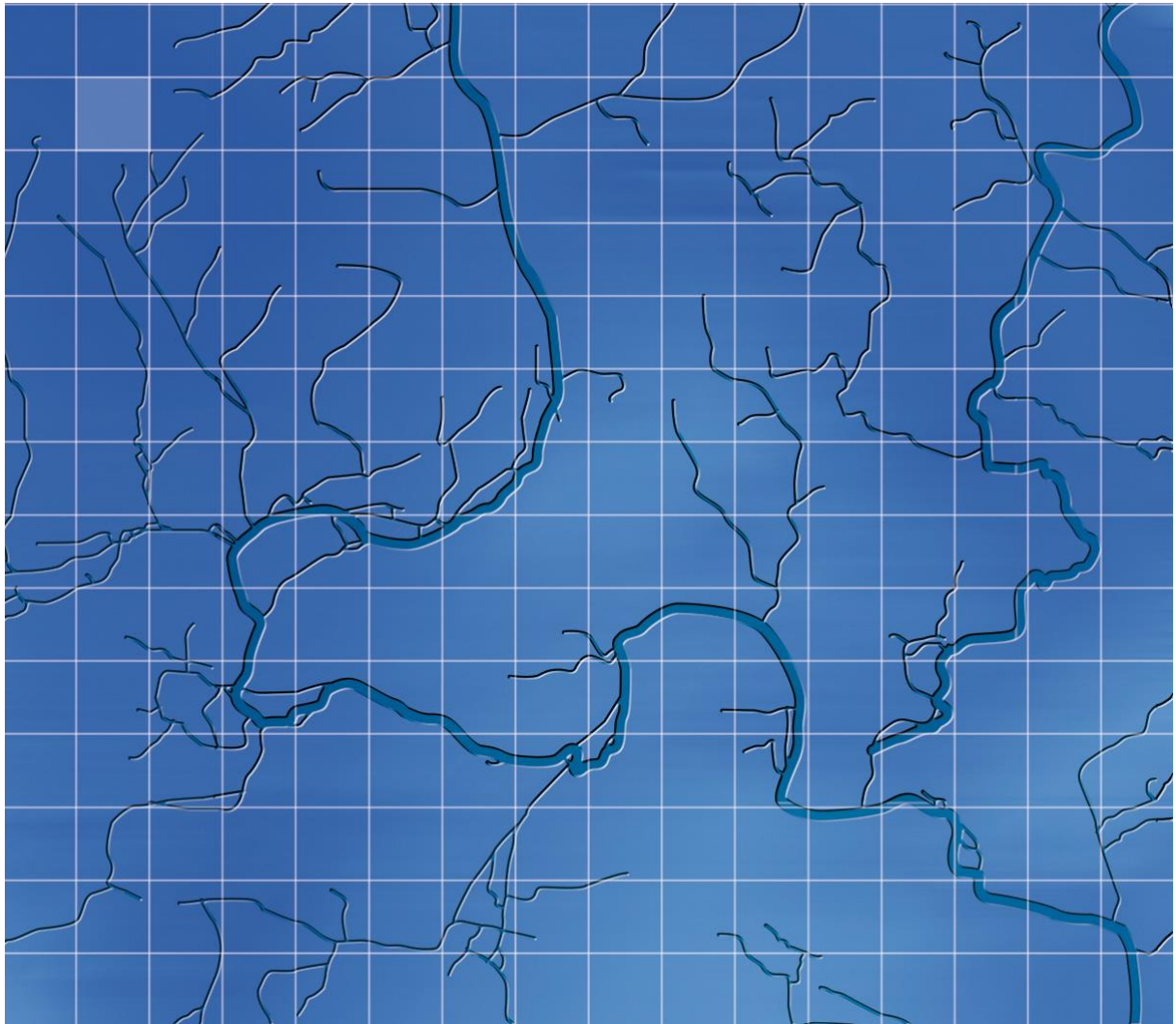
Author	Date	Title/Description
Centre for Ecology and Hydrology.	2018	The Flood Estimation Handbook Web Service. Available from: https://fehweb.ceh.ac.uk/
CIRIA	2015	C753, The SuDS Manual.
Chow	1959	Open-channel hydraulics.
NRW	May 2016	Good Practice Guide - Technical Guidance: Flood Estimation. GPG 102 by Hydrology and Water Resources Management

Appendix A Hydrological Modelling Report

Corylus

June 2020

Peak Flow Estimate for Bowling Bank



WHS

Peak Flow Assessment for Bowling Bank

Document issue details

WHS1771

Version	Issue date	Issue status	Prepared By	Approved By
1.0	29/05/2020	Draft	Harry Koido-Bunt (Consultant)	Daniel Hamilton (Senior Consultant)
1.1	01/06/2020	Final	Harry Koido-Bunt (Consultant)	Daniel Hamilton (Senior Consultant)

For and on behalf of Wallingford HydroSolutions Ltd.

This report has been prepared by WHS with all reasonable skill, care and diligence within the terms of the Contract with the client and taking account of both the resources allocated to it by agreement with the client and the data that was available to us. We disclaim any responsibility to the client and others in respect of any matters outside the scope of the above. This report is confidential to the client and we accept no responsibility of any nature to third parties to whom this report, or any part thereof, is made known. Any such party relies on the report at their own risk.



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1 Requirements

The client requires peak flow estimates and hydrographs for the River Clywedog at the Bowling Bank gauging station, Wrexham (NGR: 339550, 348250). The client requires this information to inform hydrograph inputs for hydraulic modelling of the river.

2 The Catchment

The catchment boundary is presented in Figure 1. The FEH Web Service¹ was used to derive the catchment descriptors. The area of the FEH Web Service boundary is 103.55 km². Table 1 presents the relevant catchment descriptors. The catchment has an URBEXT2000 value of 0.0983 hence is classed as 'moderately urbanised' according to FEH guidance. The catchment is reasonably permeable, assigned a BFIHOST characteristic of 0.530. The majority of the catchment is underlain by siltstone and sandstone, with superficial deposits of till and glacial and sand and gravel in evidence across the catchment. The catchment is not significantly affected by the presence of lakes, with a FARL value of 0.989.

Table 1. Relevant catchment descriptors from the FEH Web Service²

Catchment Descriptor	Value
Area (km ²)	103.55
SAAR (standard average annual rainfall 1961 - 1990mm)	852
BFIHOST (baseflow index derived from HOST soils data)	0.530
BFIHOST19 (baseflow index derived from HOST soils data)	0.532
DPLBAR	14.27
DPSBAR	62.0
FARL (index of flood attenuation due to reservoirs and lakes)	0.989
FPEXT (extent of flood plain)	0.0658
PROPWET	0.51
URBEXT 2000	0.0983

¹ <https://fehweb.ceh.ac.uk/GB/map>

² Results based upon FEH methodology and data, CEH (2015) 'CEH 2015. The Flood Estimation Handbook (FEH) Online Service, Centre for Ecology & Hydrology, Wallingford, Oxon, UK'

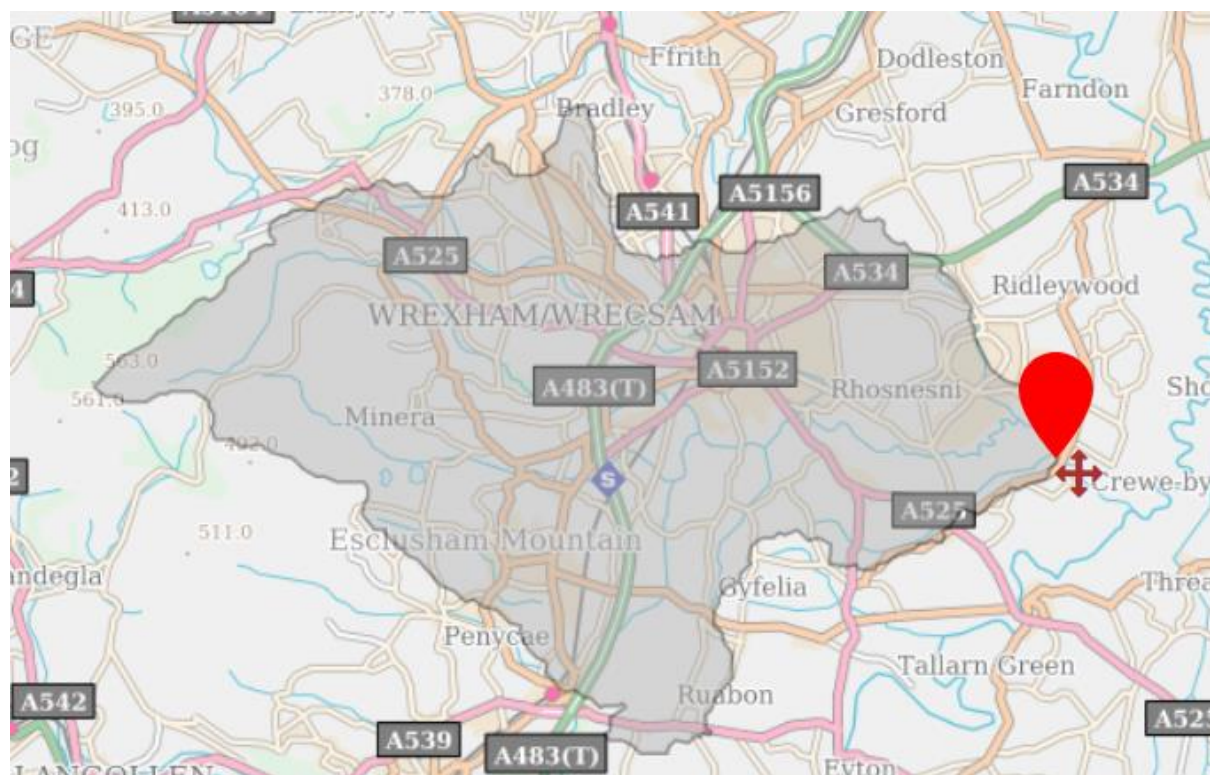


Figure 1 The FEH Web Service derived catchment is shown by the grey boundary. Contains OS data © Crown Copyright (2019) Contains CEH data © and database right NERC (CEH) 2020

3 Outline of Methodology

The flood estimates have been developed using the Flood Estimation Handbook statistical and rainfall runoff methods. The statistical methods are those as published by the Institute of Hydrology in 1999³ with updates included in the latest version of WINFAP-FEH 4⁴ as described by Kjeldsen *et al.*,⁵ and the WHS technical guidance⁶. These methods require the estimation of a normalised flood frequency curve, termed the flood growth curve and the estimation of the normalising variable; the median annual flood, QMED. The current version of NRFA Peak Flows dataset available for use in this study was NRFA Peak Flows v8⁷.

The rainfall-runoff methods are those first published by Kjeldsen⁸, which were subsequently updated in 2015 and 2019 and implemented within the ReFH2.3 software⁹ as described in the WHS technical

³ Robson, A. and Reed, D., 1999. *Flood Estimation Handbook Volume 3: Statistical Procedures for Flood Frequency Estimation*. Institute of Hydrology, Wallingford, pp338.

⁴ <https://www.hydrosolutions.co.uk/software/winfap-4/>

⁵ Kjeldsen, T.R., Jones, D.A., and Bayliss, A.C., 2008. *Improving the FEH statistical procedures for flood frequency estimation*. Environment Agency, Bristol, pp137.

⁶ <https://www.hydrosolutions.co.uk/software/winfap-4/literature/>

⁷ <https://nrfa.ceh.ac.uk/peak-flow-data>

⁸ Kjeldsen, T. R. 2007. The revitalised FSR/FEJ rainfall-runoff method. Supplementary Report No.1. CEH.

⁹ <https://www.hydrosolutions.co.uk/software/refh-2/>

guidance¹⁰. Note, the updated BFIHOST descriptor, BFIHOST19, which determines the baseflow characteristics of a catchment, is used in the estimation of the rainfall-runoff flows.

Some of the catchments being assessed are very small being less than 1km². Recent research into flood estimation in small catchments¹¹ suggests that both FEH methods (the statistical method and the Revitalised Flood Hydrograph (ReFH) event-based method) outperform older methods for estimating floods in small catchments, for example the IH 124 method (the small catchment implementation of the FSR procedures) and ADAS 345 method. The research notes that there is little evidence to suggest that the accuracy of the FEH methods when applied to ungauged catchments is particularly scale dependent and recommends the use of current versions of the FEH methods. The methods are therefore applicable to this site.

4 Peak Flow Estimation using the statistical method

As the site is ungauged, the approach adopted for estimating QMED has been to develop an FEH catchment descriptor-based estimate and to review the availability of potentially suitable donor catchments to form the basis of a data transfer exercise that would improve the QMED estimate. This is the standard application of the FEH methodology. The pooled methodology for estimation of the growth curve is then applied.

4.1 Derivation of the Median Annual Flood

The QMED for the location was first estimated from catchment descriptors as 19.372 m³s⁻¹.

Estimates of QMED from observed data (QMEDobs) at donor stations can be used to adjust the estimate of QMEDcds at the subject site. Possible donor catchments are initially sought on the basis of being geographically close. Along with geographical distance the similarity of catchment descriptors; Area, SAAR, FARL and BFIHOST with the target catchment are also considered.

The general pattern of QMEDcds to the QMEDobs for the six closest stations shows the catchment descriptor equation to consistently overestimate QMEDobs. Two stations from the donor group were rejected, these were the Ceiriog at Brynkinalt Weir (67005) and the Perry at Yeaton (54020). For the former this was based on it having a significantly higher SAAR value (+20%) relative to the target catchment. The Perry at Yeaton was rejected as it had a significantly higher BFIHOST (+20%) relative to the target catchment and showed disparities in other catchment descriptors including FARL and SAAR. One station was substituted into the pooling group, this was the Gowy at Bridge Trafford (68020) which shares many similarities with the target catchment. No further stations outside of the initial pooling group were considered suitable for donor transfer.

As a result, five stations were chosen in the donor group, from which to inform the QMED estimate. Table 2 presents the geographically closest ten stations (five of which were selected).

The donor adjusted rural QMED value derived was 14.774 m³s⁻¹. This was subsequently adjusted for urbanisation. The catchment is classed as moderately urbanised having an URBEXT value of 0.0983 which yields an urban adjustment factor of 1.125. The adjustment factor leads to a donor adjusted urban QMED value of 16.626 m³s⁻¹. This value should be used to scale the flood growth curves.

¹⁰ https://www.hydrosolutions.co.uk/software/refh-2/supporting_literature/

¹¹ Environment Agency, 2012, Estimating flood peaks and hydrographs for small catchments: Phase 1, SC090031

Peak Flow Estimate for Bowling Bank

Table 2. List of donor catchments considered for QMED adjustment¹²

Station	Distance (km)	URBEXT2000	QMED Observed (m ³ s ⁻¹)	QMED CDs (m ³ s ⁻¹)	Area (km ²)	SAAR (mm)	BFIHOST	FARL	Years of data	Accept or Reject	Comments
67008 (Alyn @ Pont-y-capel)	12.72	0.029	21.59	35.712	225.65	917	0.591	0.99	53	Accept	
67009 (Alyn @ Rhydymwyn)	14.78	0.002	8.681	15.308	81.6	968	0.615	0.99	62	Accept	
67005 (Ceiriog @ Brynkinalt Weir)	18.86	0.001	28.87	49.865	111.72	1198	0.462	1	21	Reject	SAAR 20% higher than target catchment
54020 (Perry @ Yeaton)	21.31	0.014	10.59	12.927	188.08	739	0.654	0.954	55	Reject	BFIHOST 20% higher than target catchment
66005 (Clwyd @ Ruthin Weir)	21.4	0.005	16.907	24.673	96.39	958	0.518	0.995	33	Accept	
66001 (Clwyd @ Pont-y-cambwll)	24.65	0.006	49.432	59.022	404.56	910	0.588	0.993	43	Accept	
68020 (Gowy @ Bridge Trafford)	25.28	0.017	14.962	18.023	148.66	729	0.538	0.994	39	Accept	
66004 (Wheeler @ Bodfari)	27.37	0.004	3.651	6.633	62.91	863	0.696	0.975	44	Reject	BFIHOST 20% higher than target catchment
54038 (Tanat @ Llanyblodwel)	28.66	0.001	79.126	99.498	241.13	1274	0.477	0.996	46	Reject	SAAR 20% higher than target catchment
54016 (Roden @ Rodington)	29.06	0.013	10.746	18.568	261.94	693	0.615	0.981	49	Reject	SAAR 20% lower than target catchment

¹² Results based upon FEH methodology and data, CEH (2015) 'CEH 2015. The Flood Estimation Handbook (FEH) Online Service, Centre for Ecology & Hydrology, Wallingford, Oxon, UK'

4.2 Derivation of the Growth Curve

Within the FEH methodology flood growth curves for ungauged sites are formed by pooling annual maxima data from similar catchments which are flagged as being suitable for pooling. A threshold of 500 station-years is required (a sum of record lengths) and thus an initial pooling group was formed for the development of the flood growth curve by pooling data from 13 catchments. Two stations, the Dun at Hungerford (39028) and by Brook at Middlehill (53028) were removed as they had a negative L-Skew value which reflects the fact that the distributions are bounded. This may be valid, being a result of sampling error, however it may also indicate issues with the quality of the data. Both records were removed as a precautionary approach which may result in a conservative (high) estimate of the growth factors within the target catchment.

The removal of stations 39028 and 53028 resulted in the pooling group having less station years than 500 years, therefore three stations (53023, 203043 and 39020) were added to the pooling group to rectify this.

A final pooling group containing 14 stations and 544 station years was derived. Table 3 shows the full list of pooling group members along with the reason for any stations being removed or retained. The distance shown is the distance from each candidate station to the sites in a similarity distance space (the FEH distance measure).

Peak Flow Estimate for Bowling Bank

Table 3. Pooling group selection and reasons for retaining or removing from final pooling group.¹³

Station	Distance (km)	AREA (km ²)	SAAR (mm)	FARL	URBE XT 2000	Accept or Reject	Comments
42001 (Wallington @ North Fareham)	0.147	111.67	819	0.979	0.053	Accept	
43012 (Wylfe @ Norton Bavant)	0.237	114.01	925	0.975	0.026	Accept	Permeable Adjustment Applied
39028 (Dun @ Hungerford)	0.241	100.1	786	0.988	0.004	Reject	Negative L-Skew
84007 (South Calder Water @ Forgewood)	0.246	92.32	928	0.985	0.064	Accept	
13001 (Bervie @ Inverbervie)	0.285	124.47	890	0.998	0.002	Accept	
27086 (Skell @ Ripon Alma Weir)	0.326	117.33	899	0.97	0.015	Accept	
52004 (Isle @ Ashford Mill)	0.328	87.41	891	0.979	0.026	Accept	
206001 (Clanrye @ Mountmill Bridge)	0.351	120.47	975	0.972	0.004	Accept	
43014 (East Avon @ Upavon)	0.353	85.83	759	1	0.012	Accept	Permeable Adjustment Applied
7010 (Muckle Burn @ Brodie)	0.363	80.68	810	0.984	0	Accept	
53028 (by Brook @ Middlehill)	0.392	99.49	835	0.999	0.014	Reject	Negative L-Skew
66005 (Clwyd @ Ruthin Weir)	0.405	96.39	958	0.995	0.005	Accept	
54036 (Isbourne @ Hinton on the Green)	0.405	92.83	701	0.99	0.012	Accept	
53023 (Sherston Avon @ Fosseway)	0.41	77.73	835	0.999	0.009	Accept	
203043 (Oonawater @ Shanmoy)	0.414	88.59	1003	0.974	0.002	Accept	Negative L-Skew
39020 (Coln @ Bibury)	0.44	107.3	821	0.968	0.006	Accept	Permeable Adjustment Applied

¹³ Results based upon FEH methodology and data, CEH (2015) 'CEH 2015. The Flood Estimation Handbook (FEH) Online Service, Centre for Ecology & Hydrology, Wallingford, Oxon, UK'

4.3 Results

A three-parameter generalised logistic (GL) distribution was used, which is the FEH recommended distribution for use within UK flood data to model the growth curve. Figure 2 shows the estimated flood frequency curve for the subject site and Table 4 presents the flood growth curve indexed by return period. The growth curve was also adjusted for urbanisation.

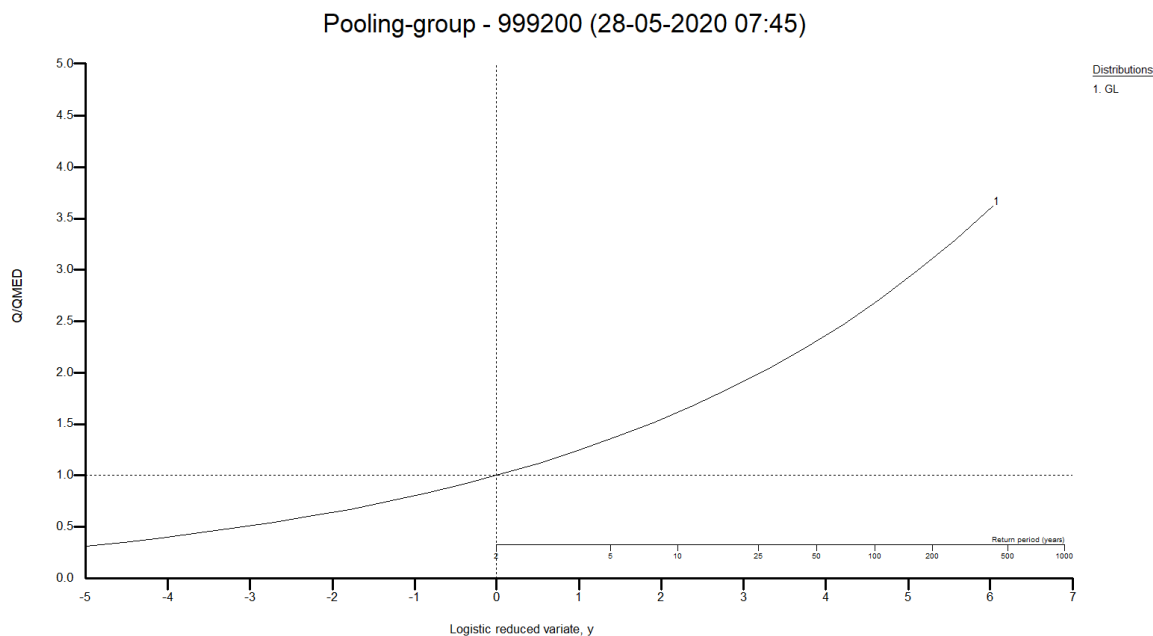


Figure 2 Growth curve

Table 4. Growth curve¹⁴

Return Period (years)	Growth Curve for Location
2	1
25	1.89
50	2.18
100	2.50
500	3.43
1000	3.93

The final peak flow is presented in Table 5. These represent the QMED value (2-year return period) scaled by the growth curve.

¹⁴ Results based upon FEH methodology and data, CEH (2015) 'CEH 2015. The Flood Estimation Handbook (FEH) Online Service, Centre for Ecology & Hydrology, Wallingford, Oxon, UK'

Table 5 Flood Peak flow estimate

Return Period (years)	Peak Flow estimate (m ³ /s)
2	16.63
25	31.47
50	36.23
100	41.59
500	57.03
1000	65.26

5 Peak Flows Estimation using the Rainfall- Runoff methodology

The catchment was modelled using the ReFH 2.3 software. This uses standard design rainfall events and catchment descriptors to produce hydrographs for the site. The recommended duration and timestep of 9.00 hours and 1.00 hours respectively were used to define the rainfall event. Default parameters for urbanisation were used.

Table 6 Peak Flow Estimates as Returned by ReFH 2 Software¹⁵

Return Period (years)	Peak Flow estimate (m ³ /s)
2	19.70
25	44.28
50	52.77
100	61.95
500	85.80
1000	96.79

¹⁵ Results based upon FEH methodology and data, CEH (2015) 'CEH 2015. The Flood Estimation Handbook (FEH) Online Service, Centre for Ecology & Hydrology, Wallingford, Oxon, UK'

6 Final Hydrology

The flood peaks estimated using the rainfall runoff methodology are higher than those produced using the statistical method. Based on NRW guidance the statistical estimates are used for return period up to and including 100 Year event. The flow estimates for the return periods above the 100 Year event are estimated by rescaling the statistical 100 Year peak flow estimate by the ratio between the ReFH 2.3 peak flow estimate for the target return period and the 100 Year return period. The final flood peaks are presented in Table 7.

Table 7 Final Peak Flows Estimates¹⁶.

Return Period (years)	Peak Flow estimate (m ³ /s)
2	16.63
25	31.47
50	36.23
100	41.59
500	57.60
1000	64.98

7 Bowling Bank Gauging Station Review

The peak flows derived are reviewed against the available flow data from the Bowling Bank Gauging station. The national river flow achieve (NRFA) does not consider the station to be suitable for QMED or pooling analysis.

The channel downstream of the gauge frequently blocks with debris from fallen trees/branches and the gauging station weir drowns at approximately 8.0 m³s⁻¹. Furthermore, a road bridge 150 m downstream of the gauging station can act as a constriction, particularly during high flows.

Multiple peak flow ratings have applied across the period of record, the most recent is valid from January 1997. The ratings diverge from one another above a stage of 0.60m. Some works were carried out in 2002/3 to attempt to contain the peak flows. The June 2007 event was almost fully contained. Before the 2002/3 works, flows were thought to bypass from the 10-year event upwards.

For these reasons, the gauge is not considered suitable to inform a peak flow assessment of the river hence why it has not been used to refine the flow estimates in this case. However, the daily flow record is plotted in Figure 3 over the stations 42-year record. This broadly shows the record to align with the peak flows estimated with no significant disparities suggesting that the peak flow estimates systematically over or underestimate river flows. Noting that the gauged flows are themselves subject to significant uncertainty.

¹⁶ Results based upon FEH methodology and data, CEH (2015) 'CEH 2015. The Flood Estimation Handbook (FEH) Online Service, Centre for Ecology & Hydrology, Wallingford, Oxon, UK'

Peak Flow Estimate for Bowling Bank

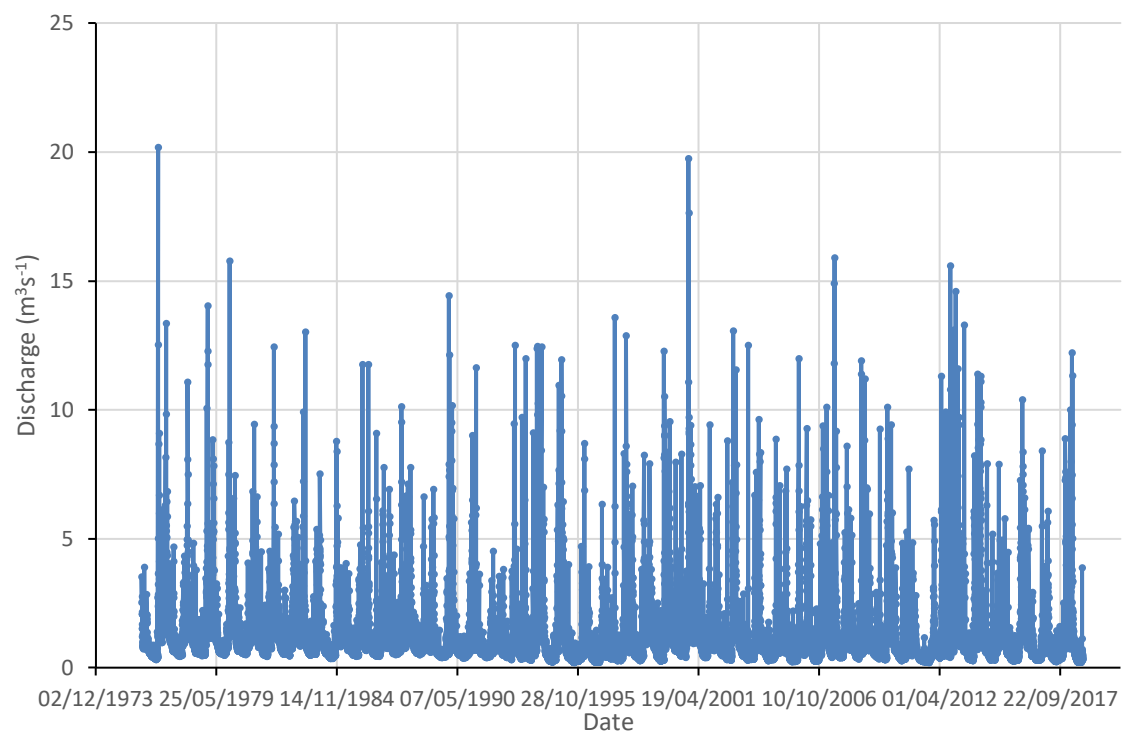


Figure 3- Daily Flow Data at 67025- Clywedog at Bowling Bank (1976-2018)

Appendix B NRW Calculation Template

Flood estimation calculation record

Introduction

This document is a supporting document to the Natural Resources Wales (NRW) Flood Estimation Technical Guidance Note (GN008). It provides a record of the calculations and decisions made during flood estimation. It will often be complemented by more general hydrological information given in a project report. The information given here should enable the work to be reproduced in the future.

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Approval

	Signature	Name and qualifications	For NRW staff: competence level
Calculations prepared by:	-	Harry Koido-Bunt BSc	
Calculations checked by:		Daniel Hamilton BSc MSc	
Calculations approved by:			
Competence levels: - level 1 – hydrologist with minimum approved experience in flood estimation - level 2 – senior hydrologist - level 3 – senior hydrologist with extensive experience of flood estimation			

Abbreviations

AM	Annual maximum
AREA	Catchment area (km ²)
BFI	Base flow index
BFIHOST	Base flow index derived using the HOST soil classification
DPLBAR	Mean drainage path length (km)
DPSBAR	Mean drainage path slope (m/km)
FARL	FEH index of flood attenuation due to reservoirs and lakes
FEH	Flood Estimation Handbook
FPEXT	Floodplain extent
FSR	Flood Studies Report
HOST	Hydrology of soil types
NRFA	National River Flow Archive
NRW	Natural Resources Wales
POT	Peaks over a threshold
QMED	Median annual flood (with return period 2 years)
ReFH	Revitalised flood hydrograph method – used for rainfall runoff method
SAAR	Standard average annual rainfall (mm)
SPR	Standard percentage run-off
SPRHOST	Standard percentage run-off derived using the HOST soil classification
Tp (0)	Time to peak of the instantaneous unit hydrograph
URBAN	Flood Studies Report index of fractional urban extent
URBEXT2000	Revised index of urban extent
WINFAP	Windows Frequency Analysis Package – used for FEH statistical method

1. Method statement

1.1. Overview of requirements for flood estimates

Item	Comments
Give an overview which includes: • purpose of study • approximate number of flood estimates required • peak flows or hydrographs • range of return periods and locations • approximate time available	Peak flow estimates and hydrographs are required for the River Clywedog at the Bowling Bank gauging station, Wrexham (NGR: 339550, 348250). This information is needed to inform hydrograph inputs for hydraulic modelling of the river. Flood estimates are required at one location for a range of return periods, with hydrographs provided for the 2yr, 25yr, 50yr, 100yr, 200yr, 500yr and 1000yr events.

1.2. Overview of catchment

Item	Comments
Brief description of catchment, or reference to section in accompanying report. Include maps where necessary.	The area of the FEH Web Service boundary is 103.55 km². The catchment has an URBEXT2000 value of 0.0983 hence is classed as 'moderately urbanised' according to FEH guidance. The catchment is reasonably permeable, assigned a BFIHOST characteristic of 0.530. The majority of the catchment is underlain by siltstone and sandstone, with superficial deposits of till and glacial and sand and gravel in evidence across the catchment. The catchment is not significantly affected by the presence of lakes, with a FARL value of 0.989, and experiences moderate rainfall with a SAAR value of 852mm.

1.3. Source of flood peak data

Item	Comments
Was the NRFA Peak Flows dataset used? If so, which version? If not, why not? Record any changes made.	The current version of NRFA Peak Flows dataset available for use in this study was NRFA Peak Flows v8.

1.4. Gauging stations (flow or level)

At the sites of flood estimates or nearby at potential donor sites. Also state gauging authority number where it is different to the NRFA number.

Water course	Station name	NRFA number (used in FEH)	Grid reference	Catchment area (km ²)	BFIHOST	FPEXT	URBEXT 2000
Clywedog	Bowling Bank	67025	SJ395482	98.6 km ²	0.530	0.0658	0.0983

1.5. Data available at each flow gauging station

Station Name	Start and end date on NRFA	Update for this study?	Suitable for QMED?	Suitable for pooling?	Data quality check needed?	Other comments on station and flow quality e.g. information from NRFA Peak Flows, trends in flood peaks, outliers
Bowling Bank	1976-2018	No	No	No	No	•The channel downstream of the gauge blocks with debris and the gauging station weir drowns at approximately $8.0 \text{ m}^3\text{s}^{-1}$. •Multiple ratings applied across the record; ratings diverge from one another above a stage of 0.60m. •For these reasons, the gauge is not considered suitable to inform a peak flow assessment. However, the daily flow record is broadly compared with the peak flow estimates to see if there are any clear disparities.

1.6. Rating equations

Station name	Type of rating e.g. theoretical, empirical, degree of extrapolation	Rating review needed?	Reasons e.g. availability of recent flow gaugings, amount of scatter in the rating
Bowling Bank	-	-	Outside of study scope plus no specific information available on ratings and flow gaugings to carry out hydrometric review.
Include a link or reference to any rating reviews carried out			

1.7. Other data available and how it has been obtained

Type of data	Data relevant to this study?	Data available?	Source of data and licence reference from NRW	Details
Check flow gaugings (if planned to review ratings)	Outside project scope	-	-	-
Historic flood data – give link to historic review if carried out	Outside project scope	-	-	-
Flow data for events	Outside project scope	-	-	-
Rainfall data for events	Outside project scope	-	-	-
Results from previous studies	Outside project scope	-	-	-
Other data or information e.g. groundwater, tides	Outside project scope	-	-	-

1.8. Initial choice of approach

Item	Comment
Outline the conceptual model. Address questions such as: • Where are the main sites of interest? • What is likely to cause flooding at those locations? (e.g. peak flows, flood volumes, combination of peaks, groundwater, snowmelt, tides) • Might those locations flood from runoff generated on part of the catchment only e.g. downstream of a reservoir?	The study is interested in fluvial flooding from the River Clywedog at the Bowling Bank gauging station. Given the size of the catchment, its relative permeability and the flatness of the terrain it is expected that flooding will be predominantly driven by overall flood volume although peak flows may also have some importance.
Any unusual catchment features to take into account? e.g. • highly permeable (BFIHOST > 0.65) – consider permeable catchment adjustment for statistical method if SPRHOST < 20% • highly urbanised – consider choice of method carefully; consider method that can account for differing sewer and topographic catchments • pumped watercourse – consider lowland catchment version of rainfall-runoff method • major reservoir influence (FARL < 0.90) – consider flood routing • extensive floodplain storage – consider choice of method carefully	The catchment exhibits moderate permeability (BFIHOST: 0.530) and is not considered highly permeable. Permeable adjustment has been applied where catchments in the pooling group had SPRHOST < 20%. The catchment is not heavily urbanised, subject to pumping or influenced significantly by reservoirs.
Initial choice of method(s) and reasons • Are FEH statistical and/or ReFH appropriate? • If not appropriate, describe why and give details of the other methods to be used. • Will the catchment be split into sub-catchments/intervening areas? If so, how will flows for intervening areas be estimated?	The FEH statistical and Revitalised Flood Hydrograph (ReFH) methods are used to derive the peak flows and hydrographs for the catchments. Research into flood estimation in small catchments¹ suggests that both FEH methods outperform older methods for estimating floods in small catchments, for example the IH 124 method (the small catchment implementation of the FSR procedures) and ADAS 345 method. The research notes that there is little evidence to suggest that the accuracy of the FEH methods when applied to ungauged catchments is particularly scale dependent and

¹ Environment Agency, 2012, Estimating flood peaks and hydrographs for small catchments: Phase 1, SC090031

	recommends the use of current versions of the FEH methods. The methods are therefore applicable to this study. The rainfall-runoff methods are those first published by Kjeldsen², which were subsequently updated in 2015 and 2019 and implemented within the ReFH2.3 software³ as described in the WHS technical guidance⁴. Note, the updated BFIHOST descriptor, BFIHOST19, which determines the baseflow characteristics of a catchment, is used in the estimation of the rainfall-runoff flows. The BFIHOST19 software is not used for the estimation of the statistical flows as the statistical method has not been recalibrated to the new dataset, therefore the BFIHOST descriptor continues to be used in the estimation of the statistical flows for this study. As recommended by NRW the peak flows from the statistical method will be used to scale the hydrographs up to a return period of 100 years. Above the 100-Year return period the hybrid method is applied with the ratio of the ReFH hydrographs peak flows to the 100-year ReFH hydrograph peak flow applied as a scaling factor, to the statistical 100-year estimate.
Software to be used (with version numbers) edit or delete as applicable, or add others	WINFAP 4.1 ReFH 2.3

² Kjeldsen, T. R. 2007. The revitalised FSR/FEJ rainfall-runoff method. Supplementary Report No.1. CEH.

³ <https://www.hydrosolutions.co.uk/software/refh-2/>

⁴ https://www.hydrosolutions.co.uk/software/refh-2/supporting_literature/

2. Locations where flood estimates are required

2.1. Summary of subject sites

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

Site code	Watercourse	Site	Easting	Northing	AREA on FEH Web Service (km ²)	Revised AREA if altered
1	Clywedog	Bowling Bank	339550	348250	103.55	-
Reasons for choosing above locations	This is an existing gauging station with useful background information and is also immediately downstream of a series of Sites in which our client has an interest.					

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

Site code	FARL	PROPWET	BFIHOST (BFIHOST19)	DPLBAR (km)	DPSBAR (m/km)	SAAR (mm)	SPRHOST	URBEXT 2000	FPEXT
1	0.989	0.51	0.530 (0.532)	14.27	62.0	852	35.32	0.0983	0.0658

2.3. Checking catchment descriptors

Item	Comment
Record how catchment boundary was checked • describe any changes • refer to maps if needed	The catchment boundary was checked against OS Terrain 50 data and determined to be an accurate representation of the watershed based on the local topography.
Record how other catchment descriptors were checked, especially soils • describe any changes • include a before and after table if necessary	The Landis Soilscales map ⁵ and BGS Geoviewer ⁶ have been used to assess the soils and bedrock/superficial deposit present in the catchment respectively. These show that the BFIHOST and BFIHOST19 values derived for the catchment are representative of the mapped geology.
Source of URBEXT / URBAN	The URBEXT2000 landcover data has been reviewed against more recent satellite data, both seem to be in broad agreement with one another. The URBEXT value for the catchment derived from the FEH Web Service (0.0983) has therefore been retained.
Method for updating URBEXT / URBAN • Refer to WINFAP4 Urban Adjustment procedures/guidance	Not applicable

⁵ Cranfield Soil and Agrifood Institute (2020), *Landis Soilscales map*, <http://www.landis.org.uk/soilscales/>

⁶ BGS (2020) *Geology of Britain viewer*, <https://mapapps.bgs.ac.uk/geologyofbritain/home.html>

3. Statistical method

3.1. Search for donor sites for QMED (if applicable)

Note that donor catchments will usually be rural but may be urban provided the data is deurbanised prior to the adjustment process. Please include a map if necessary.

Comment on potential donor sites

Mention:

- number of potential donor sites available
- distances from subject site
- similarities in terms of AREA, BFIHOST, FARL and other catchment descriptors
- quality of flood peak data

Estimates of QMED from observed data (QMEDobs) at donor stations can be used to adjust the estimate of QMEDcds at the subject site. Possible donor catchments are initially sought on the basis of being geographically close. Along with geographical distance the similarity of catchment descriptors; Area, SAAR, FARL and BFIHOST with the target catchment are also considered.

The general pattern of QMEDcds to the QMEDobs for the six closest stations shows the catchment descriptor equation to consistently overestimate QMEDobs. Two stations from the donor group were rejected, these were the Ceiriog at Brynkinalt Weir (67005) and the Perry at Yeaton (54020) lying 18.86 km and 21.31 km from the target catchment, respectively. For the former this was based on it having a significantly higher SAAR value (+20%) relative to the target catchment. The Perry at Yeaton was rejected as it had a significantly higher BFIHOST (+20%) relative to the target catchment and showed disparities in other catchment descriptors including FARL and SAAR.

One station was substituted into the donor group, this was the Gowy at Bridge Trafford (68020) which shares many similarities and is located 25.28 km from the target catchment. No further stations outside of the initial pooling group were considered suitable for donor transfer. As a result, five stations were chosen in the donor group, from which to inform the QMED estimate, all situated within 30 km of the target catchment. The stations selected appear to have good quality flood peak data, with many of the records having more than 40 years of data and all being deemed suitable for QMED estimation by the NRFA.

3.2. Donor sites chosen and QMED adjustment factors

If using WINFAP3 great caution should be taken in urban catchments that are also highly permeable (BFIHOST>0.65). Further details are provided in the EA Flood Estimation Guidelines.

NRFA number	Reasons for choosing or rejecting	Method (AM or POT)	Adjusted for climatic variation?	QMED from flow data (gauged) (m ³ /s)	QMED from flow data with urban influence removed (A) (m ³ /s)	QMEDrural from catchment descriptors (B) (m ³ /s)	Adjustment ratio (A/B)
67008	Similar catchment descriptors and aligns with QMEDobs/QMEDcads trend	AM	No	21.59	20.74	35.71	0.58
67009	Similar catchment descriptors and aligns with QMEDobs/QMEDcads trend	AM	No	8.681	8.66	15.31	0.57
67005	Rejected as SAAR 20% higher than target catchment	AM	No	28.87	28.83	49.87	0.58
54020	Rejected as BFIHOST 20% higher than target catchment	AM	No	10.59	10.35	12.93	0.80
66005	Similar catchment descriptors and aligns with QMEDobs/QMEDcads trend	AM	No	16.907	16.80	24.67	0.68
66001	Similar catchment descriptors and aligns with QMEDobs/QMEDcads trend	AM	No	49.432	49.04	59.02	0.83
68020	Similar catchment descriptors and aligns with QMEDobs/QMEDcads trend	AM	No	14.962	14.66	18.02	0.81
66004	Rejected as BFIHOST 20% higher than target catchment	AM	No	3.651	3.63	6.63	0.55
54038	Rejected as SAAR 20% higher than target catchment	AM	No	79.126	79.05	99.50	0.79
54016	Rejected as SAAR 20% lower than target catchment	AM	No	10.746	10.54	18.57	0.57
Has the WINFAP4 urban adjustment method (based on Kjeldsen, 2014) been applied? If not, why?				Yes			

3.3. Overview of estimation of QMED at each subject site

Notes for completing this table

- Methods
 - CD: catchment descriptors alone
 - DT: data transfer
 - BCW: catchment descriptors and bankfull channel width
 - FV: flow variability (using flow duration statistics)
- Urban adjustment procedures should be applied regardless of whether the subject site is rural or urban.
- If using WINFAP3, great caution should be taken in urban adjustment of QMED on catchments that are also highly permeable (BFIHOST>0.65).
- The data transfer procedure is from Science Report SC050050. 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 the initial estimate from catchment descriptors.
- If more than one donor has been used, use multiple rows for the site and give the weights used in the averaging. Record the weighted average adjustment factor in the table.

			Data transfer						
Site code	QMEDrural from CDs (m³/s)	Method	NRFA numbers for donor site/s used (see 3.2)	Distance between centroids d _{ij} (km)	Moderated QMED adjustment factor (A/B) ^a	If more than one donor		Final estimate of QMEDrural (m³/s)	Final estimate of QMEDurban (m³/s)
						Weight (if WINFAP4 method not used)	Weighted average QMED adjustment factor		
1	19.372	Donor Transfer (using 5 Donors)	67008	12.72	0.82	WINFAP 4 method used	0.763	14.774	16.626
			67009	14.78	0.82				
			66005	21.40	0.89				
			66001	24.65	0.95				
			68020	25.28	0.94				
Has the Kjeldsen (2014) urban adjustment method (as used in WINFAP4) been applied? If not, why?					Yes				

How are the weights derived?	WINFAP v4.1 weighting procedure
Are the values of QMED consistent, for example at successive points along the watercourse and at confluences?	Not applicable

3.4. Derivation of pooling groups

The composition of pooling groups is given in the Annex. 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. Include any sites that were investigated but retained in the group
A	1	No	Stations 39028 and 53028 rejected due to negative L-Skew value. May be the result of sampling error but may also indicate issues with the quality of the data, therefore removed as precautionary approach. The removal of these stations 39028 resulted in less than 500 station years, therefore three stations (53023, 203043 and 39020) were added to rectify this.
URBEXT2000 threshold used to create pooling group(s)	0.30		

3.5. Derivation of flood growth curves at subject sites

Notes for completing this table

- Abbreviations for method types
 - SS: single site
 - P: pooled
 - ESS: enhanced single site
 - FH: single site with flood history
- A pooling group (or ESS analysis) derived at one gauge can be applied to estimate growth curves at a number of ungauged sites. Each site may have a different urban adjustment, and therefore different growth curve parameters.
- Urban adjustments to growth curves should use the latest methodologies in WINFAP
- Any relevant frequency plots from WINFAP, particularly showing any comparisons between single-site and pooled growth curves (including flood peak data on the plot) should be shown here or in a project report.

Site code	Method (SS, P, ESS, FH)	If P, ESS, or FH, name of pooling group (3.4)	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
1	P	A	Generalised Logistic Reason- Showed acceptable fit, preferred over GEV distribution due to requirement for permeable adjustment of three stations within the pooling* and is the FEH recommended distribution for use within UK flood data. The method also provides the largest (most conservative) growth factors therefore safeguards against an underestimation of flood risk.	Permeable adjustment applied for stations 43012, 43014 and 39020 (SPRHOST<20)	Location: 1.000 Scale: 0.211 Shape: -0.180	2.502

* The permeable adjustment procedure cannot be applied to the GEV distribution,. The procedure is applied outside of the WINFAP software and will result in the GL distribution having better fit than first estimated by the software. More details on this procedure are provided here: <https://www.hydrosolutions.co.uk/knowledge-base/what-is-a-permeable-adjustment/>

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	25	50	100	200	500	1000
1	16.63	22.02	25.90	31.47	36.23	41.59	47.68	57.03	65.26

4. Revitalised flood hydrograph (ReFH) method

4.1. Parameters for ReFH model

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

Site code	Details of method OPT: optimisation BR: base flow recession fitting CD: catchment descriptors DT: data transfer	T _p (hours) Time to peak	C _{max} (mm) maximum storage capacity	BL (hours) baseflow lag	BR baseflow recharge
1	CD	5.1	407.509	51.436	2.822 (For 2-Year event)
Brief description of any flood event analysis carried out Provide further details either here or in a project report		Not applicable			

4.2. Design events for ReFH method

We recommend that the ReFH2 technical guidance should be referred to when completing this table

Site code	Season of design event (summer or winter)	Storm duration (hours)	Storm area for ARF (if not catchment area)	Source of design rainfall statistic (FEH13 or FEH99)
1	Winter	9	Not applicable	FEH13
Detail any changes to the default ReFH2 urbanisation model parameters Are the storm durations likely to be changed in the next stage of the study		Default ReFH 2.3 values retained		
		Not necessary for the proposed FCA modelling		

For example by optimisation within a hydraulic model?

4.3. Flood estimates from the ReFH method (urban/rural)

- Please indicate whether you have used urban or rural results
- We recommend that urban results are used regardless of the extent of urbanisation at the subject sites

Site code	URBAN Flood peak (m ³ /s) or volumes (m ³) for the following return periods (in years)								
	2	5	10	25	50	100	200	500	1000
1	19.70	27.72	34.29	44.28	52.77	61.95	71.81	85.80	96.79

5. Discussion and summary of results

5.1. Comparison of results from different methods

This table compares peak flows from the ReFH method with those from the FEH Statistical method at each site for two key return periods.

Site code	Return period 2 years (QMED)			Return period 100 years		
	Statistical	ReFH	Ratio (ReFH / statistical)	Statistical	ReFH	Ratio (ReFH / statistical)
1	16.63	19.70	1.18	41.59	61.95	1.49

5.2. Final choice of method

Choice of method and reasons

Include reference to type of study, nature of catchment, and type of data available

Hybrid Method- Due to no obvious reason to prefer one method over the other based on the nature of the catchment and data available, NRW's hybrid approach has been used to derive the final peak flows.

The statistical estimates are used for return period up to and including 100 Year event. The flow estimates for the return periods above the 100 Year event are estimated by rescaling the statistical 100 Year peak flow estimate by the ratio between the ReFH 2.3 peak flow estimate for the target return period and the 100 Year return period.

5.3. Assumptions, limitations, and uncertainty

List the main assumptions made specific to the study	QMED catchment descriptor equation overestimates QMED at the target site based on trend observed for nearby donor sites.
Discuss any particular limitations For example applying methods outside the range of catchment types or return periods for which they were developed	There is no suitable gauging station data along the Clewedog in the vicinity of the target site with which to refine and check the peak flow estimates derived. As established the Bowling Bank gauging station immediately downstream is not suitable for QMED estimation or pooled analysis.
Give what information you can on uncertainty in the results For example using the methods detailed in 'Making better use of local and historic data, and estimating uncertainty in FEH design flood estimation (FEH Local) SC130009	The QMED estimate has been derived using the donor transfer method based on FEH literature the method has a factorial standard error (F.S.E) of 1.354, below the F.S.E for the catchment descriptor equation (F.S.E = 1.431). The uncertainty associated with higher order events is more difficult to determine due to the limited length of the available gauged record and the lack of suitable gauged sites nearby. The flows do align reasonably well with the flows recorded at Bowling Bank downstream and are within the bounds of what would be expected given the catchment's size and location.
Comment on the suitability of the results for future studies For example at nearby locations or for different purposes	The study has estimated flows for the target site using the latest FEH methods and is considered a robust estimate of peak flows in the Clwedog which could be used as the basis for future studies. Ideally future studies would have and be able to apply more local data.
Give any other comments on the study For example suggestions for additional work	Bypassing of flow at the Bowling Bank station was a major issue which partly explains the divergence in ratings at the site. However, some works were carried out in 2002/3 to attempt to contain the peak flows. The June 2007 event was almost fully contained. Before the 2002/3 works, flows were thought to bypass from the 10-year event upwards. With more flows remaining in-bank the flow record for the site should become more robust over time potentially making the station suitable for refining and checking flow estimates in a subsequent study along the reach.

5.4. Checks

Are the results consistent, for example at confluences?	Single inflow, therefore unnecessary to check for consistency at confluences and moving downstream.
What do the results imply regarding the return periods of floods during the period of record?	Historical flood data has not been assessed given the scope of this study.
What is the 100-year growth factor? Is this realistic? (The guidance suggests a typical range of 2.1 - 4.0)	2.50
If 1000-year flows have been derived, what is the range of ratios for the 1000-year flow over 100-year flow?	1.56 (based on final peak flows)
What is the range of specific runoffs (l/s/ha)? Are there any inconsistencies?	2-Year: 1.61 l/s/ha 100-Year: 4.02 l/s/ha 1000-Year: 6.28 l/s/ha
How did the results compare with those of other studies? Explain any differences and conclude which results should be preferred	Not applicable
Are the results compatible with the longer-term flood history?	The daily flow record at the Bowling Bank gauging station has been plotted over the stations 42-year record. This broadly shows the record to align with the peak flows estimated with no significant disparities suggesting that the peak flow estimates systematically over or underestimate river flows. No further checks were made against historical data.
Describe any other checks on the results	High level check on flows against expected flows considering size, geology, rainfall and urbanisation within catchment.

5.5. Final results

Site code	Flood peak (m ³ /s) or volumes (m ³) for the following return periods (in years)								
	2	5	10	25	50	100	200	500	1000
1	16.63	22.02	25.90	31.47	36.23	41.59	48.21	57.60	64.98

If flood hydrographs are needed for the next stage of the study, where are they provided?

For example give a name of spreadsheet, name of hydraulic model, or reference to table below

WINFAP_Scaled_Hydrographs_v1.0.xlsx

6. Annex – supporting information

Please include details of your pooling group(s)

6.1. Pooling group composition

Station	Distance SDM	AREA (km ²)	SAAR (mm)	FARL	URBEXT 2000	Accept or Reject	Comments
42001 (Wallington @ North Fareham)	0.147	111.67	819	0.979	0.053	Accept	
43012 (Wylfe @ Norton Bavant)	0.237	114.01	925	0.975	0.026	Accept	Permeable Adjustment Applied
39028 (Dun @ Hungerford)	0.241	100.1	786	0.988	0.004	Reject	Negative L-Skew
84007 (South Calder Water @ Forgewood)	0.246	92.32	928	0.985	0.064	Accept	
13001 (Bervie @ Inverbervie)	0.285	124.47	890	0.998	0.002	Accept	
27086 (Skell @ Ripon Alma Weir)	0.326	117.33	899	0.97	0.015	Accept	
52004 (Isle @ Ashford Mill)	0.328	87.41	891	0.979	0.026	Accept	
206001 (Clanrye @ Mountmill Bridge)	0.351	120.47	975	0.972	0.004	Accept	
43014 (East Avon @ Upavon)	0.353	85.83	759	1	0.012	Accept	Permeable Adjustment Applied
7010 (Muckle Burn @ Brodie)	0.363	80.68	810	0.984	0	Accept	
53028 (by Brook @ Middlehill)	0.392	99.49	835	0.999	0.014	Reject	Negative L-Skew
66005 (Clwyd @ Ruthin Weir)	0.405	96.39	958	0.995	0.005	Accept	
54036 (Isbourne @ Hinton on the Green)	0.405	92.83	701	0.99	0.012	Accept	
53023 (Sherston Avon @ Fosseway)	0.41	77.73	835	0.999	0.009	Accept	
203043 (Oonawater @ Shanmoy)	0.414	88.59	1003	0.974	0.002	Accept	
39020 (Coln @ Bibury)	0.44	107.3	821	0.968	0.006	Accept	Permeable Adjustment Applied

6.2. Additional supporting information

See Hydrology_Peak_Flow_Report_v2.0.pdf which provides more information on the analysis applied.

Appendix C Model Review Report (including responses)

MODEL REVIEW SHEET

PROJECT	Wrexham Industrial Development, Pre-App Model Review
PURPOSE OF STUDY	Baseline flooding conditions for proposed industrial development
WATERCOURSE	River Clywedog
MODEL TYPE	ESTRY-TUFLOW
MODELLER	Corylus Planning & Environmental Ltd
FILES USED IN REVIEW	Wrexham Industrial Development, Baseline Flood Model Report. (ref 259/FLOOD/v2, June 2020) Model files Survey files

Colour coding used:

Green – suggestion for improved / good practice but which is unlikely to change the model outcome.

Amber – non-standard method or method not following guidance but unlikely to have impacted on model results.

Red – omission/error that could make the model findings subject to challenge and which requires correction/further work.

Blue - Consultant responses to NRW

Overview

A 1d-2d (ESTRY-TUFLOW) hydraulic model has been constructed for the proposed development of a site identified as Land Off Tetrapak Road, alongside River Clywedog in Wrexham.

The site is primarily at risk of fluvial flooding and is currently contained within Zone C2, in the 1 in 100 year flood outline. No defences are present in this location. Natural Resources Wales' existing flood outlines in this area are from JFLOW modelling completed in 2010.

This is the 1st submission used to establish the baseline conditions to move the modelling forwards into the FCA phase.

Hydrology

Peak flows have been derived for Bowling Bank gauging station which has a catchment area of approx. 103 km². The subject site is further upstream with a smaller catchment area of 86.02 km² (two tributary inflows between the two locations). That's ~17% less catchment area than at Bowling Bank. It's unusual to calculate the peak flows at a location which is not at the site of interest – they have not used any flows at Bowling Bank in calibration as it is not suitable for pooling or QMed adjustment so why wasn't the study carried out at the subject site?

With the above in mind, it's likely that the final peak flows are conservative and higher than they are in reality. However, these peak flows should not be used to update the flood map nor for an FCA unless they were calculated at the site of interest.

MODEL REVIEW SHEET

Section 2.2 of the report on page 4 says the catchment area is 105.5 km² when the catchment is noted as 103.5 km² further down in the WHS peak flow study and the Flood Estimation Calculation record. 103.5 km² is used in the calculations.

Method of determining QMed from catchment descriptors seems reasonable though BFIHOST has been used rather than BFIHOST19. This doesn't make much difference at this particular site however (difference of 0.04 m³/s). Winfap 4 automatically uses BFIHOST19, so not sure why it wasn't used.

As producers of the software, WHS comment that WINFAP 4 hasn't been calibrated to BFIHOST19 so it is still advisable to use the BFIHOST dataset. It is used in the ReFH estimates as ReFH 2.3 has been calibrated to BFIHOST. There are plans to update WINFAP to incorporate the BFIHOST19 dataset but not until next year.

QMed adjustment is difficult at this site given that data from Bowling Bank can't be used. I'd cautiously say that the donor adjustment is reasonable, though 5 sites weren't needed to be selected. Using the first two closest stations at Pont y Capel and Rhydymwyn gives a similar adjusted QMed to using all 5 (including Pont y Cambwll, Ruthin Weir and Bridge Trafford).

It's advisable to use as much local data and donor as possible should they all show a consistent trend. However, either WHS or the approach suggested by NRW is acceptable in this case.

Methodology used mostly follows NRW guidance and says in the report 'Above the 100-Year return period the hybrid method is applied' but the final peak flow at 200 years is from the statistical method and not the hybrid method.

This statement is incorrect. The 200-year statistical flow is 47.68 m³s⁻¹. The ratio of the ReFH 200-year (71.81 m³s⁻¹) / ReFH 100-year (61.95 m³s⁻¹) is 1.1591. This multiplied by the statistical 100-year flow of 41.59 m³s⁻¹ results in the peak flow quoted in the calculation sheet and in the hydrographs provided of 48.21 m³s⁻¹.

NRW flood estimation guidance was changed from GPG102 (as quoted in report) to GN008 <https://cdn.naturalresources.wales/media/684119/gn008-flood-estimation-technical-guidance.pdf?mode=pad&rnd=131909171450000000>

Pooling group changes have been justified.

The GEV distribution is the best fit in this study. It's not usually appropriate to choose a distribution because 'it produced the largest growth factors' as stated on the calculation record.

This was not the only reason provided for using the GL distribution, it is the FEH recommended method. Where it shows acceptable fit we therefore use it in place of the GEV distribution even if the latter shows a better fit. I've never known this approach to be rejected by regulators previously, however I accept the argument put forward.

A major reason for us also not opting to use the GEV distribution is that three of the stations in the pooling group required permeable adjustment as listed in the pooling group table in the annex. The permeable adjustment procedure cannot be applied to the GEV distribution, which is another reason why the GL distribution has been selected. The procedure is applied outside of the WINFAP software and will result in the GL distribution having better fit than first estimated by the software. More details on this procedure can be found here:

<https://www.hydrosolutions.co.uk/knowledge-base/what-is-a-permeable-adjustment/>

MODEL REVIEW SHEET

Hydraulic Model

The ESTRY-TUFLOW model have been built using TufLOW version 2020-01-AB-iDP-w64, which is appropriate for this study.

Simulations have been carried out for the existing baseline conditions for the 1% and 0.1% AEP fluvial events.

Model schematisation

The hydraulic model comprises approximately 4.0km of the River Clywedog. The model has been built using cross sections from survey undertaken by Invar Mapping Surveys in May 2020.

The cross-section locations and spacing appear sensible for the purpose of assessing flood risk at the site.

A section of the 2d domain at the upstream extent of the model is outside of the model domain.

The model domain at the upstream extent is amended.

Topographical data

The 2d model has been constructed using 1m LiDAR data and site-specific topographical survey data. A topographical survey was undertaken by Invar Mapping Surveys in May 2020. The LiDAR data levels and the topographic survey levels have been compared and are within +/-200mm difference.

The model runs with a 2d grid resolution of 5m. A 5m grid is too coarse for an FCA and we would recommend a finer grid size of 2m to better define the features within the floodplain. If a 5m grid is retained a sensitivity should be completed with a finer grid.

2m grid is used for all the model runs.

Top of bank survey has been included in the model within the development site.

2d topographical edits have been made using Z shapes to smooth areas of poor DTM filtering using the surrounding ground levels. The areas identified are large regions and based on a review of the base DTM, do not appear to have been poorly filtered.

The Z shape stability layer was modified.

Boundaries

There is 1 inflow at the top of the model inputted as a QT in the 1d domain.

HX boundaries with CN line has been used to link between the 1d-2d domain. The 2d_code boundary around cross section CLY3667 does not align with the HX boundaries.

The 2d_code boundary has been modified to align with the HX boundary.

The downstream boundary looks reasonable. It has been modelled quite far downstream from the site therefore should not have any impact on the site, however sensitivity testing has not been carried out on the downstream boundary to check that it's suitable.

Sensitivity of the downstream boundary was done, and details of the sensitivity analysis were included in the section 4.4 of the model report.

Cross sections

MODEL REVIEW SHEET

In the spot checks undertaken, the 1d cross section width and levels match with the 2d representation. The spacing between cross sections is appropriate.

Some of the open channels are skipping the intended downstream cross-section during its interpolation. i.e. Channel section CLYW3566 is interpolated between cross-sections CLYW3566.csv and CLYW3444.csv, ignoring the data from CLYW3504.csv. This is due to the weir structure occurring between the end of the open channel line and the 1d_tab line.

The copy of cross section CLYW3566 was added.

Structures

Please provide more detail in the report regarding the structures modelled.

The list of modelled structures were included in section 3.3.2 (Table 3-1) of the model report.

Bridges

There are 6 bridges in the model which have been modelled as BB bridges in 1d domain: CLYW1622B, CLYW2865B, CLYW3444B, CLYW3633B, CLYW3667B, CLYW3724B.

One bridge at CLYW1615 has been excluded to improve model stability. This is acceptable as the bridge immediately upstream hydraulically controls the levels at the site and is clearly stated in the report.

The Form Loss (LC value) which accounts for losses due to any piers and the bridge deck for all 6 bridges has been set to 1.0, this is high particularly when the water level does not reach the bridge deck at majority of the bridges. There is no explanation of how this loss was derived in the report.

FLOOD

The bridges in the model was represented as BB type Bridges. BB bridges automatically creates the LC table using the Form_Loss for the pier losses and the WConF_or_WEx for the Deck Loss coefficient, if the Form_Loss attribute is greater than 0.0001 (positive non-zero).

The Form_Loss (LC value) for all the bridges were set to 0.1 to apply pier losses and the default deck loss coefficient's were used.

The HW tables have the elevation starting at 0, elevation (H) should be metres above the datum at which the hydraulic properties apply.

The elevation value can start at a value of Zero, so that height becomes depth. As the height increases the width changes to reflect the bridge shape.

The bridge spills have been represented in 1d only. The spill of Bridge CLYW3724B should have been represented in 2d because looking at the photos of the bridge, it looks like that if the bridge was overtopped the water could flow down the road and not necessarily go straight back into the river downstream of the bridge. However, results indicate this bridge is not overtopped.

The model shows a gap in the embankment on the left bank of Bridge CLYW1622B adjacent to the channel (in the 2d). Review of the photos and survey shows this is poor filtering of the DTM and there is no gap in the embankment. The merge all z shape used in the model in this area does not rectify this.

Zshape stability patch was modified.

Comment should be made that Bridge CLYW2865B is two consecutive bridges modelled as one.

Bridge CLYW3667B spill level is set at the deck level, however this structure would overtop at the top of the stone wall (~33.1mOAD). Since the 1d domain was been restricted to the length of bridge parapet, a weir is not required as overtopping the parapet would not occur at this bridge.

Weirs

MODEL REVIEW SHEET

There are 26 weir structures specified in the model, of which 6 represent overtopping the road deck and 1 for a physical weir. **There is no justification of the other 19 weir structures. Recommend the use of interpolated open channel sections between the cross section instead of weir structures to combat instabilities.**

Interpolated cross-sections have been added where necessary to improve model stability. However, some inline weirs were included in the model where there is changed in the bed levels.

Due to large change in the bed levels for successive channels, the model is not running with interpolated channel section. Therefore, weir structures were used to run the model and improve model stability.

All weirs have been modelled using the original ESTRY weir type based on the broad-crested weir formula. The weir shape has been defined for all weirs except CLYW3330W as a rectangle using the 1d_nwk width attribute. CLYW3330W has a cross-section defined based on the survey.

Other

There is significant ponding behind the Bridge Road from River Clywedog overtopping Cefn Road. **The culvert (see Figure 1) under Bridge Road should be included to convey flow back to the Clywedog.**

The culvert was included in the model.



Figure 1 – Culvert under Bridge Road

Roughness values

Roughness coefficients (manning's n) range between 0.04 and 0.06 for the main channels (1d) and between 0.025 and 0.100 for out of bank flow (2d).

The 2d assigned manning's value for the woodland area seems high being a Manning's value of 0.1, looking at aerial imagery and photos of the area I would say that it's more around 0.06. However as this is subjective the consultant should carry out sensitivity test.

Sensitivity of the roughness was done, and details of the sensitivity analysis were included in the section 4.4 of the model report.

MODEL REVIEW SHEET

Calibrations & sensitivity

There is no data to calibrate the model with however this is not been clearly stated in the report.

No sensitivities have been completed however the report notes that further model runs will be performed to identify the sensitivity of the model output to changes to inflow, roughness and downstream boundary.

Other sensitivity that potentially may need considering include: grid size, weir calibration factor.

Model run issues

Warnings, Checks

The base model shows up to 57 WARNINGS and 10 CHECKS are recorded prior to or during the simulation. Many of these warnings are related to poor QA rather than model issues (i.e. null data) and should be resolved.

GIS software will add the null objects to the layer to indicate deleted objects (particularly if using the shapefile format). They do not affect the quality of the results.

WARNING 1100 should be reviewed and commented on.

Warning 1100 will be issued where a 1D structure's invert/bed lies below the bed of the primary upstream and/or downstream channel. Survey shows that for some structures the invert levels are below the channel bed levels. They do not affect the quality of the results. Please see section 3.5.2 of the model report for more details.

Run Time Parameters

The model end time is set at 90 hours, however the simulation peaks at around 11 hours. Reducing the model end time would reduce the overall run time from about 1 hour to 10 minutes.

Revising the 2d grid X and Y dimensions would also improve run time.

Stability

There is 2 1d negative depths recorded in the 1% AEP occurring at 1:16:58 and 1:16:59. As it is only a few warnings at a single location and timestep in the simulation, it is normally not an issue.

The final cumulative mass error reported in the tlf file for the overall model is 2.45% (1% AEP) and 4.23% (0.1% AEP) which is above the commonly quoted toleration range of $\pm 1\%$.

ddv is very high (185.9%) indicating that the model may have been unsteady and not running smoothly at some point.

The mass balance error of 2.82% (1%AEP) is occurring at the early part of the simulation. Mass balance grid outputs confirm that poorer convergence occurs predominantly as a result of water ponding on the 2D domain near the industrial estate. The details of the model performance were included in the section 3.5 of the model report.

Baseline results

The report provides adequate justification as to why the baseline results these differ from the existing Flood Map. However, there are deficiencies in the model that could result in changes to the model results.

MODEL REVIEW SHEET

Conclusion

The approach taken seems appropriate for this type of study, however there are several significant issues highlighted in this review which mean the model is not fit for purpose in its current state. It is strongly recommended that the modeller reviews all the comments above.

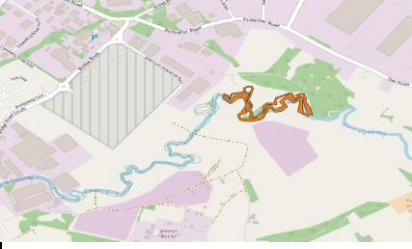
The key comments relate to the site-specific hydrology, grid size, use of topographical edits for stability and the excessive use of weirs.

Improved quality checking of the model and more detail in the model report (particularly on the structures) are recommended for any future work on this or other models.

REVIEWED BY	Denika Moes (NRW Flood Risk Analysis)
DATE	29/07/2020

Flood risk modelling undertaken by a third party has been used in support of this application and Natural Resources Wales has applied a risk based approach to assessment of this model. Natural Resources Wales has not undertaken a full assessment of the fitness for purpose of the modelling and can accept no liability for any errors or inadequacies in the model.

Appendix D Model Log

Job Description		Wrexham ESTRY TUFLOW model						
TUFLOW Modelling Log								
Date	Modeller	Comments	.tcf	.ecf	.tgc	.tbc	bc_dbase	Event_Name
19/05/2020	LY	Baseline model run with the draft inflows for 100year event	Clywedog_baseline_1AEP_01.tcf	Clywedog_baseline_1AEP_01.ecf	Wrexham_baseline_002.tgc	Wrexham_baseline_002.tbc	Clywedog_Baseline.csv	100year
05/06/2020	LY	Baseline model run with the final inflows. Topo survey of the development site ground levels included The material layer stability patch was added at the downstream of the model to improve stability.	Clywedog_baseline_1AEP_02.tcf	Clywedog_baseline_1AEP_02.ecf	Wrexham_baseline_003.tgc	Wrexham_baseline_002.tbc	Clywedog_Baseline.csv	100year and 1000year
								
		1D watercourse in the 2d domain was removed. The survey bank levels was included using zline and zpoint layer. Z shapes have been used to smooth areas of poor LiDAR filtering using the surrounding ground levels Grid orienation was changed Model extent was amended						
05/06/2020	LY	Material stability patch were removed. Weirs were included in the 1d_nwk to improve model stability. Hx lines were modified accordingly.	Clywedog_baseline_0.1%AEP_03.tcf	Clywedog_baseline_0.1%AEP_03.ecf	Wrexham_baseline_004.tgc	Wrexham_baseline_003.tbc	Clywedog_Baseline.csv	100year and 1000year
06/06/2020	LY	1d wll lines were included. The model stability was improved.	Clywedog_baseline_0.1%AEP_04.tcf	Clywedog_baseline_0.1%AEP_04.ecf	Wrexham_baseline_005.tgc	Wrexham_baseline_004.tbc	Clywedog_Baseline.csv	100year and 1000year
08/06/2020	LY	The model stability was improved by adjusting the HX lines The 2d downstream boundary was modified The 2d_code was changed according with the 2d downstream boundary adjustment.	Clywedog_baseline_0.1%AEP_05.tcf	Clywedog_baseline_0.1%AEP_05.ecf	Wrexham_baseline_006.tgc	Wrexham_baseline_005.tbc	Clywedog_Baseline.csv	100year and 1000year



Planning

Landscape

Architecture

Hydrology

Ecology