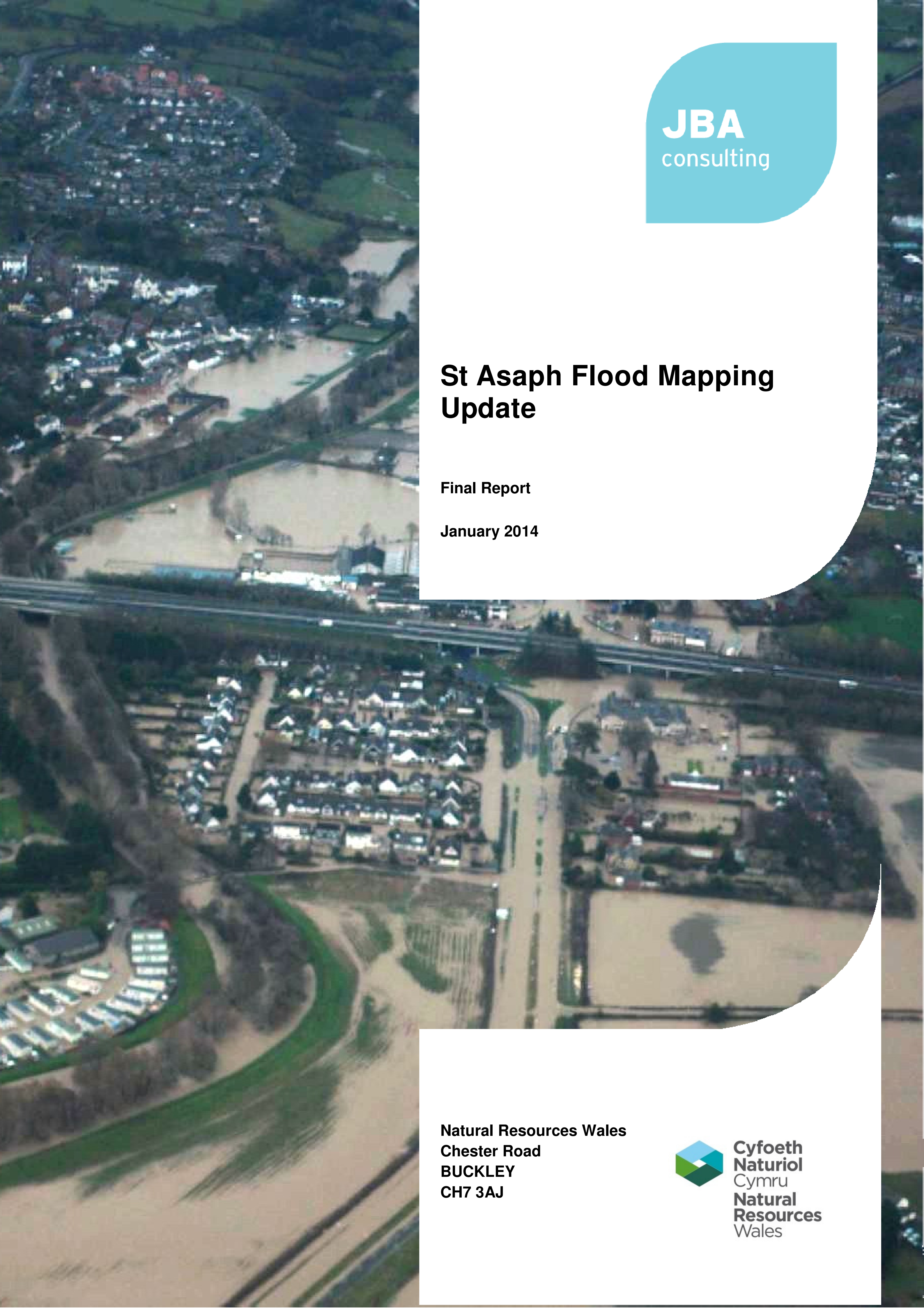

St Asaph Flood Mapping Update

Final Report

January 2014

Natural Resources Wales
Chester Road
BUCKLEY
CH7 3AJ

JBA Office

JBA Consulting
Bank Quay House
Sankey Street
Warrington
WA1 1NN

JBA Project Manager

Chris Smith BSc PhD CEnv MCIWEM C.WEM MCMI

Revision History

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Final Report 31/01/14	Updates following model review and NRW comments	Richard Weston/Rob Green
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Contract

This report describes work commissioned by Richard Weston, on behalf of Natural Resources Wales, by a letter dated 14 January 2013. Natural Resources Wales's representative for the contract was Richard Weston. Julia Hunt and Chris Smith of JBA Consulting carried out this work.

Prepared by..Julia Hunt BSc

Analyst

Reviewed by ....Chris Smith BSc PhD CEnv MCIWEM C.WEM MCMI

Principal Analyst

Purpose

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Executive Summary

Following the November 2012 flood event that occurred within St Asaph, Natural Resources Wales (NRW) commissioned JBA Consulting to undertake post event analysis and as a result the hydraulic model of the River Elwy through St Asaph has been calibrated using available data for the event. The calibrated hydraulic model has been used to update the flood mapping deliverables for St Asaph. The post event analysis has shown that the November 2012 event was between a 1% and 0.5% AEP event in magnitude.

As part of this flood mapping update, the hydrology of the Elwy catchment has been investigated using data from the November 2012 flood event. Data from Pont Y Gwyddel flow gauge upstream of St Asaph on the River Elwy has been used to inform the hydrological assessment. A standard FEH assessment of the hydrology was undertaken incorporating the latest data. In addition to this, an alternative approach using a routing model to transfer flow from Pont Y Gwyddel to St Asaph was also investigated. From this catchment event modelling approach an alternative set of design flows at St Asaph were created, these flows consistently increased with catchment area unlike the design flow calculated using the standard FEH methods. As a result the flows calculated using the alternative method were used as the design flows for St Asaph.

The existing ISIS-TUFLOW hydraulic model of the River Elwy through St Asaph (constructed by JBA in 2011) has been updated and calibrated based on data available for the November 2012 event. As well as adding in the routing sections between Pont Y Gwyddel and the hydraulic model through St Asaph, additional inflows were added to the model to represent the increase in catchment area between the gauge and the town. Adjustments were made to structures within the model in order to calibrate it and manning's values were carefully considered and updated through the town. The model has been calibrated based on the levels recorded at the St Asaph gauge on the downstream face of the A55 road bridge in the town and other observations of flood levels and extents.

The following design events have been investigated using the calibrated model; 3.33%, 1.33%, 1%, 1% plus climate change, 0.5% and 0.1% AEP events. The model has been configured for the defended and undefended scenario as there are formal flood defence embankments along much of the River Elwy through St Asaph.

The predicted flood risk to St Asaph using the model calibrated to the 2012 event is significantly greater than the flood risk predicted by the 2011 Flood Risk Mapping (FRM) study. 40 properties within the Roe Parc area of St Asaph are predicted to be at risk of flooding during the 3.33% AEP defended design event and 236 properties within St Asaph overall are predicted to flood during the 1% AEP defended design event. The 1% AEP flood extent shows that the flood embankments through St Asaph do not provide protection up to the 1% AEP event in certain locations. Standard of Protection (SoP) analysis has been undertaken as part of study.

Given that the calibrated model predicts that properties are at risk during the 3.33% AEP defended event in Roe Parc; the model was used to test a number of short term flood risk mitigation options in St Asaph. Following testing using the model, the defence height of the embankment protecting Roe Parc has been increased and trees on the banks of the River Elwy have been removed through the town to increase conveyance within the channel.

The number of properties at risk of flooding in St Asaph increases in the undefended scenario; 306 properties are predicted to flood in the 1% AEP undefended event. The Flood Zones developed for this study are larger than the existing ones produced by the previous Flood Map update by JBA in 2011.

As part of this study, the impact of Spring Gardens Bridge on flood risk in St Asaph has been investigated using the calibrated model. The November 2012 event was run through a version of the calibrated model with the bridge removed to determine its impact. This test found that without the bridge in place flooding is not predicted to the Spring Gardens Caravan

Park and flood depths at Roe Parc are reduced. Upstream of the A55, the removal of Spring Gardens Bridge has a negligible impact on predicted flood risk.

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Abbreviations

Abbreviation	Definition
AEP	Annual Exceedance Probability
AMAX	Annual Maximum Flood
CBHE	The Chronology of British Hydrological Events
FEH	Flood Estimation Handbook
ISIS	1D Modelling Software
LiDAR	Light Detecting and Ranging
ReFH	Revitalised Flood Hydrograph
STW	Sewage Treatment Works
NCD BDY	Normal/Critical Depth Boundary
NFCDD	National Flood and Coastal Defence Database
OS	Ordnance Survey
QMED	Median Annual Flood
TAN15	Note 15
TuFLOW	2D Modelling Software

1. Introduction

1.1 Purpose and Scope of the Study

The purpose of this study is to update the Flood Map for St Asaph in North Wales and gain a better understanding of flood risk from the River Elwy through the town. A 1D-2D ISIS-TuFLOW linked model was developed by JBA Consulting in 2011 to assess flood risk within the town. In November 2012, extensive flooding occurred through St Asaph. Using the data and information available for this event, post-event analysis has been undertaken by JBA. The existing ISIS-TUFLOW model has been calibrated based on the November 2012 event data and as a result the flood mapping deliverables have been updated. This report explains how the model has been calibrated, the hydrological analysis that has been undertaken post-event and presents the flood mapping update.

The following design events have been investigated using the calibrated model; 3.33%, 1.33%, 1%, 1% plus climate change, 0.5% and 0.1% AEP events. The model has been configured for the defended and undefended scenario. The undefended flood extents produced will be used to update the Flood Map. The results of this study will ensure that Natural Resources Wales (NRW) has sufficient information to enable compatibility with Technical Advice Note 15 (TAN 15) planning guidelines[1].

1.2 Watercourse and Catchment Description

The study area extends along a 4.5km reach of the River Elwy running through the town of St Asaph. The upper limit of the study area is located at Bryn Polyn Nurseries (NGR 304126, 372776) draining through St Asaph into the River Clwyd approximately 2km downstream of the town. The Clwyd confluence was the downstream extent of the previous flood mapping study model (2011), the model has been extended using sections from the River Clwyd model developed by JBA in 2011. The downstream extent of the model is now at Rhuddlan (NGR 302165, 378037) on the River Clwyd. Upstream of the study area, the River Elwy drains a catchment area of 246km^2, increasing to 253km^2 at the confluence with the River Clwyd. The land is predominately mountainous (Myndd Hiraethog mountain range) with impermeable Shales, Mudstones and Limestone strata. At the upstream modelled extent, the land is predominantly rural in nature with the exception of Wigfair Isaf, a small settlement on the left bank of the Elwy. Through St Asaph and extending towards the confluence with the River Clwyd, the River Elwy is constrained by large flood embankments (Figure 1-1), up to 2m higher than the surrounding floodplain. Residential and commercial properties are located in close proximity to the River Elwy as the watercourse flows through the town. There have been past flood incidents in St Asaph including the large event in November 2012 during which the River Elwy overtopped its banks and the defence embankments through the town causing widespread flooding. Approximately 320 properties and 70 caravans were flooded on the 27th November 2012. This flood event is discussed in more details in subsequent sections of the report and has been used to calibrate the hydraulic model as discussed in Section 3.

[1] Planning Policy Wales. Technical Advice Note 15 (TAN15): Development and Flood Risk. July 2004.

Figure 1-1 Flood Defence in St Asaph

Through St Asaph, there are five bridges; three road bridges and two footbridges. The most upstream of these is St Asaph Old Bridge (Figure 1-2). This is a large (span ~70m) five arch stone bridge which carries the A525 and is designated as a Scheduled Ancient Monument. The next bridge downstream is Elwy Cycle Bridge, which was built in 2007 and is located ~300m downstream of the St Asaph Old Bridge. This cycle bridge is not considered a significant hydraulic control and not represented in the current ISIS model. The third bridge is a high level road bridge which carries the A55 (Figure 1-3). There is a level gauge (station 66627) located at this bridge which has been operating since 1997. The next bridge downstream is a low level flat road bridge (Figure 1-4), which acts as an access bridge to the Sewage Treatment Works (STW) and Caravan Site. This is a hydraulic control on the River Elwy during large flood events, as the soffit level of the bridge is relatively low in comparison to the other bridges on the watercourse. The fifth bridge (Figure 1-5) is a footbridge located downstream of the town, ~700m upstream of the River Elwy confluence with the River Clwyd.

Figure 1-2 St Asaph Old Bridge (all of bridge not shown)

Figure 1-3 A55 Road Bridge

Figure 1-4 Sewage Works Bridge

Figure 1-5 Footbridge

1.3 Flood History

St Asaph flooded very recently in November 2012 when large flows caused overtopping of river banks and defences at various locations throughout the town. This event was the only out-of-bank event on the Elwy since the flood defences were reinforced in the 1970's. The November 2012 event is discussed in detail in Section 3 as it has been used to calibrate the hydraulic model of the River Elwy.

There is limited evidence of recent flooding prior to November 2012 within the Elwy catchment, perhaps due to the large flood embankments protecting St Asaph. However, there are a number of entries provided on the Chronology of British Hydrological Events web site[2] (CBHE). Those relating to flooding are highlighted on Table 1-1, along with all other flood evidence.

[2] http://www.dundee.ac.uk/geography/cbhe/

Table 1-1 Flood History

Date/Year	Description	Source
1871	1871 July Rainfall observer for St Asaph (Llannerch) noted (p97) "Weather showery and broken, but no floods or continuous heavy rains; generally cold for the season; hay harvest not finished. [R. Clwyd]	CBHE
1882	1882 Observer at St Asaph (Nantlys) noted (p[106]) "Total rainfall 4 in. above the average of 16 years, yet fewer floods in the river than for some years [Clwyd]	CBHE
1896	1896 August 31 Rainfall observer at St Asaph noted, p[14], “Great rain and floods, the Holywell Road, near Clwyd bridge, was under 6 ft. of water. Flooding also at Colwyn Bay and Denbigh.”	CBHE
1913	1913 April 29 Quoting The Times, "Serious damage to crops and property was reported from various parts of North Wales in consequence of the heavy floods. The Rivers Dee, Severn, Wye and Clwyd have overflowed their banks, and thousands of acres of crops and pasturage are inundated. Sheep and cattle have been carried down by the floods."	CBHE
1970's	Flood defences have been built at St. Asaph (River Clwyd) and Llanfair (River Elwy) in response to flooding incidents in the seventies.	Appendix G to report - Flooding in Wales October/ November 2000 (Appendix G History of other Notable Flood Events)
Nov-00	Llys y Felin sheltered housing flooded, caused by overland flow from a surcharging combined sewer system being trapped behind the defences	Unknown (Forecasting Study[3])
Dec-10	Verbal reports for flooding at sewage works bridge due to blockages. This is driving the blockage scenarios in this study.	Information from local resident relating to flooding from overtopping of defences

1.4 Available Data

The modelling study has been based upon the following data;

- The existing ISIS-TuFLOW model of the River Elwy developed by JBA in 2011. This model is mainly based on channel survey collected for an earlier River Elwy S105 study and data collected in 2011 by InfoMap Surveys Ltd. Bank height information was also collected for the 2011 study by InfoMap and was incorporated into the linked model.
- Filtered and unfiltered LiDAR data (flown April 2004) at 1m resolution used to define the floodplain represented in 2D using TuFLOW.
- Recorded water level data from Rhuddlan gauge used to define the downstream boundary in both the ISIS and TuFLOW components of the model.
- Defence heights along the railway embankment from the Dee and Clwyd Strategy, used to define the boundary of the 2D model.
- Hydrometric data - including data from St Asaph level gauge, level and flow data at Pont Y Gwyddel upstream of St Asaph on the River Elwy, level data at Rhuddlan and rainfall data for a number of rain gauges in and around the study area.

[3] JBA Consulting, on behalf of Environment Agency Wales, July 2007. River Clwyd and River Elwy Flood Forecasting Models. Final Report.

2. Hydrological Assessment

2.1 Overview

Design flow estimates for the River Elwy through St Asaph have been reviewed using the latest data available. Full details of the calculations undertaken can be found in the FEH Calculation Record in Appendix A of this report. Flow estimates were derived for three locations on the River Elwy for the St Asaph Flood Risk Mapping (FRM) Study completed by JBA in 2011 using both Flood Estimation Handbook (FEH) Statistical and Revitalised Flood Hydrograph (ReFH) methods. The final peak flow estimates used within the study were calculated using the FEH Statistical approach; the 1% AEP peak flow estimates used in the 2011 FRM study are shown in Table 2-1 along with the locations of the flow estimation points.

Table 2-1 2011 FRM stud flow estimation points and 1% AEP peak flow estimates

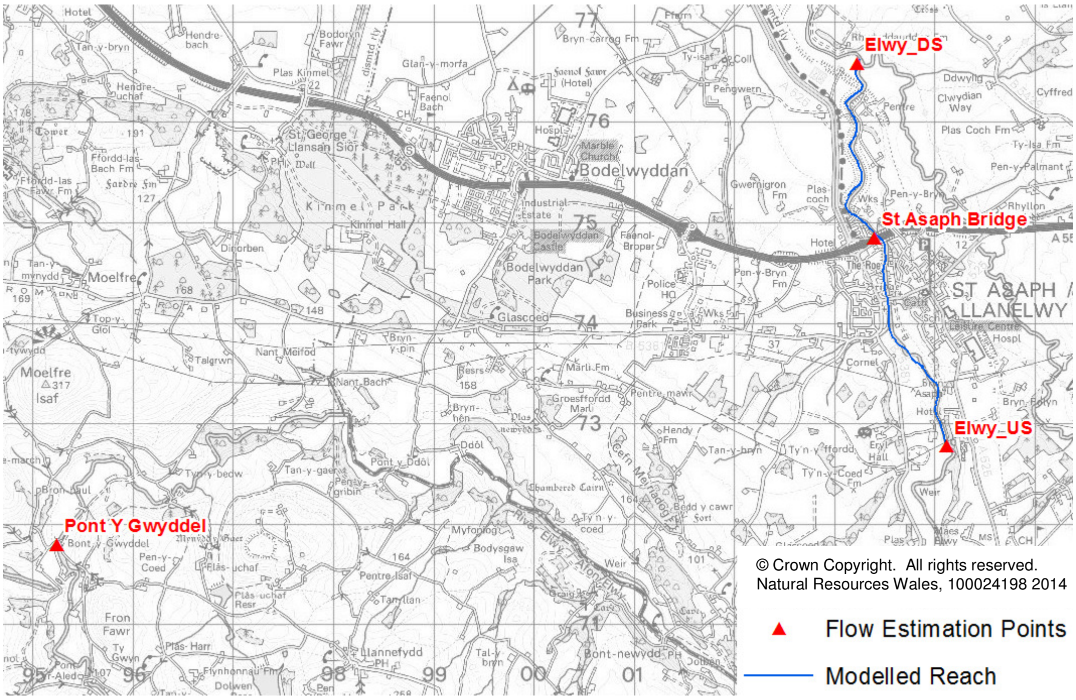
Site Name	Watercourse	Location	Easting	Northing	2011 FEH Statistical Peak Flow Estimate QMED (m^3/s)	2011 FEH Statistical Peak Flow Estimate 1% AEP Event (m^3/s)
ELWY_US	River Elwy	Upstream extent of 2011 hydraulic model (Bryn-polyn Nurseries)	304100	372750	74.8	181.0
St_Asaph_Bridge	River Elwy	St Asaph Old Bridge (A525)	303500	374200	75.8	183.4
ELWY_DS	River Elwy	Downstream extent of 2011 hydraulic model (120m upstream of Elwy confluence with River Clwyd)	303200	376500	75.9	183.5

As part of this flood mapping update, the hydrology of the Elwy catchment has been investigated using data from the November 2012 flood event. Data from Pont Y Gwyddel flow gauge upstream of St Asaph on the River Elwy has been used to inform the hydrological assessment.

2.2 Flow Estimation Points and Catchment Descriptors

Flow estimates have been derived for the same three locations as in the 2011 FRM study, as listed in Table 2-1. Flow estimates have also been calculated at Pont Y Gwyddel. Figure 2-1 shows the location of the flow estimation points used in this study.

Figure 2-1 St Asaph Flow Estimation Points



The catchment descriptors for each of the flow estimation points have been extracted from the FEH CD-ROM v3.0[4]. Each boundary from the FEH CD-ROM has been checked to ensure there are no obvious errors in the catchment boundaries and no changes have been made. Catchment descriptors for each estimation point are detailed in Table 2-2 below.

Table 2-2 Key Catchment Descriptors at Flow Estimation Points

Site code	Easting	Northing	AREA	FARL	BFIHOST	SAAR (mm)	SPRHOST	URBEXT 2000	FPEXT
Pont Y Gwyddel	295250	371799	191.37	0.98	0.476	1185	39.46	0.001	0.0318
ELWY_US	304100	372750	245.52	0.981	0.484	1114	38.40	0.001	0.035
St_Asaph_Bridge	303500	374200	250.19	0.982	0.483	1107	38.42	0.002	0.0364
ELWY_DS	303200	376500	253.04	0.982	0.484	1103	38.38	0.003	0.0393

2.3 FEH Statistical Method

The FEH Statistical method consists of two main stages; the estimation of the index flood (QMED) and the derivation of a growth curve. Pont Y Gwyddel gauging station was used as a donor site for QMED to improve the estimates through St Asaph by relating them to locally measured data in the 2011 FRM study. Since the FRM study, additional data for Pont Y Gwyddel is available and this gauge has been analysed as part of this study to determine the impact of the latest data on flow estimates.

2.3.1 Pont Y Gwyddel QMED Calculation

QMED at Pont Y Gwyddel gauge was calculated using the up to date AMAX data at the gauge supplied by NRW. NRW have supplied the AMAX data for Pont Y Gwyddel gauge up to and including the November 2012 flow event. Although less than half of the 2012-2013

[4] CEH 2009. The Flood Estimation Handbook CD-ROM Version 3.0. Centre for Ecology and Hydrology, Wallingford, UK.

water year, which the November 2012 event falls within, has passed at time of writing it was decided that the event would be included as an AMAX value at Pont Y Gwyddel for this hydrological analysis. This is justified as it is the largest flow event on record and is 30% higher than the previously recorded highest flow at the gauge; it has therefore been assumed that a larger flow will not be recorded within the remaining months of the water year (February-September 2013 inclusive). QMED at the Pont Y Gwyddel gauge is estimated as 73.025m^3/s.

2.3.2 Pont Y Gwyddel Growth Curve Derivation

The peak flow during the November 2012 event was derived by NRW through extrapolating the stage-flow rating at Pont Y Gwyddel gauge in WISKI. The peak level of 91.045mAOD recorded at 7am on the 27th November 2012 was confirmed as realistic on site by NRW staff based on tide marks within the gauging hut. Based on the extrapolated rating curve this corresponds to a flow of 202m^3/s. Some water is known to have by-passed the gauge which would be in addition to the flow in the rated channel section; NRW estimates that this was less than 10m^3/s. For this analysis a peak flow at Pont Y Gwyddel of 212m^3/s has therefore been used in the absence of further information about the bypassing flow. It should be noted that the peak flows and levels for the November 2012 event at Pont Y Gwyddel are much larger than any of the flow measurements used to construct the rating curve. As such the extrapolated rating curve and estimated flow from the November 2012 event are subject to a degree of uncertainty.

In order to gain a better understanding of the scale of the November 2012 event within the Elwy catchment, flood frequency analysis has been undertaken for the catchment to the gauge at Pont Y Gwyddel. The return period of an event can be best estimated where there are good quality records of flood peak data for at least twice as long as the return period of the event being estimated. In such cases, the FEH Statistical method can be used to fit a single-site flood frequency curve to the annual maximum flows at the site and the return period is then identified for the flow associated with the event. NRW state in their hydrology report following the widespread flooding in North Wales in November 2012 that the peak flow recorded at Pont Y Gwyddel during the event exceeds the current 1 in 100 year flow estimates at Pont Y Gwyddel and is likely to have a return period of between 1 in 100 and 1 in 200 years.

38 years worth of data were available at Pont Y Gwyddel for this study; therefore single site analysis at the gauge is only realistically appropriate up to the 1 in 20 year return period. A number of growth curves have been derived to obtain peak flow estimates at Pont Y Gwyddel using different methods within WINFAP-FEH v3.0.

The methods tested for deriving growth curves at the Pont Y Gwyddel gauge were:

- Single Site analysis without November 2012 event included in AMAX series
- Single Site analysis with November 2012 event included in AMAX series
- Pooled Analysis - enhanced single site with November 2012 event included in AMAX series
- Pooled Analysis - treating Pont Y Gwyddel as an ungauged site

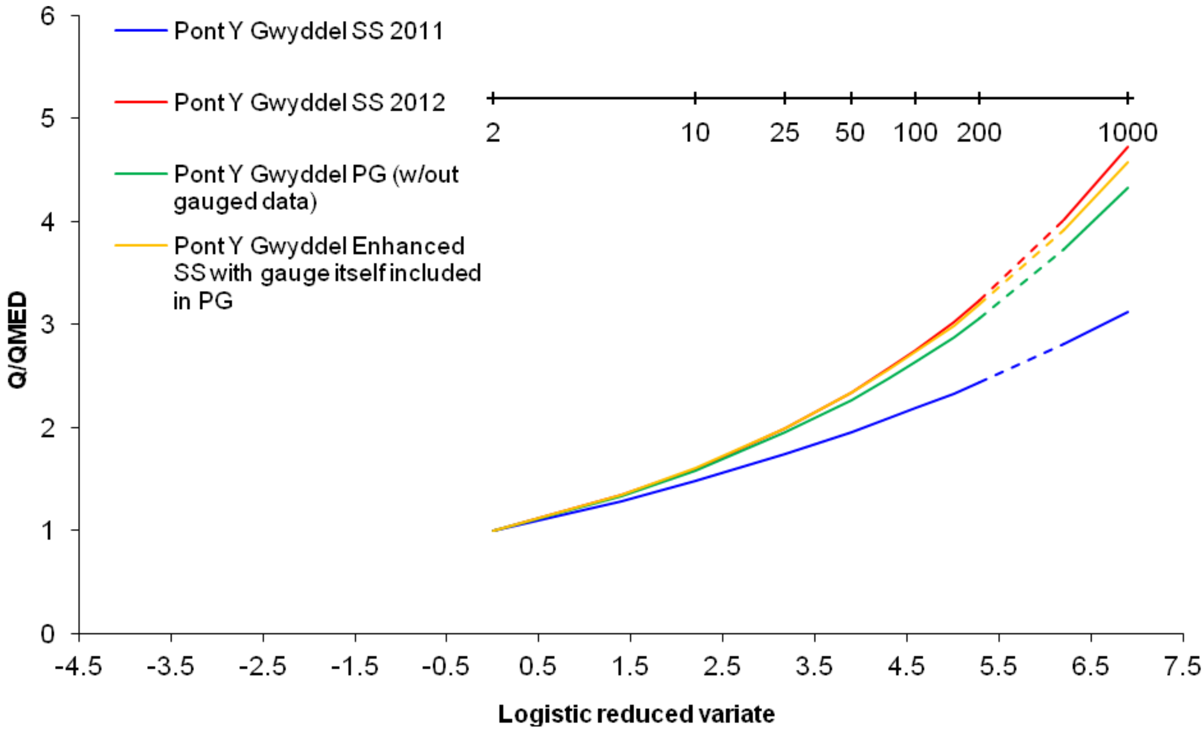
The growth curves derived from the methods above were all applied to the same QMED value (73.025m^3/s) that was calculated using the up to date AMAX values at Pont Y Gwyddel including the November 2012 event. Therefore, the differences between the 1% AEP peak flow estimates derived (as shown in Table 2-3) are solely a result of the different methods used to construct a growth curve to relate the QMED value to higher return period flows. The growth curves are shown in Figure 2-2.

Table 2-3 Comparison of FEH peak flow estimates for the 1% AEP event at Pont Y Gwyddel using different methods

Site	Pooled (P) or Single Site (SS) Analysis	Distribution - Generalised Logistic (GL) or Generalised Extreme Value (GEV)	Parameters of distribution (location, scale and shape)	Growth factor for 100-year return period	FEH Statistical 1% AEP Peak Flow Estimate
Pont Y Gwyddel	SS - without Nov 2012 event included in AMAX series	GL	0.991, 0.187, -0.133	2.18	159.53
	SS - with Nov 2012 event included in AMAX series	GL	0.973, 0.205, -0.246	2.68	200.64
	P - enhanced single site analysis*	GL	1.00, 0.213, -0.228	2.68	199.32
	P - treated as ungauged site	GL	1.000, 0.207, -0.218	2.64	192.50

*Enhanced single site analysis uses data from the gauged site (Pont Y Gwyddel) and includes the site in the pooling group used to derive the growth curve. A greater weight is assigned to the gauged site than the other sites making up the pooling group.

Figure 2-2 Pont Y Gwyddel Growth Curves



The 1% AEP peak flow estimate produced using the enhanced single site method is very similar to that produced for the single site analysis (including the November 2012 event) due to the weighting given in the enhanced single site analysis to the gauged flows. The growth curves calculated using these two methods are almost identical as shown in Figure 2-2. However, it should be noted that Hi-Flows recommends that Pont Y Gwyddel is not a suitable site for pooling and it had to be manually included in the pooling group to perform the enhanced single site analysis. The single site analysis without the November 2012 event included in the AMAX data for Pont Y Gwyddel (Pont Y Gwyddel SS 2011 on Figure 2-2) produces a significantly lower growth curve than the single site analysis with the November 2012 event included in the AMAX series indicating the scale of the event.

The growth curve derived treating the Pont Y Gwyddel site as ungauged (Pont Y Gwyddel PG) is similar to those derived through the single site analysis including November 2012 in the AMAX series and through the enhanced single site analysis. The Pont Y Gwyddel PG curve is very slightly lower than the curves calculated using the gauged data up to 2012. Given this is the standard method for this site, is not dependent on the precise magnitude of the Nov 2012 event and gives very similar results to the methods using data from the site it is proposed to use this as the growth curve for Pont Y Gwyddel.

Based on the rating at Pont Y Gwyddel flow gauge, the peak flow during the November 2012 event was 202m^3/s. The peak flow was potentially higher as the gauge was by-passed during the event and the amount of water by-passing the gauge is thought to be <10m^3/s by NRW. A Nov 2012 peak flow of around 212 m3/s therefore has a return period greater than 1% AEP and perhaps closest to a 0.66% AEP (1 in 150 year).

2.3.3 St Asaph Flow Estimation Points QMED Derivation

In the FEH Statistical method Pont Y Gwyddel has been used as a donor for QMED for the St Asaph sites as it was for the 2011 FRM study. Due to the inclusion of the additional AMAX data at Pont Y Gwyddel in the estimation of QMED for the subject sites, a higher value for QMED at each of the subject sites has been estimated approximately 4m^3/s higher than in the 2011 study, now estimated at 79.5m^3/s at St Asaph Bridge. As well as the November 2012 event, there were relatively large peak flows recorded at Pont Y Gwyddel in November 2009 (104m^3/s) and February 2011 (90.2m^3/s).

It is worthwhile noting that the QMED estimates derived through St Asaph are only about 10% larger than those derived at Pont Y Gwyddel despite the catchment area increasing by more than 50km^2 between the sites (approx 25%). This has led us to investigate whether alternative information can be used to estimate QMED at St Asaph. Two approaches have been considered:

1) Use of St Asaph level gauge POT data to give a QMED estimate. There are less than four years of reliable record at this gauge. A QMED value based on this POT level data gives a value of 12.06mAOD which is ~93m^3/s in the calibrated hydraulic model. However this should have a climatic adjustment applied which will reduce that value when compared to the longer term record at Pont Y Gwyddel which show the last four years have been wetter than average. The very short record length at St Asaph gauge makes this method unreliable and very prone to change year on year as more data becomes available. Therefore it has been discarded at this time.

2) Correlation of QMED level from Pont Y Gwyddel to St Asaph gauge using the flood forecasting correlation. The level relationship between Pont Y Gwyddel and St Asaph is well established and used in flood forecasting. A QMED level at Pont Y Gwyddel is ~1.97mASD from the Nov 2012 event corresponds to ~3.0 mASD at St Asaph (~11.91mAOD). Based on an approximately calibrated model this level corresponds with a flow of ~82m^3/s. Note this is fairly approximate as the correlation has been read off a graph.

This QMED value is only slightly larger than the 79.5m^3/s value derived from FEH catchment descriptors and Pont Y Gwyddel scaling. This alternative QMED estimate is actually very consistent with the standard approach with a difference of only ~5% and it is therefore not proposed to deviate from the FEH value of 79.5m^3/s.

2.3.4 St Asaph Flow Estimation Points Growth Curve Derivation

Given the large distance between Pont Y Gwyddel and the flow estimation points through St Asaph, it was not deemed appropriate to apply the growth curve parameters derived for the gauged site to the ungauged St Asaph sites. In the absence of flow data for St Asaph, growth curves were derived using pooling groups for the flow estimation points in St Asaph. Since the FRM study was completed, a new version of Hi-Flows has been released by the Environment Agency (version 3.1.2, December 2011) meaning that there slightly more data available at the gauges in the pooling groups used to derive the growth curves for subject sites. For example; the pooling group derived for the St_Asaph_Bridge site, which contains the same sites as those used in the FRM study, is made up of 9 years more data than the pooling group used in the FRM study.

The distribution that gave the best fit for the St Asaph flow estimation points pooling groups was Generalised Extreme Value (GEV), however, Generalised Logistic (GL) is the most commonly used distribution for catchments within the UK. The flow estimates derived using both the GEV and GL methods to derive growth curves at the St Asaph flow estimation points are given in Table 2-4.

Table 2-4 shows that the growth curves derived using a GL distribution produce higher peak flow estimates than those derived using a GEV distribution. GL distribution was used in the 2011 FRM study to define the growth curves. The 2011 FRM peak flow estimates are provided in Table 2-4 for comparison. The 1% AEP peak flow estimates derived for this study using the most recent data are approximately 10m^3/s higher than those derived for the 2011 study. It is suggested to use the GL derived values as that is the favoured UK distribution, gives slightly higher results and is consistent with the distribution at Pont Y Gwyddel.

Table 2-4 Flow Estimates for St Asaph Flow Estimation Points

Site	Pooled (P) or Single Site (SS) Analysis	Distribution - Generalised Logistic (GL) or Generalised Extreme Value (GEV)	Parameters of distribution (location, scale and shape)	QMED	Growth factor for 100-year return period	FEH Statistical 1% AEP Peak Flow Estimate	2011 FRM Study 1% AEP Peak Flow Estimate
Elwy_US	P	GEV	0.892, 0.293, -0.028	78.6	2.33	183.13	
	P	GL	1.000, 0.195, -0.188	78.6	2.42	190.43	181.0
St_Asaph _Bridge	P	GEV	0.893, 0.290, -0.037	79.5	2.35	186.55	
	P	GL	1.000, 0.194, -0.194	79.5	2.44	193.81	183.4
Elwy_DS	P	GEV	0.895, 0.282, -0.056	79.5	2.37	188.88	
	P	GL	1.000, 0.191, -0.206	79.5	2.46	195.84	183.5

2.3.5 FEH Statistical Method Design Flows

FEH statistical method design flows are given below. The lack of design flow increase from Pont Y Gwyddel to St Asaph is of concern as the catchment area increases by over 50 km^2. As Pont Y Gwyddel is a reliable flow gauge these estimates are considered more robust than the ungauged St Asaph.

Table 2-5 FEH Statistical Flow Estimates

Site code	Flood peak (m3/s) for the following return periods (in years)										
	2	5	10	25	50	75	100	150	200	500	1000
Pont Y Gwyddel PG	73.03	97.49	115.63	142.32	165.66	180.89	192.50	210.10	223.54	279.15	333.25
ELWY_US	78.58	102.84	120.26	145.21	166.48	180.13	190.43	205.88	217.55	270.76	320.24
St Asaph Bridge	79.47	104.00	121.72	147.23	169.09	183.17	193.81	209.81	221.93	275.27	325.37
ELWY_DS	79.54	103.92	121.76	147.73	170.21	184.78	195.84	212.54	225.24	277.85	328.28

2.4 St Asaph Flows Using Routing Model

An alternative approach to design flows at St Asaph is proposed using a routing model to transfer flow from Pont Y Gwyddel to St Asaph and adding to this appropriate inflows from the additional catchment area. From this method the design flows are taken at the upstream of St Asaph where the routing model joins the hydraulic model. The steps involved were:

1. The routing model has been calibrated to several flood events during 2012 to ensure the timing in particular is appropriate (not including the November 2012 event as the St Asaph level gauge stuck during the event).
2. The ReFH inflow at Pont Y Gwyddel has had baseflow and Tp calibrated to improve representation of the November 2012 event at the gauge. These are only relatively minor changes, e.g. the peak flow with and without the changes are 212 and 222 m^3/s, less than a 5% difference.
3. These calibrated parameters have been transferred to the tributary ReFH inflows used.
4. Design events have been modelled using 18.25hr duration storm (duration giving highest flows from ReFH model) with design rainfall using the calibrated ReFH units. The Pont Y Gwyddel peak is scaled to the statistical design flow (different for each event). The other inflows also use the 18.25hr storm and the same scaling factors. This is slightly shorter than the November 2012 event when rainfall was spread over closer to 24 hours.

From this catchment event modelling approach an alternative set of design flows at St Asaph have been created – see Table 2-6 below. Several of these assumptions are tested in the sensitivity testing below to show whether they would influence the conclusions.

Table 2-6 Flow Estimates Comparison

Site code	Flood peak (m3/s) for the following return periods (in years)										
	2	5	10	25	50	75	100	150	200	500	1000
Pont Y Gwyddel Statistical	73.0	97.5	115.6	142.3	165.7	180.9	192.5	210.1	223.5	279.2	333.3
ELWY_US_Statistical	78.6	102.8	120.3	145.2	166.5	180.1	190.4	205.9	217.6	270.8	320.2
ELWY_US_Routing	84.6	112.9	134.0	165.0	191.9	209.5	222.9	243.2	258.4	322.9	384.8

At low return periods these flows are only 5% higher than using FEH statistical but for the larger return periods the flows are up to 20% higher at St Asaph. The flows are now more consistent that those based around the gauge at Pont Y Gwyddel, i.e. flow estimates increase in line with the increase in catchment area. These design flows are now proposed to be used as the design flows for St Asaph.

2.4.1 Sensitivity Testing

Sensitivity testing around some of the assumptions have been carried out to include:

- Default ReFH parameters for each catchment. Requires different scaling of peaks.
- No scaling of additional ReFH inflows, leaves Pont Y Gwyddel scaled to statistical peaks but the other inflows are not scaled.

- Duration – Fix scaling at 18h.25hr values as these are highest flows in ReFH at Pont Y Gwyddel. Adjust duration for all inflows, determine flow at St Asaph. Primarily a check that the combination of flows does not lead to an alternative duration becoming important.

Table 2-7 Sensitivity Testing for 1% AEP Design Event Flows

Model run	**1% AEP Peak flow at St Asaph (m^3/s)**
Design Event	222.9
Default ReFH parameters (require different scaling to Pont Y Gwyddel L peak)	222.4
No scaling on additional ReFH inflows	226.8
8.25 storm duration	214.0
12.25 storm duration	220.0
18.25 storm duration (design event)	222.9
24.25 storm duration	219.4
36.25 storm duration	203.7

The tests undertaken generally show little difference to peak 1% AEP peak flows and therefore suggest the approach is relatively robust and not overly sensitive to the assumptions made.

2.5 Severity of November 2012 Event

The November 2012 event has also been modelled in a similar manner to the design events. Pont Y Gwyddel inflow is set at 212 m^3/s and other inflows are included based on appropriate rainfall inputs (based on Plas Pigot and St Asaph raingauges) to calibrated ReFH units. This gives a peak flow at St Asaph of 248.5 m^3/s.

Using the FEH Statistical method at St Asaph would suggest a return period, between 0.5% and 0.2% ARP (1 in 200 and 1 in 500 year) but this is inconsistent with the FEH Statistical method at Pont Y Gwyddel gauge with a return period around 0.67% AEP (1 in 150 years) and has little increase in flow for the additional ~50km^2 catchment area from there to St Asaph. Therefore the catchment modelled approach is favoured for the design event estimates at St Asaph which gives higher flows than the FEH Statistical approach, e.g. 1% AEP event at St Asaph increases from 190 to 223 m^3/s.

At both Pont Y Gwyddel and St Asaph the severity of the November 2012 event is closest to a 1 in 150 year event (0.67% AEP) or given the inherent uncertainties involved it can be said to be between a 1% and 0.5% AEP event (1 in 100year and 1 in 200 year).

2.6 Hydraulic Model Hydrographs

For unsteady model simulations, a set of flood hydrographs are required within ISIS. These have been generated within the ReFH method using the ReFH boundary units within ISIS. A storm duration of 18.25 hours has been used as this was found to produce the highest peak flows during the hydrological assessment. The hydraulic model was used to test the 18.25 hour and a 24.25 storm duration to determine whether the hydraulic controls within the system had an effect on the flood extent and peak water levels predicted for different storm durations. The 18.25 hour storm duration produced the highest peak water levels and largest flood extent and was therefore taken forward for the design events.

For all design events modelled, the predicted ReFH hydrographs at Pont Y Gwyddel have been scaled to the peak flow estimates in Table 2-6. The scaling factor used for Pont Y Gwyddel has then been applied to the other model ReFH inflows in order to be consistent across the model. These scaling factors are highlighted in Table 2-8.

The model inflows are discussed in detail in Section 3-1, which explains how the hydraulic model has been calibrated for the November 2012 event.

Table 2-8 St Asaph Scaling Factors

	Return Period				
Scaling Factor	3.33%	1.33%	1%	0.50%	0.10%
	0.864	0.883	0.888	0.889	0.912

2.7 Pont Y Gwyddel Rating

For the hydrological investigation carried out and reported above the existing NRW rating curve at Pont Y Gwyddel gauging station has been used, with an additional allowance made for gauge bypassing during the November 2012 flood event. As work has continued it has become apparent that it may be necessary to more formally review the rating at Pont Y Gwyddel gauge to improve confidence in the estimated flows at the gauge and downstream, both for the November 2012 event and for design events.

As improvement works were undertaken at Pont Y Gwyddel gauge in 2006, the current rating is based on spot gaugings taken since the construction works were finished as well as hydraulic modelling to extend the rating beyond the gauged flows. The rating was last reviewed in 2009 by NRW, 19 flow gaugings were available at the time for low to medium flows with the highest gauged flow being 67.3m^3/s; a 1D-only hydraulic model was used to extend the rating. As there are now a greater number of gaugings available and the highest gauged flow recorded at the gauge is 102m^3/s, there is potential for the rating to be improved for high flows. As a significant amount of bypassing was witnessed at the gauge during the November 2012 event, it is likely that the extension of the rating could be improved by modelling the gauge site using a 1D-2D linked model. The hydrometry team advise that there is potentially not enough data to carry out a full re-rating exercise but it would be beneficial to review the rating before any flood defence scheme options are considered for St Asaph as it may have an impact on the return periods.

Any changes to the rating may have implications for the QMED values calculated through St Asaph as Pont Y Gwyddel was used as a donor site for QMED estimation. However, it may be that a change to the rating for higher flows will not affect QMED. If there is greater confidence in the gauge for high flows following a rating review, the Pont Y Gwyddel site could potentially be included in the pooling group used to define growth curves for the St Asaph flow estimation points. The gauge is currently classified as not suitable for pooling in HiFlows 3.1.2 due to the known bypassing at the site, HiFlows recommends that evaluation of bypassing flow is required and that the current limit of confidence at the gauge is around 2.4m. Changes to the estimated flows for the November 2012 event may require some re-calibration of the hydraulic model.

3. Hydraulic Model

3.1 Overview

The existing ISIS-TUFLOW hydraulic model of the River Elwy through St Asaph (constructed by JBA in 2011) has been updated and calibrated based on data available for the November 2012 event. This section describes the version of the model developed through this study that has been used to produce the flood mapping deliverables for the River Elwy through St Asaph. Section 4 describes the calibration process that was undertaken following the November 2012 event in detail.

3.2 ISIS Model

The majority of ISIS cross-sections are based on survey data collected in 1999. Cross-sections at structures within the model were updated for the 2011 FRM study using data collected by InfoMap Surveys Ltd in 2011. Additional survey data was not collected for this study; however the ISIS model has been updated through the calibration process. This section describes the ISIS model used to update the flood mapping deliverables.

The hydraulic model has been extended incorporating the Clwyd reach downstream of the confluence with the Elwy as far as Rhuddlan to improve downstream boundary representation within the model. Clwyd cross-sections were taken directly from the Clwyd ISIS model built by JBA in 2011 for the Tidal Clwyd Flood Map Update[5]. The Clwyd cross-sections were not altered for this study.

A schematic of the River Elwy ISIS-TuFLOW is shown in Figure 3-1, located at the back of this report.

Figure 3-1 River Elwy ISIS-TuFLOW Model Schematic (located at back of report)

3.2.1 Representation of Structures

There are five structures within the hydraulic model. The structures and how they have been represented within the model are described below. Some of the structures have been updated as a result of the calibration process, these changes are discussed in Section 4 of this report.

St Asaph Old Bridge

St Asaph Old Bridge carries the A525 (High Street) and is the first structure included in the model. The bridge is a large stone arch bridge with five openings and has been modelled with an ARCH BRIDGE unit within ISIS. The bridge geometry was updated in 2011 using survey data collected by InfoMap Surveys Ltd in January 2011. Overtopping of this structure has not been modelled as the peak 0.1% AEP event water level predicted is 16.05mAOD, this is 1.22m lower than the lowest level of the bridge parapet. Therefore, overtopping of this structure will not occur for any of the return period events modelled in this study.

There is a wall immediately upstream of the bridge on the left bank although there is a gap between the wall and the bridge; the two structures are shown in Figure 3-2. The wall extends approximately 80m upstream of the bridge and further upstream ties into an earth flood embankment through the back garden of several residential properties.

[5] Tidal Clwyd Flood Map Update, JBA, 2011

The use of the orifice flow option for flow surcharging the bridge has been retained from the 2011 FRM study model with the transition distance remaining at 0.25m above and below the bridge soffit. This option has been available since ISIS version 3.3 and models the bridge with an orifice equation if the structure is flowing full. This is something ISIS had previously not been able to represent well. Predicted peak water levels are increased when using the orifice flow option but this is considered appropriate and is now the recommended approach to use. This option has been used for all bridges within the model.

Figure 3-2 St Asaph Old Bridge and wall upstream

Cycle Bridge

The cycle bridge was not included in the hydraulic model for the 2011 FRM study and it has not been included in the model developed for this study. The bank height survey from 2011 shows a rise in the embankment levels on both left and right bank to about 15.85m AOD at the location of the bridge from about 15.00m AOD so the bridge is raised up significantly from the defence crest levels both upstream and downstream. Scaling from an as built drawing (provided by NRW) suggests a soffit level of around 15.08m AOD. This is above upstream defence levels (on the left bank especially) and is not even reached in the 0.1% AEP event (peak water levels are 14.99m AOD at the nearest upstream cross section). Therefore, given that the bridge soffit is above both the defence and flood levels, it is unlikely that the bridge will influence the results and therefore has not been included in the modelling.

A55 Road Bridge

This bridge is a high level bridge carrying the A55; there are eight pillars on either side of the channel in the direction of flow creating three openings across the channel at the bridge. In the 2011 FRM study, the bridge was represented using an ARCH BRIDGE unit. For this study, a USBPR 1978 BRIDGE unit has been used to allow the influence of the pillars on flow to be modelled more specifically. The pillars have been represented using the Pier Data tab within the bridge unit, the total pier width is 2.2m (the total width of the pillars across the channel) and the Number of Piers has been set to 3 or more (as there are eight in the direction of flow). The pier shape has been set to cylinder with semicircular faces. Changing the representation of this bridge appeared to have little effect on the predicted flooding for the November 2012 event but the flat bridge unit with piers has been retained as it potentially provides a more accurate representation of the bridge in reality. Given the height of the bridge above the channel, overtopping is unlikely to occur at this structure and has therefore not been modelled in either 1D or 2D.

Spring Gardens Bridge

The Spring Gardens Bridge services the Sewage Works and Spring Gardens Holiday and Leisure Park downstream of the A55 in St Asaph. The bridge has been represented using an ARCH BRIDGE unit with one opening as in the 2011 FRM study. During that study a USBPR 1978 BRIDGE unit was tested to represent this flat decked structure and resulted in slightly lower water levels. The bridge has a low soffit level and does cause a constriction to flows. Other configurations to represent the bridge within the model were tested to determine the sensitivity of the model to this structure. The configurations tested were:

- ARCH BRIDGE with default calibration parameter (1) as in 2011 FRM study
- USBPR 1978 BRIDGE with default calibration parameter (1)
- ORIFICE unit

The ARCH BRIDGE representation from the 2011 FRM study was retained for this study because changing representation of the bridge had no impact on water levels when the orifice flow option is used to model surcharged flow at the bridge.

Footbridge

There is a footbridge located 680m upstream of the River Elwy confluence with the River Clwyd. The footbridge is located downstream of the town and is not anticipated to have an impact on peak water levels through St Asaph since its soffit level is relatively high. Representation of the footbridge was not updated in the 2011 FRM study and new survey data was not collected for this structure. Similarly, the structure has not been updated for this study and is represented using an ARCH BRIDGE unit. Overtopping of the structure has not been modelled as the structure does not run full during the 0.1% AEP event.

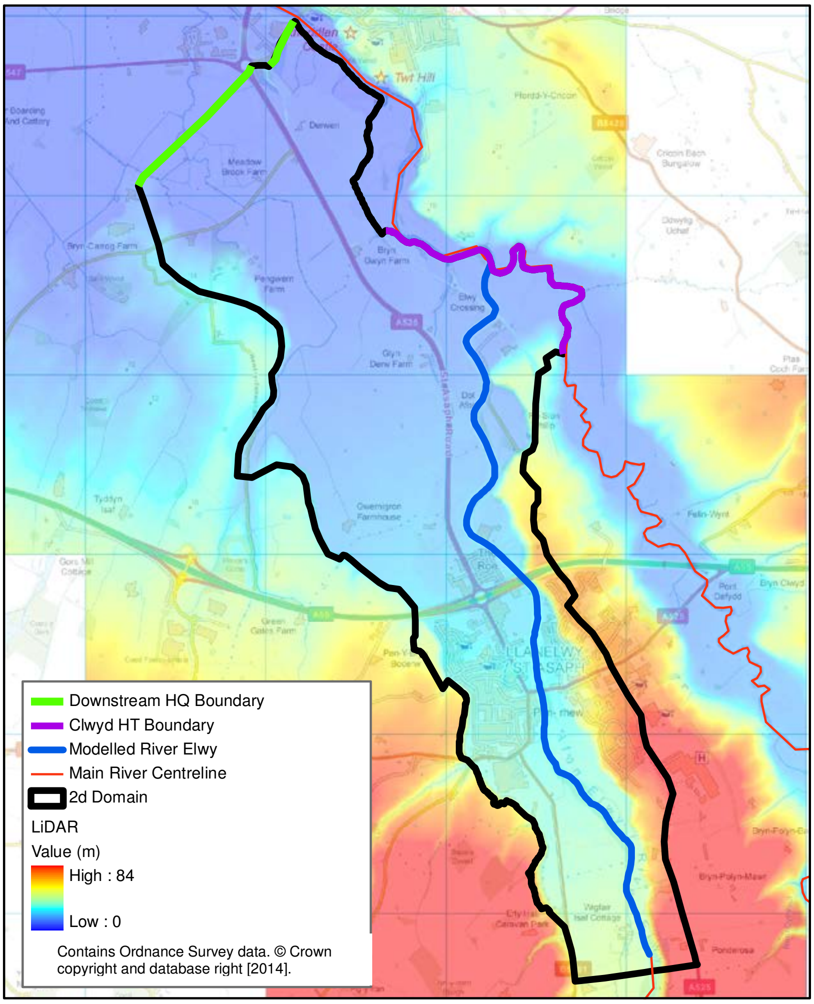
Rhuddlan Bridge

Within the additional sections representing the Clwyd downstream of the River Elwy used to extend the model to Rhuddlan, there is one structure called Rhuddlan Bridge. This is an arched bridge with two openings and has been represented within the model using an ARCH BRIDGE unit. The structure was taken directly from the Clwyd model developed by JBA in 2011 and has not been changed for this study mainly as it is downstream of the area of interest and is not a key structure within the model. A 1D spill is attached to this structure in ISIS to represent overtopping of the bridge.

3.3 TuFLOW 2D Domain

A 2d TuFLOW floodplain model was developed as part of the 2011 FRM study and linked to the 1D ISIS model of the River Elwy. The extent of the 2D domain has been retained from the 2011 FRM study and is shown in Figure 3-3. The domain has been delineated by topography on the east and west of St Asaph, often following field boundaries and roads where applicable. A check has been undertaken to ensure this contains the 0.1% AEP defended/undefended event. During high magnitude events, floodwater from the River Elwy is predicted to extend further downstream of St Asaph and merge with the Clwyd floodplain. The Clwyd itself has large tidal embankments (downstream of the River Elwy) which prevent fluvial and tidal overtopping from the River Clwyd, but also prevents floodwater from the River Elwy re-entering the Clwyd channel.

Figure 3-3 Elwy 2D Domain



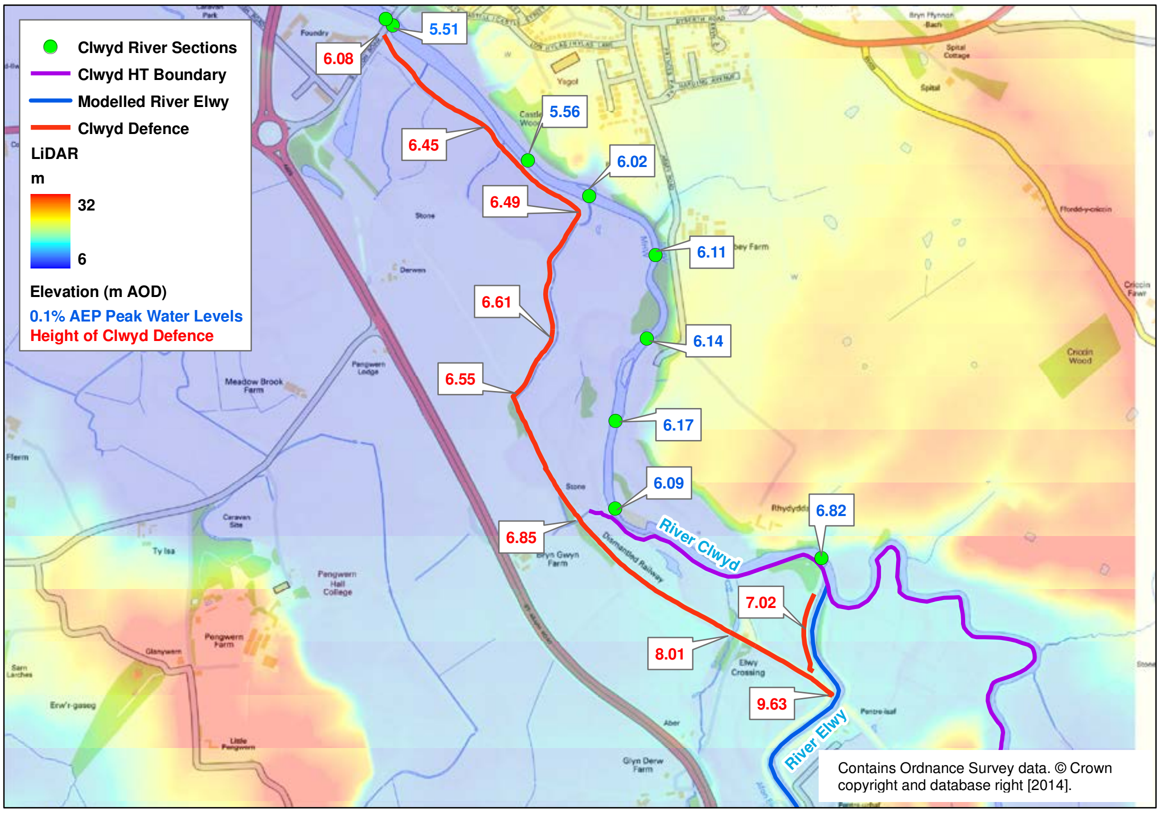
Two downstream boundaries operate within the 2D domain. A HT boundary defines the 2D boundary condition along the Clwyd at the downstream extent of the Elwy. For the calibrated model, the recorded levels at Rhuddlan were applied to this boundary. Sensitivity tests were undertaken to determine the impact of this downstream boundary by changing levels ±1m.

The results of the sensitivity tests showed that changing the downstream HT boundary did not affect the predicted flooding through St Asaph.

The downstream boundary of the model was configured along the Clwyd defence where possible or otherwise set across the Clwyd floodplain sufficiently far downstream that there was no impact on the modelled flood extents in St Asaph. Figure 3-4 below compares the defence levels along the Clwyd with the 0.1% AEP peak fluvial water levels in the River Clwyd (taken from the 2011 Strategy). This illustrates that the peak water levels in the Clwyd are not predicted to exceed the defence heights. A check has also been made to ensure floodwater from the River Elwy does not overtop this embankment in the 0.1% AEP event.

Along the TuFLOW boundary, the HT boundary has also been applied where interaction between floodwater in the Clwyd and Elwy is likely. This represents any outflow into the Clwyd from the Elwy floodwater, but also represents inflow into the floodplain from the Clwyd. This prevents floodwater ponding up at the downstream boundary. The resultant flood extent is therefore likely to have a straight line at the Clwyd floodplain boundary and this should be considered when updating the Flood Map.

Figure 3-4 Clwyd Embankments and Model Interaction



A 2D model grid covering the floodplain was constructed from filtered LiDAR data at a 4m resolution. This was chosen as an appropriate cell size to model flood conveyance along expected flow routes within the town. For the 2011 FRM study a sensitivity test using a 2m cell size for the model grid was undertaken but given the size of the 2D domain, this resulted in unmanageable run times.

The spill elevation between ISIS and TuFLOW was constructed by linearly interpolating bank levels from the bank height survey carried out by InfoMap Surveys Ltd, January 2011. Through the town, the bank height survey provided bank levels at roughly 10m intervals. Outside of the urban area, bank heights were not routinely surveyed so bank heights in these regions were taken from each surveyed river section. For model stability and to improve model definition, additional elevation points were added (based on filtered LiDAR) in a number of areas, which include: 1) the left bank of the River Elwy immediately upstream of the Glascoed Stream and 2) the right bank of the River Elwy immediately upstream and downstream of the A55 Road Bridge. On the left hand bank of the River Elwy, upstream of St Asaph Old Bridge, surveyed top of wall levels from the bank height survey were retained in the model for the defended events.

The 1D and 2D models are linked via a linear system of TuFLOW (HX) boundaries that determines the flux across the 1D-2D boundaries. These HX boundary lines were snapped to the crest points of the bank (described above).

In addition to the HX boundaries, it was necessary to add a TUFLOW (HQ) downstream boundary (akin to a normal flow boundary) across the open Clwyd floodplain to allow floodwater to exit the 2D domain (Figure 3-3). This prevents water from ponding up against the downstream boundary of the 2D model that may result in unrealistic flood outlines.

A small topographic adjustment has been applied on the right bank of the River Elwy, at St Asaph Sewage Works, to remove a low spot in the LiDAR. The low spot coincides with the treatment beds within St Asaph Sewage Works since LiDAR has not accurately picked up water levels in the beds. The elevation of the bed has been increased to 10.55m AOD (i.e. surrounding ground levels). This is not unrealistic as the treatment beds would likely be full of water (i.e. they would have little or no storage capacity) and also have a wall around them that would prevent floodwater entering the beds.

A TuFLOW z-line has been used represent the raised defence along the left bank of Glascoed Stream. This has been based on the bank height survey carried out by InfoMap Surveys Ltd, January 2011. In additional to this, further DEM adjustments have been made to raise the Clwyd defence levels in areas that had been filtered out of the LiDAR.

TuFLOW z-shape and z-point patches have also been used to represent the bridge decks at St Asaph Old Bridge, A55 Road Bridge and the Sewage Works Bridge. For the calibrated model to represent the November 2012 event, a z-line has been applied across the parapet at the upstream face of Spring Gardens Bridge that raises levels to that of the actual deck plus 30% of the railing height. It has been assumed where debris collected in the railings of the bridge, flow was completely blocked.

Across the TuFLOW domain, spatially varying hydraulic roughness values have been defined using OS MasterMap data to distinguish between roads, buildings and open areas. These are unchanged from the 2011 FRM study. Table 3-1 below highlights the floodplain roughness values used. Buildings were set with high roughness values to obstruct the movement of water whereas roads, tracks, paths and pavements were set with lower roughness value to reflect the fact that these smoother surfaces would likely act as preferential flow routes during an event. A small patch of elevated roughness (Manning's n of 1) was added at the downstream extent of the ISIS model to help stabilise the model.

Table 3-1 St Asaph Floodplain Roughness Values

OS Mastermap Category	Land use Type	Manning n Roughness Value
1	Roads, Tracks, Paths and Pavements	0.025
2	Inland Water	0.03
3	Buildings	1.00
4	Natural Environment and Scrub	0.065
5	General Surfaces e.g. gardens	0.05
6	Structures	0.065
7	Non-coniferous and Coniferous Trees	0.07

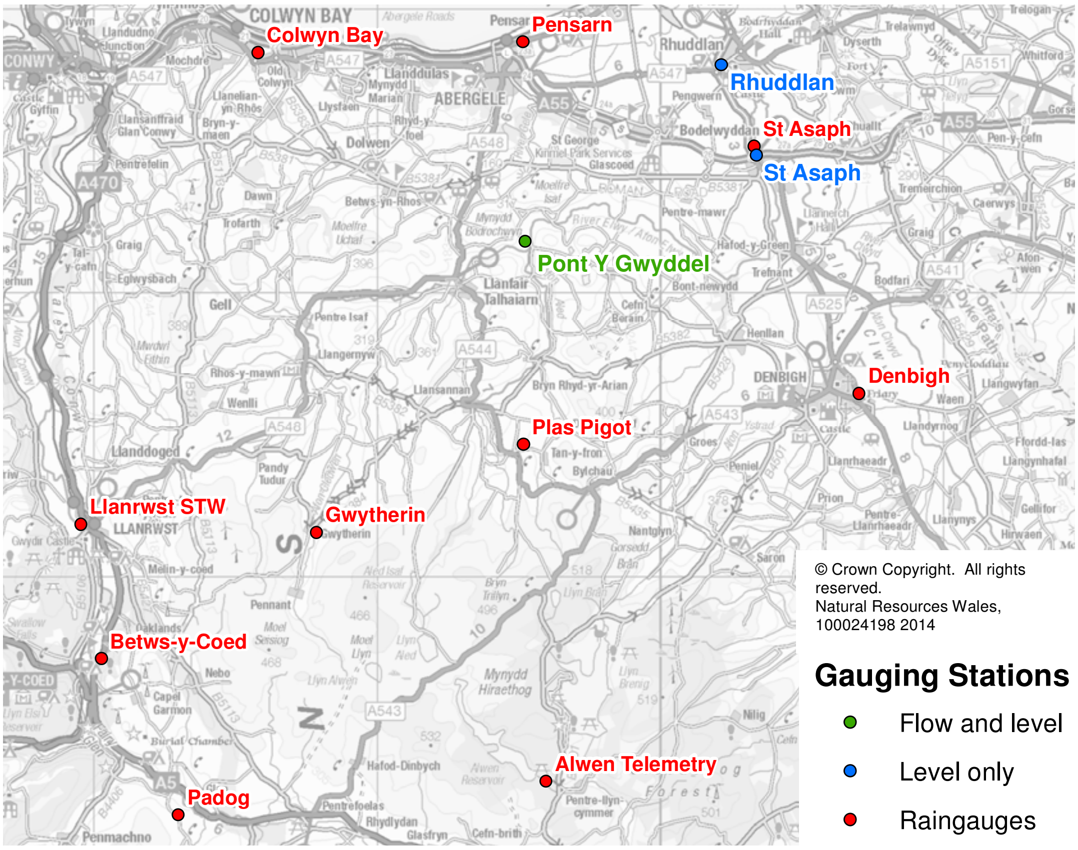
4. Hydraulic Model Calibration

4.1 Available Data

4.1.1 Hydrometric Data

There are a number of hydrometric gauges within and around the study area; these are shown in Figure 4-1.

Figure 4-1 Hydrometric Gauge Locations



Flow Data

Pont Y Gwyddel flow gauge is on the River Elwy downstream of the confluence with the River Aled and approximately 15km upstream of St Asaph (see Figure 4-1). Flow data at Pont Y Gwyddel was supplied by EA Wales for the period from 01/01/2009 to 31/12/2012. Information on the rating derived for the gauge was also supplied.

The gauge has a relatively long record of 39 years; works were carried out in 2009 to reduce bypassing at the site which was previously a problem during high flows. Data from the gauge is good quality with 94% of the data provided rated as 'Good within rating', for the data period supplied there is no missing data at the gauge, 3% of the data is marked as 'Estimated below lower limit' and 2% is labelled unchecked (the majority of this is data towards the end of December 2012). During the highest flows of the November 2012 event, the data at the gauge is labelled as 'Estimated beyond upper limit', the extrapolated rating for the gauge was used to calculate the flows during this time.

Level Data

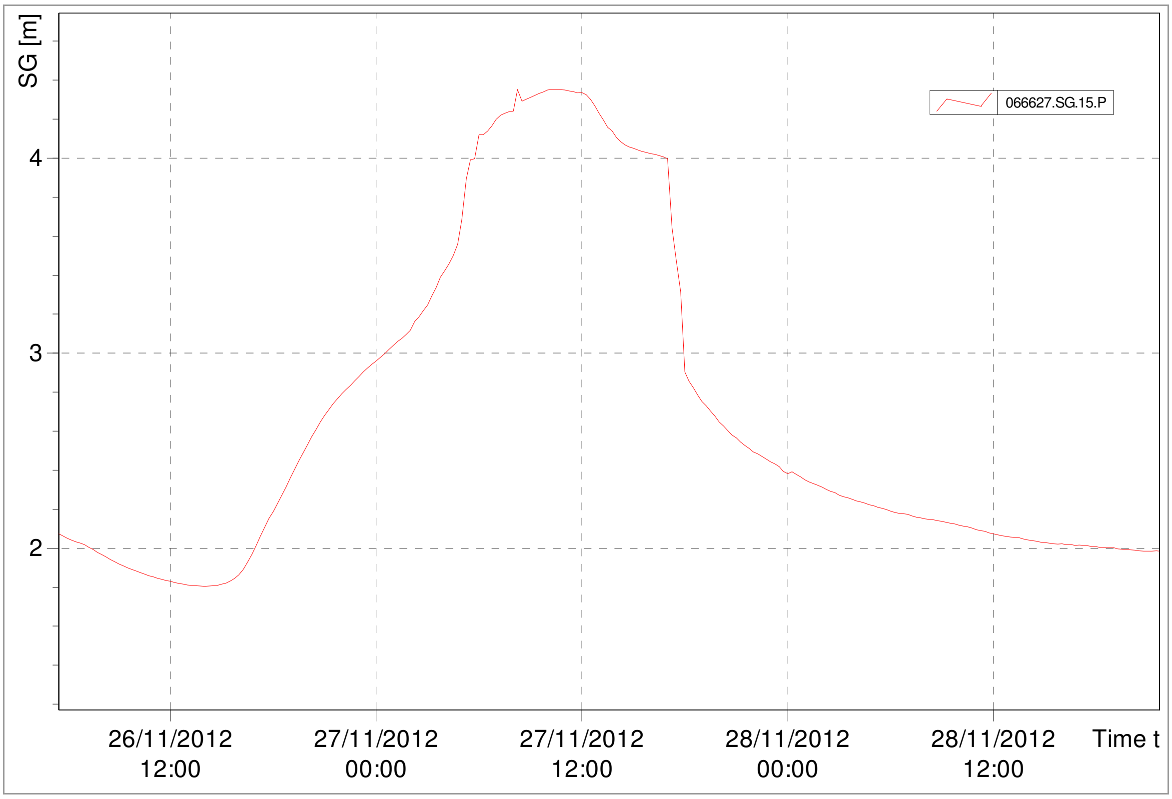
Level data was available for the following gauges within the River Elwy catchment:

- Pont Y Gwyddel (NGR 295250, 371800)
- St Asaph (NGR 303400, 374850)
- Rhuddlan (NGR 303250, 376600)

Level data was supplied for each of the gauges for the period 01/01/2009 to 31/12/2012.

The St Asaph gauge is at the downstream face of the A55 Bridge over the Elwy in St Asaph and recorded levels during the November 2012 event. However, the peak level recorded at the gauging station for the event was 4.352m (13.264 mAOD) but the peak river level recorded manually on site was 4.78m (13.692 mAOD) that is 0.428m higher than the gauged level. The staff gauge from which the manual readings were taken is on the downstream side of the A55 bridge pillar. It is not fully understood why the gauge did not record the peak level of the event but there may have been a blockage at the gauge as the gauge appeared to correct itself when water fell below bankfull. The level time series recorded at the gauge during the event is shown in Figure 4-2. The level time series has been used to calibrate the hydraulic model of the River Elwy through St Asaph, although the higher manually recorded peak flow has been used in the calibration.

Figure 4-2 St Asaph Gauge Recorded Levels during November 2012 Event



Rainfall Data

15 minute rainfall data was supplied for the following raingauges covering the River Elwy catchment and surrounding areas:

- Alwen (NGR 295986, 352748)
- Betws-y-coed (NGR 280286, 357077)

- Colwyn Bay (NGR 285816, 378474)
- Denbigh (NGR 307032, 366440)
- Gwytherin (NGR 287884, 361536)
- Llanrwst STW (NGR 279566, 361824)
- Padog (NGR 283003, 351564)
- Pensarn (NGR 295156, 378850)
- Plas Pigot (NGR 295183, 364643)
- St Asaph (NGR 303327, 375166)

Data was supplied for each of the gauges covering January - December 2012.

HYRAD radar rainfall data was supplied by NRW as well. This was compared to data recorded at the raingauges and provided information on the pattern of flooding across the Elwy catchment. HYRAD rainfall depths were supplied from 9:00 20/11/2012 to 08:45 30/11/2012. HYRAD data was supplied for the Plas Pigot and Gwytherin raingauge locations within the Pont Y Gwyddel catchment and compared to the data recorded at each raingauge. The HYRAD rainfall data total for the period it was supplied was less than the recorded rainfall data at both gauges, however the data was not consistently lower throughout the record.

HYRAD images were supplied by NRW to show the pattern of rainfall across the catchment and where the highest rainfall occurred. These were useful when deciding on the data to use from raingauges within the calibrated model, although the HYRAD rainfall depths recorded were not actually used within the model.

Immediately after the November 2012 event, NRW analysed the rainfall data and calculated estimates of the rainfall return period at different gauges within the study area including Plas Pigot, St Asaph, Gwytherin and Denbigh. This is an excerpt from the NRW hydrology report[6]:

Analysis of rainfall data gives a range of return periods of between <1month (Pensarn) and 1 in 13 years (Plas Pigot) for the 72 hours up to and including 09:00 on 27/11/12. When the analysis is extended to include rainfall on 22nd November, this gives a range of return periods of between 1 in 2 years (Pensarn) and 1 in 14 years (Plas Pigot). Rainfall totals for the month up to 26th November were not unusual, if looked at without any further information; and in-line with the Long Term Averages for that month. However, rainfall totals for the 7 days leading up to the 26th November were particularly high, with totals on the 26th November significantly so.

When viewed in isolation the rainfall data corresponding to the November 2012 flood event and the return periods calculated do not suggest an event of the scale witnessed in St Asaph. The data does show that high rainfall occurred in the Elwy catchment prior to the November 2012 event and it is likely that the catchment was already highly saturated when the rainfall event on the 26th/27th November occurred leading to the high flows witnessed on the 27th November.

4.1.2 Topographic Data

LiDAR data was supplied by NRW covering the River Elwy catchment from Pont Y Gwyddel to the downstream extent of the watercourse.

[6] Hydrology_Flooding North Wales November 2012 FINAL_Amended 030113, NRW, 2013

Bank top levels on the flood embankments taken immediately after the November 2012 event were supplied by NRW and were checked against the embankment levels included in the existing hydraulic model (collected by InfoMap Surveys Ltd in 2011).

4.1.3 Previous Studies

A number of previous studies have been completed within the study area for this project. Most recently, JBA completed a flood risk mapping study of the River Elwy through St Asaph in 2011. The flood risk mapping study involved hydrological analysis and the development of a 1D-2D model to determine flood risk through St Asaph. The Clwyd Strategy was also completed by JBA in 2011; this involved the development of a hydraulic model of the Clwyd. In 2007, JBA completed a study which developed flood forecasting models for the River Elwy and River Clwyd.

4.2 ISIS Model Updates

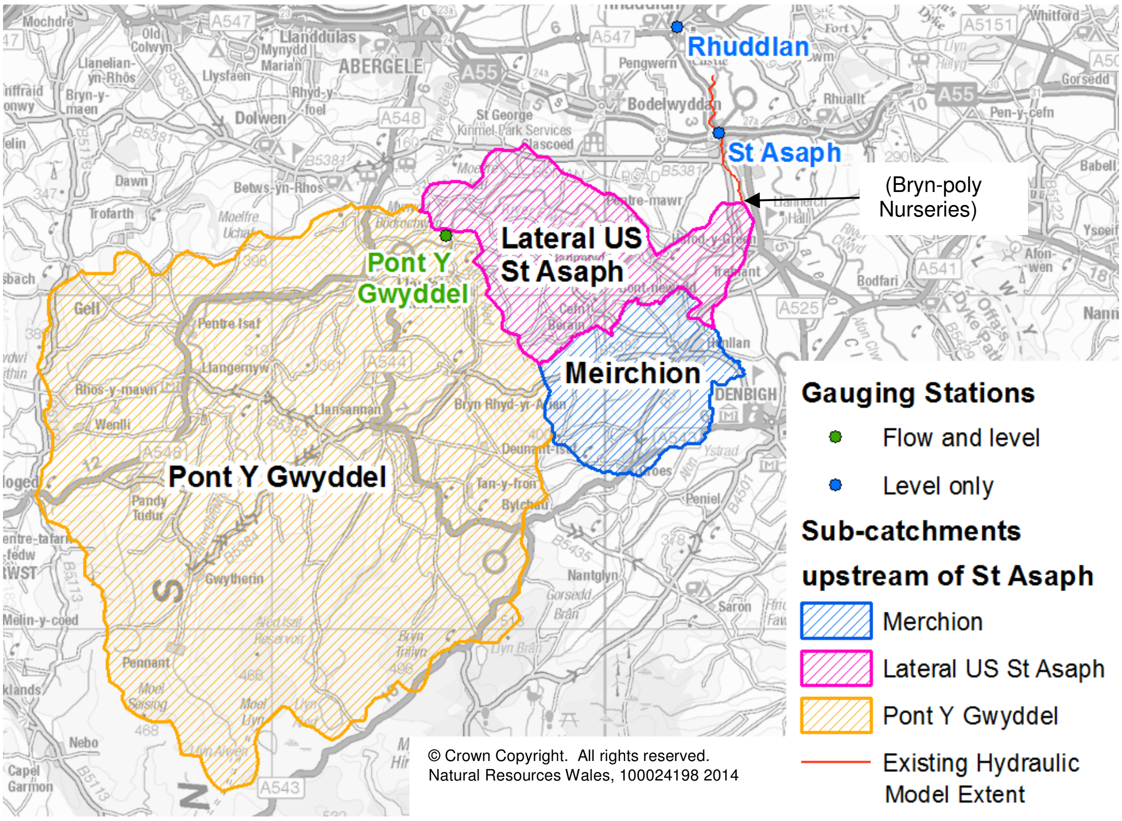
4.2.1 Extending Model Upstream to Pont Y Gwyddel

As good quality flow data was available at Pont Y Gwyddel and to limit uncertainty within the hydraulic model, routing sections were used to extend the existing ISIS model upstream to the Pont Y Gwyddel gauge. The upstream extent of the existing hydraulic model of the River Elwy through St Asaph is at Bryn-polyn Nurseries. Pont Y Gwyddel flow gauge is located 15km upstream of this location. LiDAR cross-sections at 1km spacing have been used to define the routing section using River Muskingham X-SEC units in ISIS.

4.2.2 Model Inflows

Three main sub-catchments were defined to the upstream extent of the Elwy hydraulic model (at Bryn-polyn Nurseries); these are shown in Figure 4-3. A QT inflow boundary representing the catchment area upstream of Pont Y Gwyddel has been attached to the most upstream routing cross-section within the model. Recorded flows at Pont Y Gwyddel have been used to define this upstream inflow. The catchment increases in size significantly between Pont Y Gwyddel and the upstream extent of the hydraulic model, the additional inflows along this reach have been represented by a tributary inflow within the routing section. The Meirchion is the main tributary of the Elwy between Pont Y Gwyddel and Bryn-polyn Nurseries, the additional flow for this catchment area has been represented as a direct inflow into the routing section of the model. For the purposes of this assessment, it is not critical that the lateral catchment area upstream of St Asaph is independently represented within the model; therefore its area and associated flows have been represented within the Meirchion tributary inflow boundary. The aim of the routing section and the tributary inflow are to ensure that water levels and flows are accurate downstream in the hydraulic section of the model through St Asaph.

Figure 4-3 Sub-catchments Upstream of St Asaph



The combined area of the Meirchion and the Lateral US St Asaph sub-catchments is 54.15km^2; one ReFH boundary unit has been used to represent this area within the model referred to as the MEIRCHION inflow from now on. Within the existing hydraulic model, there is a lateral inflow along the Elwy through St Asaph called ELWY_LAT to represent runoff through St Asaph itself, this is included in the model as an ReFH boundary unit. The ELWY_LAT inflow makes up a very small proportion of the flows through St Asaph, ~3% during the November 2012 based on the ReFH inflow boundary.

In order to simulate historical events in the model, it was necessary to analyse the available rainfall data for the Elwy catchment and construct time series that were then tested in ReFH boundaries to determine how well the events could be replicated. There are no gauges in the MEIRCHION, Lateral US St Asaph or ELWY_LAT sub-catchments to determine the performance of ReFH boundaries. A ReFH boundary for the Pont Y Gwyddel catchment was created and its ability to replicate recorded flows at the Pont Y Gwyddel gauge was tested. Four high flow events occurred in 2012 within the Elwy catchment, rainfall time series were constructed for each event. Details of the four events used in the calibration process are given in Table 4-1.

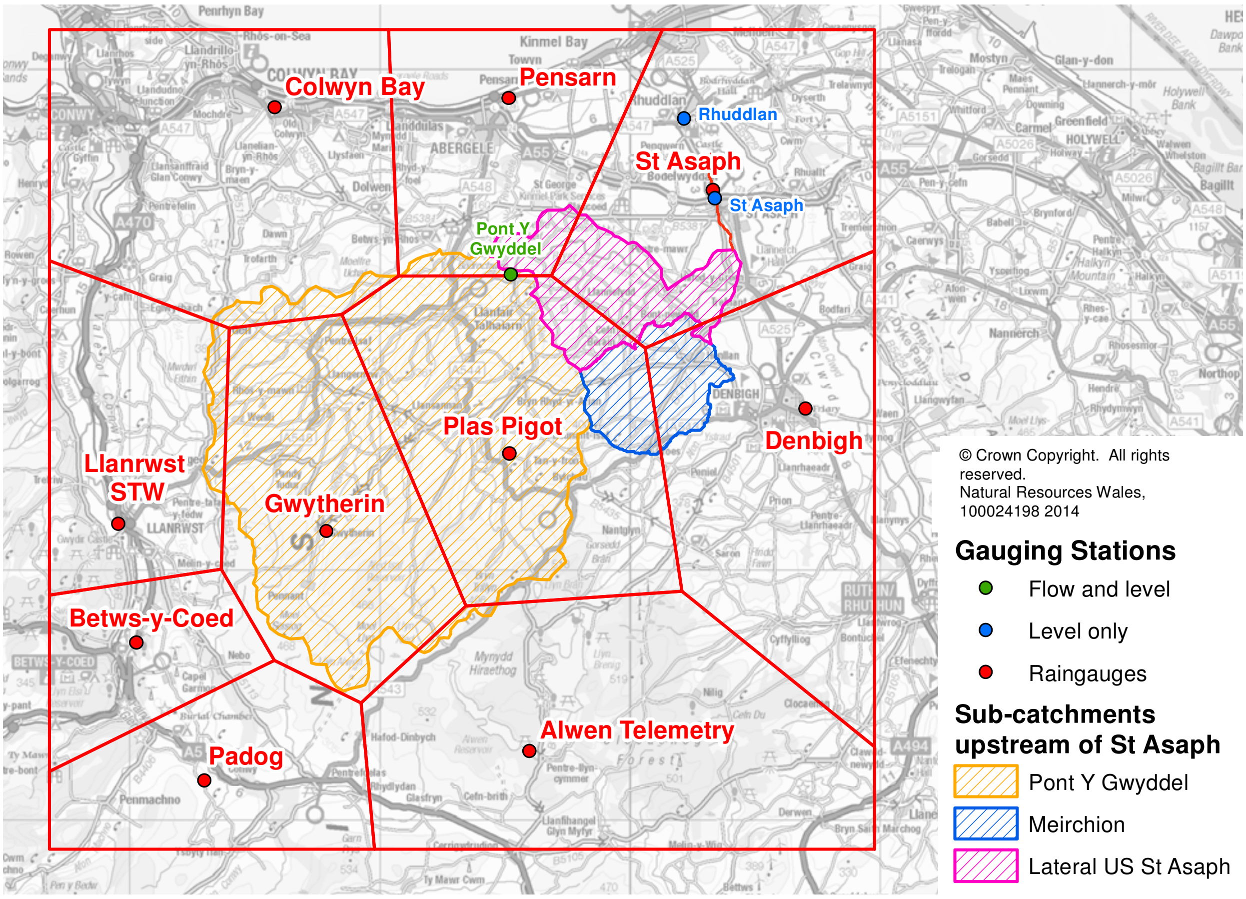
Table 4-1 Calibration Events

Event Name	Date range of calibration simulation	Peak flow recorded at Pont Y Gwyddel (m^3/s)	Peak stage recorded at St Asaph (mAOD)
April 2012	29/04/2012 07:00 – 01/05/2012 17:30	72.6	11.84
July 2012	06/07/2012 00:00 – 08/07/2012 13:00	59	11.57
September 2012	24/09/2012 01:00 –	75.3	11.93

	26/09/2012 11:00		
November 2012	22/11/2012 00:00 – 27/11/2012 23:45	202	13.26

Initially the Thiessen polygon approach was investigated, where a weighted rainfall time series can be created for a given catchment area based on the distribution of raingauges in and around the catchment. Thiessen polygons were created using the raingauge network shown in Figure 4-1 and were then compared to the sub-catchments shown in Figure 4-3. The resulting comparison is shown in Figure 4-4 below.

Figure 4-4 Thiessen Polygons across the Study Area



The Elwy catchment to Pont Y Gwyddel is mainly covered by the Gwytherin and Plas Pigot raingauge Thiessen polygons with a small proportion of the catchment covered by the Thiessen polygons for other raingauges (Llanrwst STW, Colwyn Bay, Pensarn and Alwen Telemetry). Based on the fact that the Gwytherin and Plas Pigot raingauges lie within the Pont Y Gwyddel catchment, are at high elevations (the majority of the catchment is upland) and the catchment is mostly covered by the Thiessen polygons for these gauges; they were used to define a rainfall time series for the Pont Y Gwyddel catchment. To create the rainfall time series, weightings of 0.52 and 0.48 were applied data from the Gwytherin and Plas Pigot raingauges respectively.

A weighted rainfall time series for each of the calibration events shown in Table 3-1 was constructed and tested in an ReFH unit representing the Elwy catchment to Pont Y Gwyddel. To refine the flows predicted by the ReFH boundary, combinations of different values for the ReFH parameters (Time to Peak - Tp(0), Catchment Wetness - Cini, Baseflow Lag - BL and

Baseflow Recharge - BR) were tested and compared with the default values calculated using catchment descriptors. Using the default parameters, the ReFH boundary performed well in predicting the recorded flows at Pont Y Gwyddel. However, it was found through testing that adjustments to the Tp(0), BL and BR parameters helped to define flows and the shape of the hydrograph recorded at Pont Y Gwyddel more accurately. The final scaling factors used to adjust these parameters are provided in Table 4-2. The scaling factor applied to the BR value is low but this parameter represents baseflow recharge, which would have been low during the November 2012 as the catchment was already saturated

The Thiessen polygon approach was also tested to define the rainfall time series for the MEIRCHION and the ELWY_LAT inflows within the model. The rainfall time series constructed for the MERICHION catchment was made up of weighted rainfall from the Plas Pigot, Denbigh and St Asaph raingauges. Rainfall data from the St Asaph gauge was used for the ELWY_LAT inflow boundary.

Initial 1D model runs indicated that flows were underestimated using the Thiessen polygon derived weighted rainfall data approach. The rainfall input data was investigated further, HYRAD data was analysed to determine whether it could be useful. Compared to the recorded rainfall depths at the Plas Pigot and Gwytherin raingauges, the HYRAD depths during November 2012 were generally low although not consistently so. As the model at this stage was underestimating flows, it was not thought appropriate to use the lower HYRAD rainfall dataset in the ReFH boundaries within the model. The HYRAD data was used to inform the analysis though. The spatial pattern of rainfall depths from HYRAD data across the Elwy catchment (indicated by the red line) from 00:00 26th November to 27th November 2012 is shown in Figure 4-5.

Figure 4-5 HYRAD Rainfall Depths 00:00 26th November - 23:45 27th November 2012

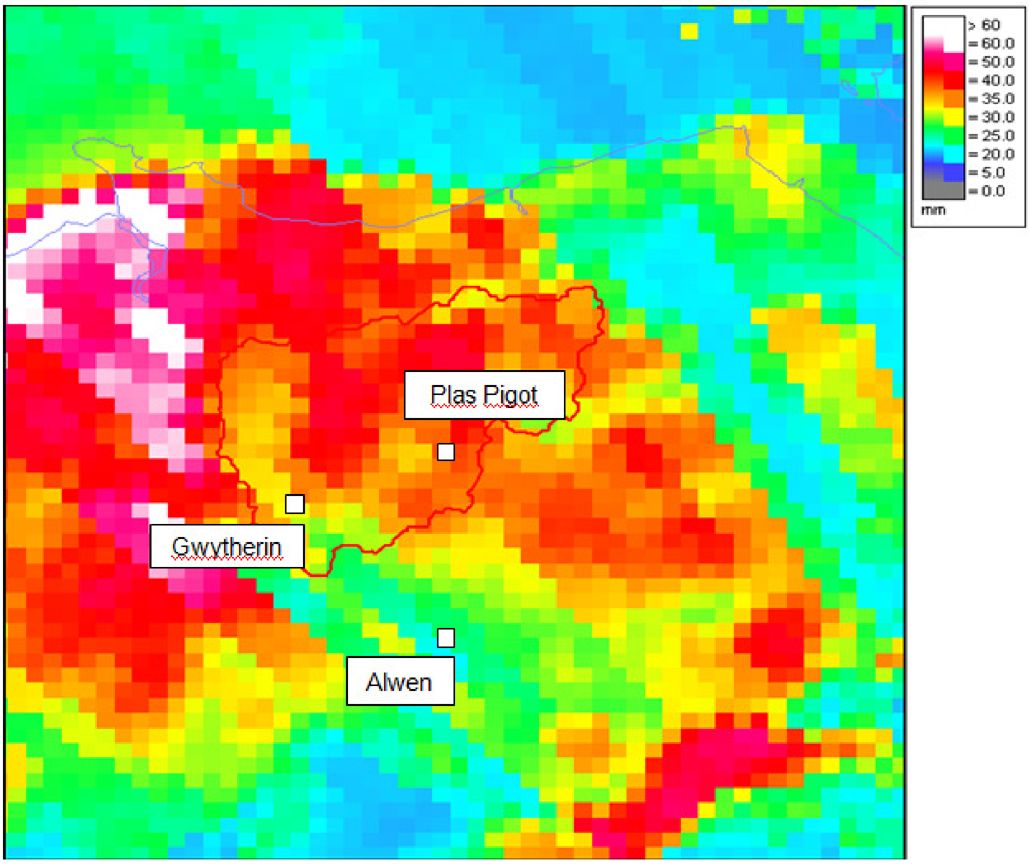


Figure 4-5 shows that during the November 2012 event, Plas Pigot experienced some of the highest rainfall depths within the catchment. The rainfall depths experienced at Plas Pigot appear to be representative of a large proportion of the catchment. The elevation of the Plas Pigot raingauge is also more similar to the majority of the catchment upstream of St Asaph. The elevation of the catchment between Pont Y Gwyddel and St Asaph ranges from approximately 40 (in the valley) to 360mAOD. Plas Pigot raingauge is situated at an elevation of 250m, whilst the raingauges at Denbigh and St Asaph are at lower elevations of 40 and 10 mAOD respectively.

Given that the initial model runs simulating the calibration events indicated that the model was under predicting flows, it was decided that data from Plas Pigot alone would provide a better representation of rainfall across the Meirchion sub-catchment that provides the majority of the additional flows along the Elwy between Pont Y Gwyddel and St Asaph. Using the Plas Pigot rainfall for the Elwy_lat inflow boundary was not feasible given that the sub-catchment has a much lower altitude than Plas Pigot and the St Asaph raingauge is within the Elwy_lat sub-catchment itself. St Asaph rainfall data has therefore been used to represent rainfall over the Elwy_lat sub-catchment. Table 4-2 summarises the inflow boundaries used within the ISIS model.

Table 4-2 Model Inflow Boundaries

Inflow	Catchment Area (km^2)	Boundary Unit Type	Boundary Data Source
Pont Y Gwyddel	191.37	Flow-Time (QTBDY)	Recorded Flow Data at Pont Y Gwyddel Gauge
Meirchion (inc Lateral US St Asaph)	54.15	ReFH	Plas Pigot Rainfall Data
Elwy_lat	7.52	ReFH	St Asaph Rainfall Data

4.2.3 Model Downstream Boundary

The Elwy discharges into the tidal Clwyd approximately 1.7km downstream of the Spring Gardens area of St Asaph. In order to determine whether levels on the Clwyd have an impact on water levels on the Elwy through St Asaph and in order to replicate the November 2012 event more accurately, the hydraulic model has been extended incorporating the Clwyd reach downstream of the confluence with the Elwy (cross-sections taken from Clwyd ISIS model built by JBA in 2011). Level data from the gauge at Rhuddlan (shown on Figure 4-1) on the Clwyd has been used to define the downstream boundary of the 1D ISIS model.

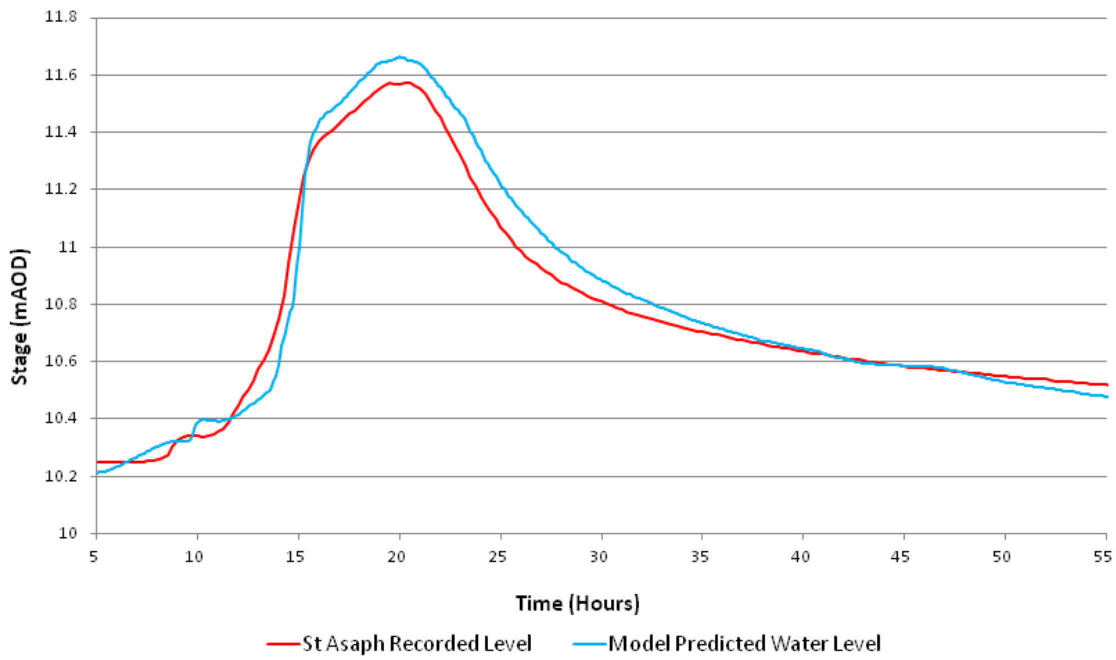
4.2.4 Routing Model Calibration

Once the boundary conditions for the ISIS model had been updated, calibration of the routing model was undertaken by changing parameters within the Muskingham X-SEC units in ISIS. The 2012 calibration events (shown in Table 4-1) were run through the model and the predicted water level time series at the node representing the downstream face of the A55 Bridge (SA015C) were compared to the recorded level data at the St Asaph gauge. Of the calibration events, out of bank flow only occurred during the November 2012 event. The three other events, April, July and September 2012 were used to calibrate the 1D model.

The routing sections within the Elwy model have been used to transfer recorded flows at Pont Y Gwyddel to the hydraulic model sections through St Asaph. The first step in calibrating the model involved ensuring that the timing of the peak flow predicted at St Asaph was correct. There is approximately a three hour travel time between Pont Y Gwyddel and the St Asaph gauge based on a comparison of the data for past events recorded at the gauges. The reach slope setting and manning's n roughness values within the routing sections were adjusted until the travel time between Pont Y Gwyddel and the St Asaph level gauge predicted by the model was appropriate. A consistent reach slope of 0.02 has been used for all the routing sections within the model and the manning's n roughness value has been set to 0.1 for all of them. 0.1 is a high roughness value, especially for river channel sections but as the hydraulics of the reach upstream of St Asaph to Pont Y Gwyddel have not been modelled this value was a necessary part of the calibration to ensure flows into the hydraulic part of the model were high enough and the travel time of the hydrograph was long enough.

For the three calibration events that stayed within the Elwy channel (April, July and September 2012), the adjustments made to the routing sections in the model meant that the predicted water levels within the model at the downstream face of the A55 correlated well with those recorded at the St Asaph gauge. The water levels predicted by the model and those recorded at the St Asaph gauge during the July 2012 event are shown in Figure 4-6.

Figure 4-6 Comparison of Predicted and Recorded Water Levels at St Asaph Gauge - July 2012 Event



4.2.5 Hydraulic Model Calibration

Once the routing section within the model had been configured and the ISIS model tested for the smaller flow events in 2012, data for the November 2012 event was used to run the event through the linked ISIS-TuFLOW model. The hydraulic components of the ISIS model and the TuFLOW domain at this stage were left unchanged from the 2011 FRM study. The predicted flood extent, timing of overtopping, predicted water levels at the A55 Bridge in St Asaph and predicted depths on the floodplain were used to assess how well the model replicated what happened during the November 2012 flood event.

This initial model run showed that in general the pattern of flooding experienced during the November 2012 event was replicated by the model. The extent of flooding predicted was less than that observed and overtopping of some of the defence embankments during the event was not predicted by the model. Of particular concern was the fact that the embankment on the left bank of the Elwy immediately upstream of the A55 Bridge was not predicted to overtop. Figure 4-7 clearly shows this embankment overtopping resulting in flooding to the cattle market behind it.

Figure 4-7 Overtopping of left Elwy embankment to Cattle Market

The structures within the model and their representation are described in Section 3.2.1. Changes were made to the representation of St Asaph Old Bridge and Spring Gardens Bridge in order to calibrate the hydraulic model better with the November 2012 event.

St Asaph Old Bridge

For the 2011 FRM study, it was assumed that the wall would prevent flow through the left most arch of the bridge and restrict flow through the next one (shown in Figure 3-2). The bridge was modelled using an ARCH bridge unit in ISIS with three full openings and a fourth smaller opening on the left bank. However, there is a gap of approximately 2-3m between the end of the wall and the bridge meaning that during a large flood event, it is likely that some water would be able to pass through the arches on the left bank. As the flows and water levels predicted by the model for downstream of St Asaph Old Bridge were not high enough (indicated by the lack of overtopping adjacent to the Cattle market), the representation of the bridge within ISIS was reviewed. The wall on the left bank is represented in TUFLOW, therefore it was decided that the five arches at the bridge could be modelled as open to potentially allow more flow through the bridge. The representation of the bridge with the five open arches has been retained within the calibrated model as it does help to move water downstream towards The Roe area of St Asaph, although this change alone was not sufficient to cause overtopping of the embankment adjacent to the cattle market within the model.

Spring Gardens Bridge

For the model calibration, changes were made to the configuration of Spring Gardens Bridge. Figure 4-8 shows a photo taken during the November 2012 event of the bridge. A large amount of debris carried from upstream by the river during the event collected in the wire mesh railings of the Spring Gardens Bridge. It has been estimated that the debris blocked approximately 30% of the railing height above the deck level of the bridge. Overtopping of this structure has been modelled in 2D rather than 1D; therefore the blockage of the railings has been represented in 2D using a z line to set the deck level of the bridge to that of the actual deck plus 30% of the railing height. It has been assumed where debris collected at the bridge, flow was completely blocked.

Figure 4-8 Blockage of Railings across Spring Gardens Bridge

It is possible that some blockage occurred to the opening of the Spring Gardens Bridge during the flood event due to the large amount of debris supplied from upstream. There is no evidence that blockage of the bridge opening itself did occur but residents suggest that some blockage did occur. Within the calibrated model, a 10% blockage has been applied to the bridge opening in order to account for blockage that may have occurred during the event. The blockage proportion was agreed with NRW who doubted that it would have been anymore than 10% as clearance activities were not required at the bridge opening itself after the event.

The changes to St Asaph Old Bridge and Spring Gardens Bridge outlined above did not increase predicted water levels within the model sufficiently. For example, overtopping of the embankment adjacent to the cattle market was still not apparent within the model.

The hydraulic ISIS model was reviewed further and changes to model parameters tested to determine how the November 2012 event could be represented better within the linked 1D-2D model. This section describes the changes tested and those retained within the ISIS model in order to calibrate the hydraulic model.

Table 4-3 describes the parameter changes tested within the ISIS model. The impact of the parameter changes were mainly assessed by comparing how much the predicted water level at St Asaph gauge (node SA015C within the model) changed compared to the initial model runs that incorporated the updates to structures within the ISIS model.

Table 4-3 ISIS Parameters Tested during the River Elwy Model Calibration Process

Parameter	Baseline (as in 2011 FRM Study)	Changes Made	Comments	Predicted Peak Water Level at St Asaph Gauge (mAOD) Manually Recorded Peak = 13.692mAOD
Baseline Model (with changes to structure incorporated)				13.45
Bed Levels	Surveyed bed levels - combination of survey data collected in 1999 and 2011 for previous studies	Increase all bed level by 0.1m	Peak water level changed by much less than 0.1m	13.53
		Increase bed levels not updated by 2011 survey by 0.1m (i.e. cross sections based on older survey data)	Peak water level changed by much less than 0.1m	13.50
Bank Roughness	Manning's n was set to either 0.05 or 0.07 on the River Elwy banks throughout the 2011 FRM model	Increased bank roughness to 0.1 downstream of St Asaph Old Bridge due to dense tree cover along this reach	Some impact on model results but predicted levels at the gauge still not high enough	13.50
		Increased bank roughness to 0.5 downstream of St Asaph Old Bridge due to dense tree cover along this reach	Large impact on water levels in parts of the model but not at St Asaph gauge itself	13.50
		Changed bank roughness to 0 to represent no conveyance along banks downstream of St Asaph Old Bridge due to dense tree cover along this reach	Run appeared to be unstable and results were not deemed reliable	13.66
Additional Inflows (Meirchion and Elwy_lat)	ReFH boundaries driven by data from raingauges within the Elwy catchment	ReFH parameter Cini (initial catchment wetness) increased to maximum value	Impact along upstream extent of model but little impact at St Asaph gauge	13.53
Channel Roughness	Channel roughness was set	Channel roughness downstream of St	Increases levels at St Asaph gauge close to	13.60

	to 0.035 throughout the 2011 FRM model	Asaph Old Bridge set to 0.04	level required to simulate overtopping of embankments upstream of A55	
		Channel roughness downstream of St Asaph Old Bridge set to 0.045	Increases levels significantly at St Asaph gauge - enough to simulate overtopping of embankments upstream of A55	13.67
		Channel roughness upstream of St Asaph Old Bridge reduced to 0.03 and channel roughness downstream of St Asaph Old Bridge set to 0.04	Lowering roughness upstream of St Asaph Old Bridge increases conveyance towards the centre of St Asaph and does act to increase levels at St Asaph gauge slightly	13.61

The testing of the parameters within the ISIS model showed that changing roughness values within the model had the greatest impact on results. NRW were keen to ensure that the dense tree cover on the River Elwy banks downstream of St Asaph Old Bridge was represented within the model. As the model test run using a Manning's n value of zero did not produced reliable results and was unstable, it was decided that a value of 0.5 would be used to represent the banks along this reach. This is a very high Manning's value to use within ISIS but it was important that the limited conveyance along the Elwy banks was represented within the model.

Increasing channel roughness downstream of St Asaph Old Bridge had the greatest effect on water levels predicted at the St Asaph gauge. 0.045 is a relatively high Manning's value to use for the river bed in this location as it is not overly rough. It was hard to justify using this value for the channel based on a review of the River Elwy bed using photographs and through discussion with NRW. Therefore, the lower 0.04 Manning's n value was used to represent the roughness of the channel bed in order to raise the water levels predicted in the channel compared to using the previous 0.035 value.

Reducing the channel roughness upstream of St Asaph Old Bridge acted to slightly increase water levels within the River Elwy through the centre of St Asaph and at the gauge. As a result the Manning's n values for channel roughness upstream of St Asaph Old Bridge were set to 0.03 to increase conveyance to the centre of town. This is realistic as a large proportion of debris was observed in the channel downstream of St Asaph Old Bridge during the November 2012 event whilst upstream of the bridge; there was not a large proportion of debris.

The calibrated ISIS model had the following key features:

- St Asaph Old Bridge - all five arches modelled as open
- A55 bridge represented as an USBPR 1978 BRIDGE unit with pillars included
- 0.5 Manning's n value used to represent dense tree cover on River Elwy banks downstream of St Asaph Old Bridge
- 0.04 Manning's n value used to represent the channel bed roughness downstream of St Asaph Old Bridge
- 0.03 Manning's n value used to represent the channel bed roughness upstream of St Asaph Old Bridge
- 10% blockage applied to the opening of Spring Gardens Bridge

The only change made to the 2D domain within the calibration process was that buildings within the floodplain were raised by 300mm to represent their threshold level above ground as this led to better representation of the November 2012 flood extent within the model. This threshold level has been assumed and is a generally accepted threshold level to use for buildings.

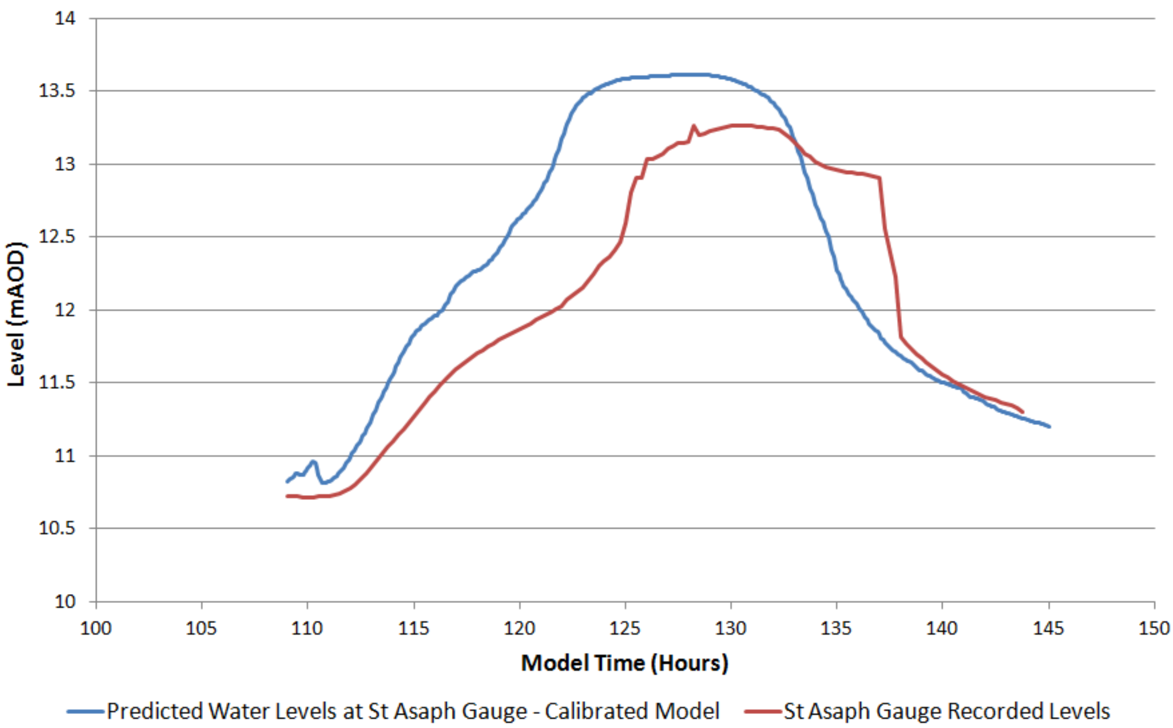
It is possible the further work on the Pont Y Gywddel rating curve and changes to the inflows may require some degree of re-calibration of the hydraulic model.

4.3 Calibrated Model Results

The predicted water levels within the calibrated model are compared with the levels recorded at St Asaph gauge during the November 2012 event as shown in Figure 4-9. As stated in Section 2, the St Asaph gauge did not record the peak water level during the November 2012 event, the manually recorded peak water level was 13.692 mAOD. The calibrated model predicts a peak water level of 13.62 mAOD at the location of the St Asaph gauge (the downstream face of the A55 Bridge).

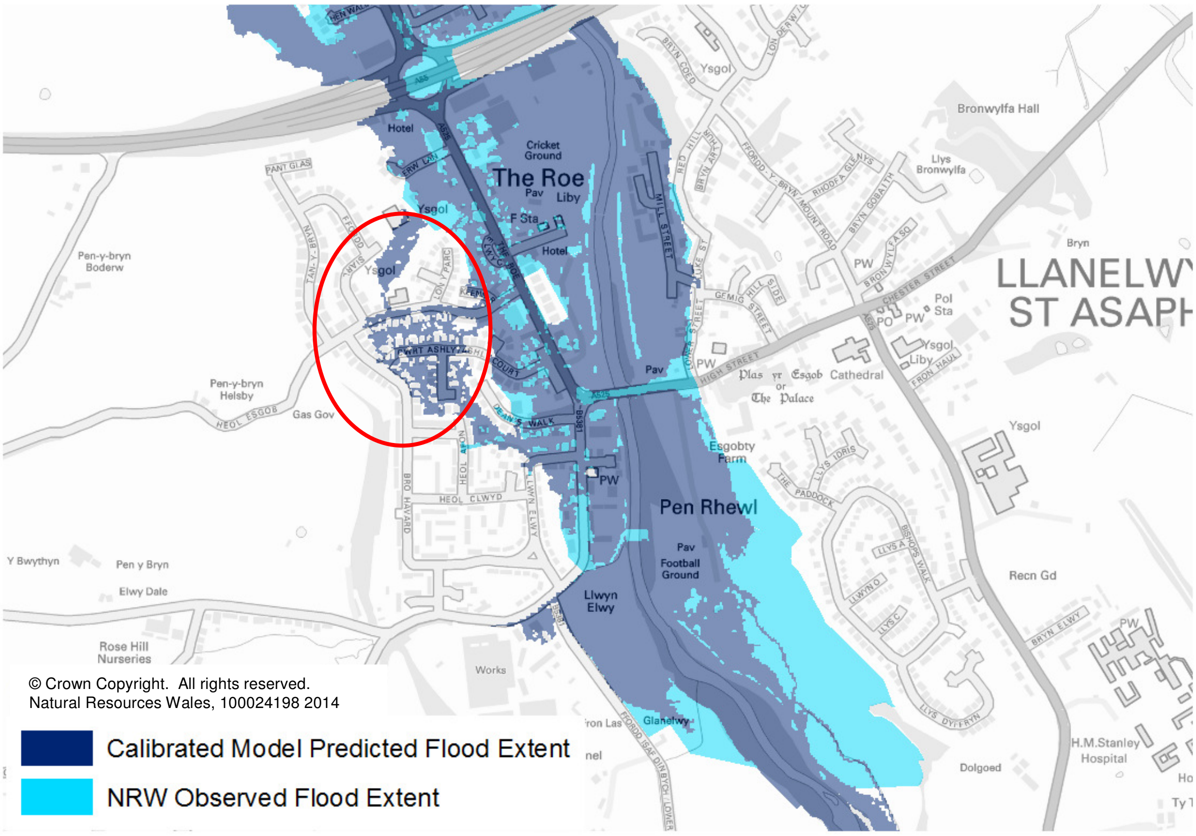
The rising limb of the hydrograph in the calibrated model predicts higher flows than those recorded at the St Asaph gauge. Unfortunately, attempts to lower the predicted levels on the rising limb resulted in a reduced peak flow predicted and therefore a reduced overall flood extent through St Asaph. The gauge did not properly record the falling limb of the hydrograph during the event, potentially due to blockage. The gauge did appear to reset after the event as indicated by the sudden drop in recorded levels shown on Figure 4-9. Where the gauged levels appear sensible on the falling limb (around 138 hours on Figure 4-9), the model predicted levels are close to those recorded at the gauge.

Figure 4-9 Calibrated Model Predicted Water Levels and St Asaph Gauge Recorded Water Levels



The flood extent predicted by the calibrated model through St Asaph upstream of the A55 is compared to the NRW observed flood outline in Figure 4-10. The overall pattern of flooding is predicted well by the model and the sequence of overtopping through St Asaph is predicted accurately in the model. On the right bank of the Elwy near Pen Rhewl, the flood extent is under predicted by the calibrated model. The channel through this area has a lower bed roughness value than the rest of the model of 0.03 following calibration with the levels at St Asaph gauge and this may result in lower water levels predicted through this reach and therefore reduced flooding. However, even with higher Manning's n values tested along this reach, the extent of flooding on the right bank in this location predicted by the model is not as extensive as that observed during the event.

Figure 4-10 Calibrated Model Predicted Flood Extent and NRW Observed Flood Outline Upstream of A55

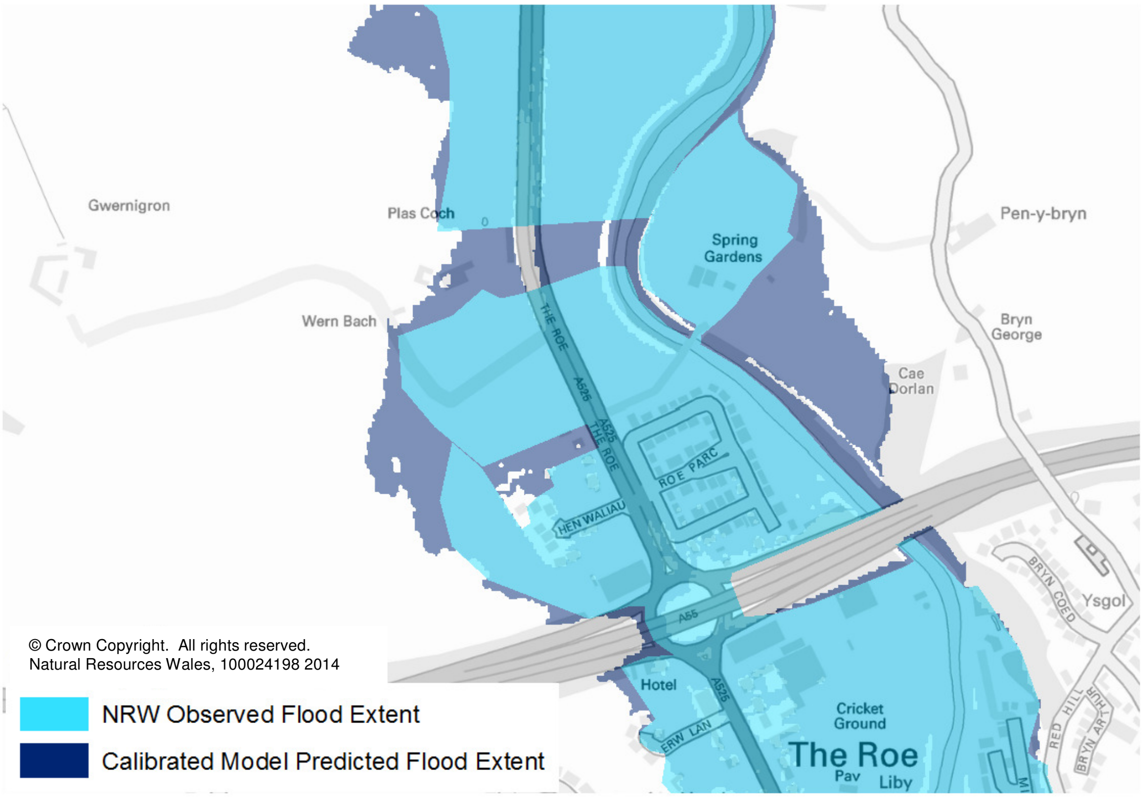


The area circled on Figure 4-10 is predicted to flood by the calibrated model, flooding in this area did not occur during the November 2012 event. However, the flow route predicted by the model across the gardens of properties on Dean's Walk was observed during the event. The 2D floodplain within the model is represented by filtered LiDAR data and does not include the representation of walls, fences or curbs. Relatively shallow flooding is predicted by the model in this area where flooding was not observed during the event and it may be that flood water ponded up behind a raised feature such as a curb or wall and prevented the flooding spreading as far as the model predicts. As the flow route is through back gardens, it is likely that there are a number of walls in this area that are not represented within the 2D domain of the model.

Figure 4-11 shows the calibrated model predicted flood extent downstream of the A55. As with upstream of the A55, the overall predicted flood extent from the model is close to that observed during the November 2012 event but the model predicts additional flooding that did not occur in reality. The main area where this is apparent is the flooding predicted to the sewage works south of Spring Gardens Holiday Park, this did not flood during the event. It is unclear why there is a discrepancy between the observed flood extent and the modelled flood extent in this location but it is assumed that local conditions during the flood prevented water flowing onto the sewage works site during the November 2012 event.

As with any model, there is uncertainty associated with the results of the calibrated model and it does not represent the November 2012 event perfectly. The sequence of flooding through St Asaph is predicted well by the model. The model predicts overtopping early on during the event at Pen Rhewl, quickly followed by flooding to Spring Gardens Holiday Park and Roe Parc downstream of the A55. Water overtopping the left bank of the River Elwy near Pen Rhewl flows northwards to The Roe area after the areas downstream of the A55 have flooded.

Figure 4-11 Calibrated Model Predicted Flood Extent and NRW Observed Flood Outline Downstream of A55



The pattern of flooding predicted by the model has been compared to the record log compiled during the event that provides information about the timing of overtopping during the event as well as other information. Table 4-4 shows how the model results compare to the recorded log of events.

Table 4-4 Comparison of Model Predicted Flooding to the Record Log Taken During the November 2012 Flood Event

FLOOD EVENT LOG – 27th November 2012		MODEL SIMULATION			
Log Entry	*Time*	*Location of Flooding*	*Date*	*Time*	*Comparison with incident log*
		Overtopping of right bank upstream of St Asaph Old Bridge	26th November 2012	20:30	
		Overtopping of left bank just downstream of Bryn Asaph begins	26th November 2012	21:30	
		Flooding into grassy area north of football ground at Pen Rhewl	26th November 2012	21:30 - 00:30 27th Nov	
		Overtopping of right bank just downstream of Bryn Asaph begins	26th November 2012	23:00	
		Overtopping of left bank near to football ground	27th November	00:00	
Water level reached deck height at Spring Gardens Bridge	04:10	Deck Level at Spring Gardens Bridge reached	27th November	02:00	2hrs earlier
Overtopping beginning at Row Park, shallow depths on roads	05:35	Overtopping to Roe Parc begins	27th November	02:30	3hrs earlier
Rhuddlan - St Asaph carriage way flooding	06:00	Flooding to Spring Gardens Caravan Site and flooding onto Rhuddlan-St Asaph carriageway	27th November	03:00	3hrs earlier
Overtopping upstream right bank near Mill Street	07:05	Overtopping of right embankment immediately downstream of St Asaph Old Bridge (nr Mill St)	27th November	04:00	3 hrs earlier
Mill Street flooded	08:05	Flooding along Mill Street	27th November	04:30	3hrs 30 earlier
Embankment overtopping near The Plough and Cricket Club	06:50	Embankment near The Plough and Cricket Club overtops	27th November	05:00	1hr 50 earlier
		Embankment adjacent to Cattle Market on left bank overtops	27th November	05:00	
		Flooding along the A525 (The Roe)	27th November	05:30	
		Flood water passes under A55 flyover	27th November	07:30	
St Asaph Gauge board at 4.78m	09:45	Peak stage at St Asaph Gauge (13.62m AOD in model)	27th November	08:00	1hr 45 earlier

5. Flood Risk Mapping

5.1 Overview

The calibrated model has been used to update the flood mapping deliverables for the River Elwy through St Asaph. Some changes were made to the calibrated model before the design events were run through to make it appropriate for flood mapping purposes:

- Model inflows - ReFH boundary units have been used within ISIS to represent all the model inflows; Pont Y Gwyddel, Meirchion and Elwy_lat. For all design events modelled, the predicted ReFH hydrographs at Pont Y Gwyddel have been scaled to the peak flow estimates developed through the hydrological analysis as described in Section 2 of this report. The scaling factor used for Pont Y Gwyddel has then been applied to the other ReFH inflows in order to be consistent across the model. These scaling factors are highlighted in Table 2-8.
- Downstream Boundary Condition - the HT boundaries at the downstream extent of the 1D and 2D domains for the calibrated model used recorded level data at Rhuddlan during the November 2012 event. For the design events, recorded data at Rhuddlan from the highest tidal event that occurred during 2012 has been applied at the downstream boundaries. The tidal peak has been timed to coincide with the fluvial peak for the design events. The sensitivity testing showed that the downstream boundary does not affect water levels within the River Elwy.
- Blockages at Spring Gardens Bridge - the 10% blockage at the opening of Spring Gardens Bridge and the 30% blockage of the railings across Spring Gardens Bridge were not included in the model used to run the design events. For flood risk mapping purposes, it is assumed that all structures are unblocked and free-flowing.

5.2 Undefended Event

As there are formal flood defences along much of the River Elwy through St Asaph, an undefended model was configured for the 2011 FRM study and the methods used to remove the defences from the 2D domain have been used within this study also:

- Surveyed bank heights along the masonry wall immediately upstream of St Asaph Old Bridge and Glascoed Stream have been replaced with approximate floodplain elevations.
- A Z shape patch along the cells within the 2D model representing the embankments removes the raised defences from the model. This was set with the approximate floodplain level. This was required as the defence widths are more than one cell wide. Elevation points were added along the z shape (snapped to vertices), in order to provide a smooth change in elevation from one end of the embankment to the other (as the floodplain elevation behind the defences was found to vary).
- Increasing the length of the downstream boundary to account for any changes in the pattern of flooding between defended and undefended scenarios.

5.3 Model Run Times and Key Assumptions

The model runs have been carried out in ISIS version 3.6 and TuFLOW version 2012-05-AE-iDP-w64. The models were run with a 1D (ISIS) timestep of 1 second and a 2D (TuFLOW) time-step of 2 seconds. Model runs took between 2.5 and 6.5 hours to complete on a standard desktop PC depending on the return period. Model stability is generally good; there is no poor convergence in ISIS during all runs. There is some minor oscillation between the ISIS and TuFLOW domains during all runs that is caused by absence of defences near the confluence with the River Clwyd. This is located downstream of St Asaph and does not impact the flood outline through the town. The flux between the 1D and 2D domains through St Asaph is smooth.

The key modelling assumptions specific to this model include:

- The ISIS and TuFLOW downstream HT boundary assumes that the peak water level on the River Elwy would coincide with the peak water level on the River Clwyd.
- A masonry wall immediately upstream of St Asaph Old Bridge has been retained in the model for the defended runs. The defended model therefore assumes that the wall would stand up during a major flood event (as it did in November 2012). The wall is predicted to overtop in the 1% AEP event.
- All defended runs assume the defences remain at their existing (surveyed) levels during flood events and do not breach.
- The model does not take into account any flooding from minor surface water or sewer networks. Llys y Felin sheltered housing was flooded in November 2000, caused by overland flow from a surcharging combined sewer system being trapped behind the defences.
- The representation of the Sewage Works Bridge is key to the pattern of flooding in the downstream extent of St Asaph.
- Flood water can exit the downstream extent of the 2D domain in proportion to a normal flow boundary based on an approximate floodplain gradient.

5.4 Sensitivity Testing

All hydraulic models require the estimation of model parameters that can have a significant effect upon the modelled flood outlines. Although the River Elwy model has been calibrated for the November 2012 event, a suite of sensitivity tests have been undertaken to help understand the potential impact of adjusting model parameters and the way hydraulic structures may have been modelled. The sensitivity tests have been carried out for the 1% AEP design event. The following tests were carried out on the model;

- Channel and floodplain roughness: - modelled by adjusting both channel and floodplain roughness values by ± 20% to represent potential uncertainties in the allocation of Manning's 'n' values.
- Representation of urban areas: - modelled using an increased roughness approach where buildings are modelled at ground level (taken from LiDAR) and assigned a high roughness value to slow flow through them as would happen in reality. Within the calibrated model, a 300mm threshold level has been assigned to buildings as this gave more realistic results for the calibration event.
- Downstream boundary condition - the impact of the assumed boundary condition has been tested by adjusting the water level profile in both the ISIS and TuFLOW HT boundaries by ±1m.

A 2m cell size was impractical due to both the size of the model and run times and therefore a 4m cell size was used for the final models.

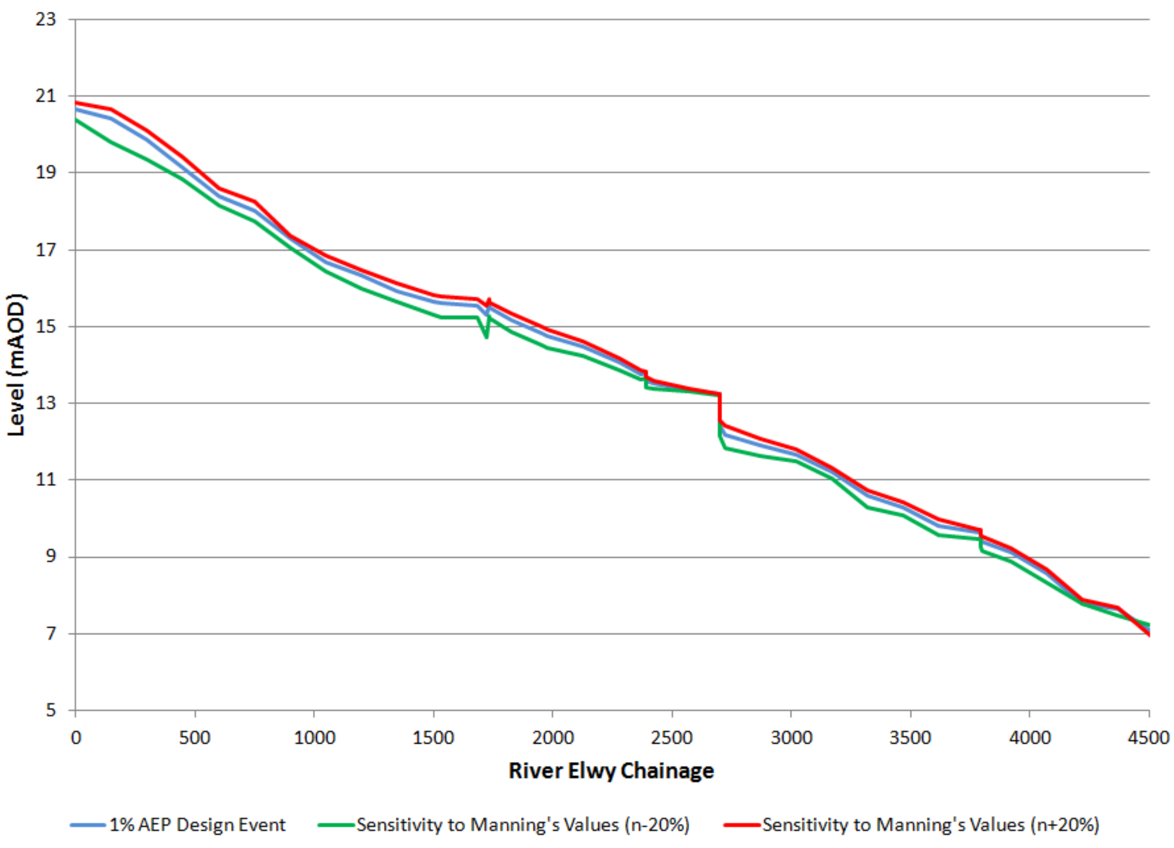
The impact of sensitivity tests have been analysed in two ways. Firstly, in terms of peak water level in the 1D model and secondly based on predicted flood extents.

5.4.1 Sensitivity to Roughness Values

The model was found to be most sensitive to the roughness values assigned within model, the calibration process showed that changing Manning's n values within the channel had a large impact on the model results. Figure 5-1 shows the changes in peak predicted water levels for the roughness sensitivity tests carried out for the 1% AEP design event. The largest difference in levels is predicted upstream of St Asaph Old Bridge where a 20% increase in roughness values results in a 170mm increase in water levels. Upstream of St Asaph Old Bridge, a 20% reduction in roughness values results in water levels 310mm lower than the design event levels (roughness values as defined through the calibration process).

The effect of changing the roughness values on water levels translates to marked differences in the predicted flood extents; this is particularly true for the 20% reduction in Manning's n values within the model that produces a much smaller flood outline compared to the 1% AEP design event as shown in Figure 5-2.

Figure 5-1 Long Section showing Peak Water Levels for Manning's Value Sensitivity Tests



5.4.2 Sensitivity to Downstream Boundary Condition

For this study the downstream boundary has been extended and a small section of the tidal Clwyd now forms the lower reach of the hydraulic model. Changing the downstream boundary at Rhuddlan by ±1m within the ISIS model only results in changes in predicted water level within the Clwyd reach modelled. There is a 1.5m drop in bed levels from the River Elwy to the River Clwyd, which is why changes to the downstream boundary within ISIS do not have an effect on the River Elwy itself as shown in Figure 5-3. Changing the HT boundary in 2D also has a minimal effect on the model results and the flood outlines predicted through St Asaph are unchanged regardless of the downstream boundary condition applied as the boundary is so far downstream of the town and on the Clwyd rather than the Elwy itself.

Figure 5-2 Predicted Flood Extents for Manning's n Sensitivity Tests

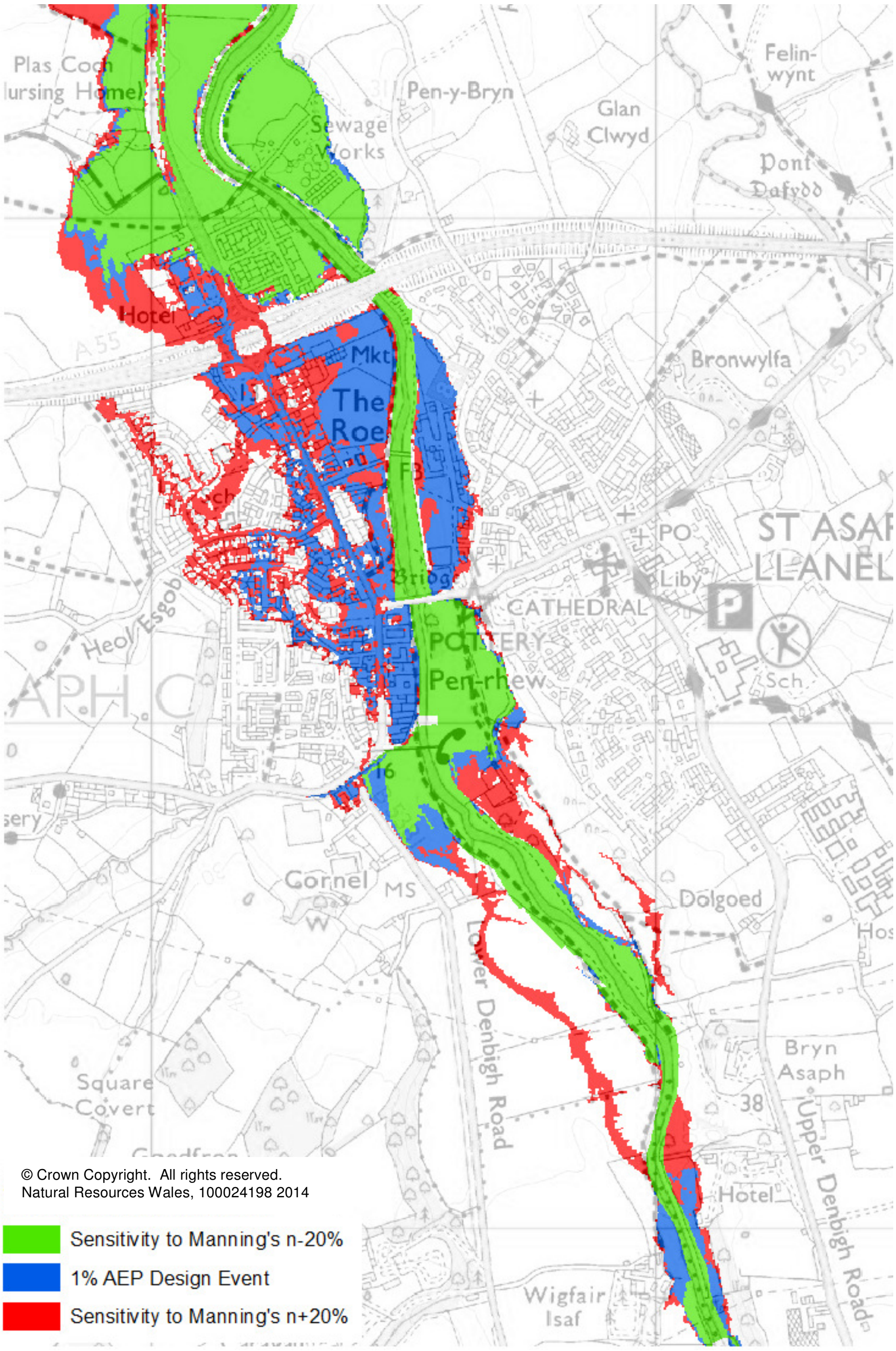
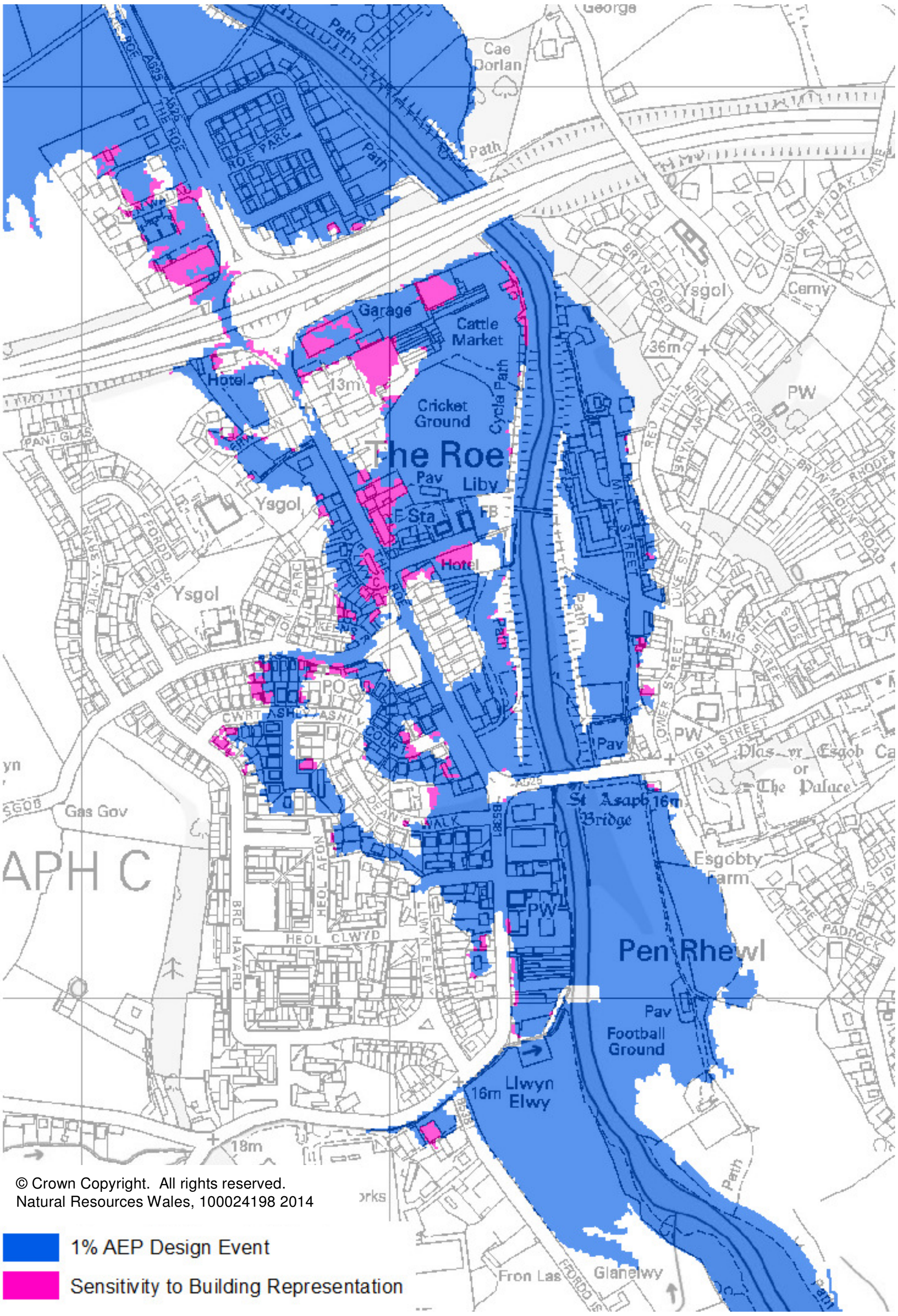


Figure 5-3 Predicted Peak Water Levels at Downstream Extent of the 1D ISIS Model for the Downstream Boundary Sensitivity Tests

5.4.3 Sensitivity to Buildings Representation

Within the calibrated model and the 1% design event baseline for the sensitivity testing, buildings have been represented with a 300mm threshold level above ground levels (taken from LiDAR) and a high Manning's n roughness value of 1 to slow flow through them as would happen in reality. An alternative approach to modelling buildings within the 2D domain is to model them at ground level with an increased roughness value to simulate the slower flow that would occur through them during a flood. The sensitivity test using this approach produced a very negligible effect on predicted peak water levels within the 1D model. The main impact of this sensitivity test is within the 2D domain, Figure 5-4 shows the difference between the buildings sensitivity test and the 1% AEP design event in terms of predicted flood extent. The buildings sensitivity test is generally a larger outline than the 1% AEP design event through St Asaph but as using the 300mm threshold approach produced better results for the calibrated model; this method has been used for the design events as it may predict a more accurate pattern of flooding.

Figure 5-4 Sensitivity to Building Representation Flood Extent



5.5 Design Events

Using the model developed through this study, flood extent, depth and velocity information has been produced within the study area for the 3.33%, 1.33%, 1%, 1% plus climate change, 0.5% and 0.1% AEP undefended flood events. The data for the 1% AEP event is formally presented in the flood risk mapping layouts contained within Appendix D. The sections below describe the methodology that was used to delineate the final flood maps and summarise the areas at risk of flooding from the River Elwy within the study area.

5.6 Processing Model Data

The flood extents for this mapping study were obtained from the linked ISIS-TuFLOW model. The process involved in obtaining flood extent, depth and velocity deliverables is described below.

5.6.1 Flood Depth and Extent Information

- Maximum depth information produced by the ISIS-TuFLOW model was converted into ASCII (.asc) file format based upon a 2m grid and imported into MapInfo to produce a depth grid.
- The depth grid was contoured using one interval to produce the flood outline.
- The flood outline was then 'cleaned' in MapInfo to remove dry islands and small isolated areas of flooding.
- This resultant flood outline was then used to trim the depth grid to remove isolated areas of flooding.

5.6.2 Velocity and Flood Hazard Information

Flood velocity and hazard information has been processed in the same way as the flood depth information described above. The peak velocity and flood hazard grids created have been trimmed to the cleaned flood outline to produce a consistent set of GIS layers.

Predicted flood depth and velocity data for the study area are discussed in the sections below.

5.7 Flood Depth and Extent Information

The discussion in this report focuses on flooding in St Asaph, flood extent and depth information for the River Elwy downstream of St Asaph is provided within the GIS deliverables that accompany this report.

5.7.1 Predicted Flood Depth and Extent for the 1% AEP Defended Event

The predicted flood depths and extent for the 1% AEP defended event through St Asaph are shown in Figure 5-5. The extent of flooding predicted using the calibrated model is significantly greater than that predicted for the 1% AEP event in the 2011 FRM study. Overtopping of the Elwy defence embankments is predicted to occur in a number of locations during the 1% AEP event including adjacent to the cattle market, near to The Plough pub and around St Asaph Old Bridge. 395 properties in St Asaph are within the predicted 1% AEP flood outline as well as Spring Gardens Caravan Park. Property counts have been undertaken using combination of National Receptor Database (NRD) point data and building footprints from OS Mastermap data, this means that the count includes properties that are partly flooded on the edges of flood outlines as. Downstream of St Asaph, there are an additional 12 properties within the 1% AEP event flood outline. The 1% AEP flood extent shows that the flood embankments through St Asaph do not provide protection up to the 1% AEP event in certain locations. Standard of Protection (SoP) analysis has been undertaken as part of this study and the results of this are presented in Appendix F.

The main areas with properties at risk are Roe Parc, The Roe, the left bank of the River Elwy near Pen Rhewl and the right bank of the river opposite The Roe. Pen Rhewl is shown to flood and depths of over 1m are predicted in this area but there are few properties here. The football ground and its pavilion at Pen Rhewl are within the 1% AEP outline. High depths of over 2.5m are predicted to parts of the Spring Gardens caravan park as it sits in a low point adjacent to the river where water collects. As witnessed during the November 2012 flood event, flooding occurs early on to Spring Gardens during the 1% AEP event when the access bridge becomes surcharged. In general the flood depths on the left bank of the River Elwy are shallower than those on the right. The majority of flooding on the left bank is <0.2m in depth, deeper flooding is shown to properties upstream on St Asaph Old Bridge on the left bank. Upstream of Glascoed Stream, flood depths of over 0.5m are predicted but there are no properties within this area.

Properties within St Asaph are predicted to flood for all return period events modelled. In the 3.33% AEP event, 47 properties within Roe Parc downstream of the A55 are predicted to flood as well as Spring Gardens Caravan Site and the football ground at Pen Rhewl. Flooding to 188 properties is predicted for the 1.33% AEP event in St Asaph including properties upstream of the A55 as well as in Roe Parc and Spring Gardens. The areas upstream of the A55 that flood during this event are the right bank of the Elwy opposite The Roe and on the left bank upstream of St Asaph Old Bridge.

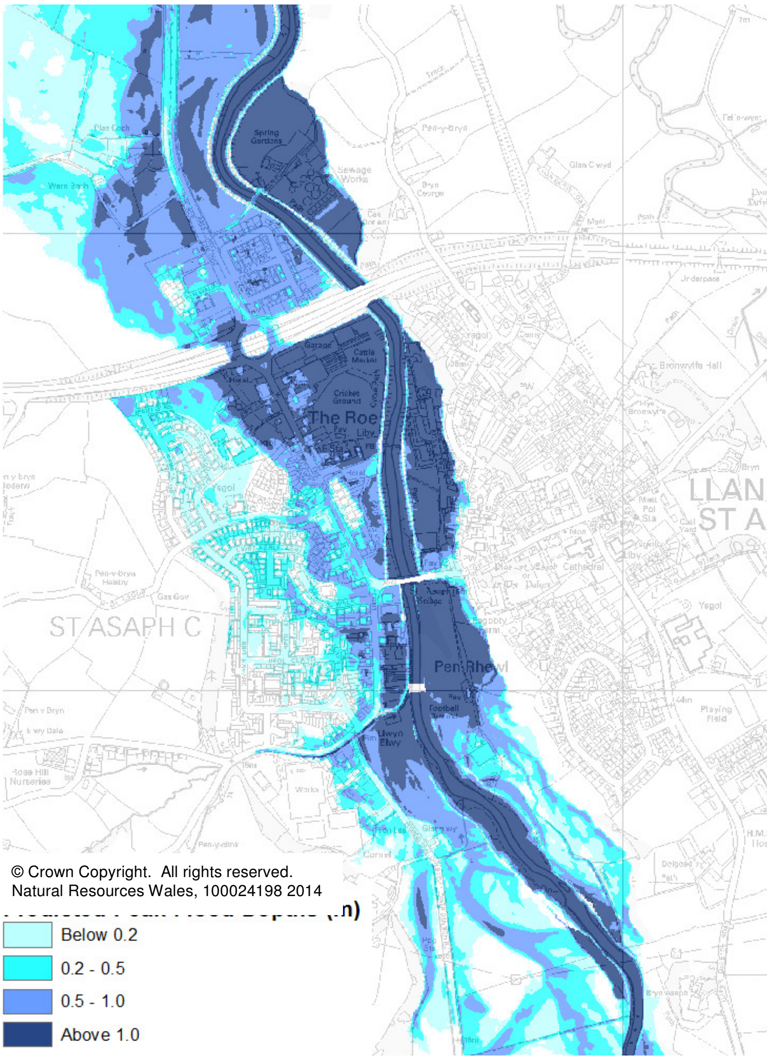
Figure 5-5 Predicted Flood Depth and Extent in St Asaph for the 1% AEP Design Event

Given that the calibrated model predicts that properties are at risk during the 3.33% event in Roe Parc; the model was used to test a number of short term flood risk mitigation options in St Asaph. Following testing using the model, the defence height of the embankment protecting Roe Parc has been increased and trees on the banks of the River Elwy have been removed through the town to increase conveyance within the channel. These measures will provide some degree of additional flood protection through St Asaph until longer term options have been evaluated and can be put in place. Appendix G provides information on the short term measures tested within the model and their predicted impact on flood risk through St Asaph.

5.7.2 Predicted Flood Depth and Extent for the 0.1% AEP Defended Event

The predicted flood depth and extent information for the 0.1% AEP defended event is shown in Figure 5-6, a large proportion of St Asaph is predicted to flood during this event. Flood depths of over 2m are predicted within Spring Gardens and The Roe. Flooding to the west of The Roe further away from the river is relatively shallow with the majority of the area flooded to depths <0.2m and limited areas flooded up to 0.5m. 851 properties are at risk in St Asaph during this event. The widespread deep flooding during the 0.1% AEP event means that there would be high hazard associated with this event; flood hazard is discussed further in Appendix E.

Figure 5-6 Predicted Flood Depth and Extent in St Asaph for the 0.1% AEP Design Event

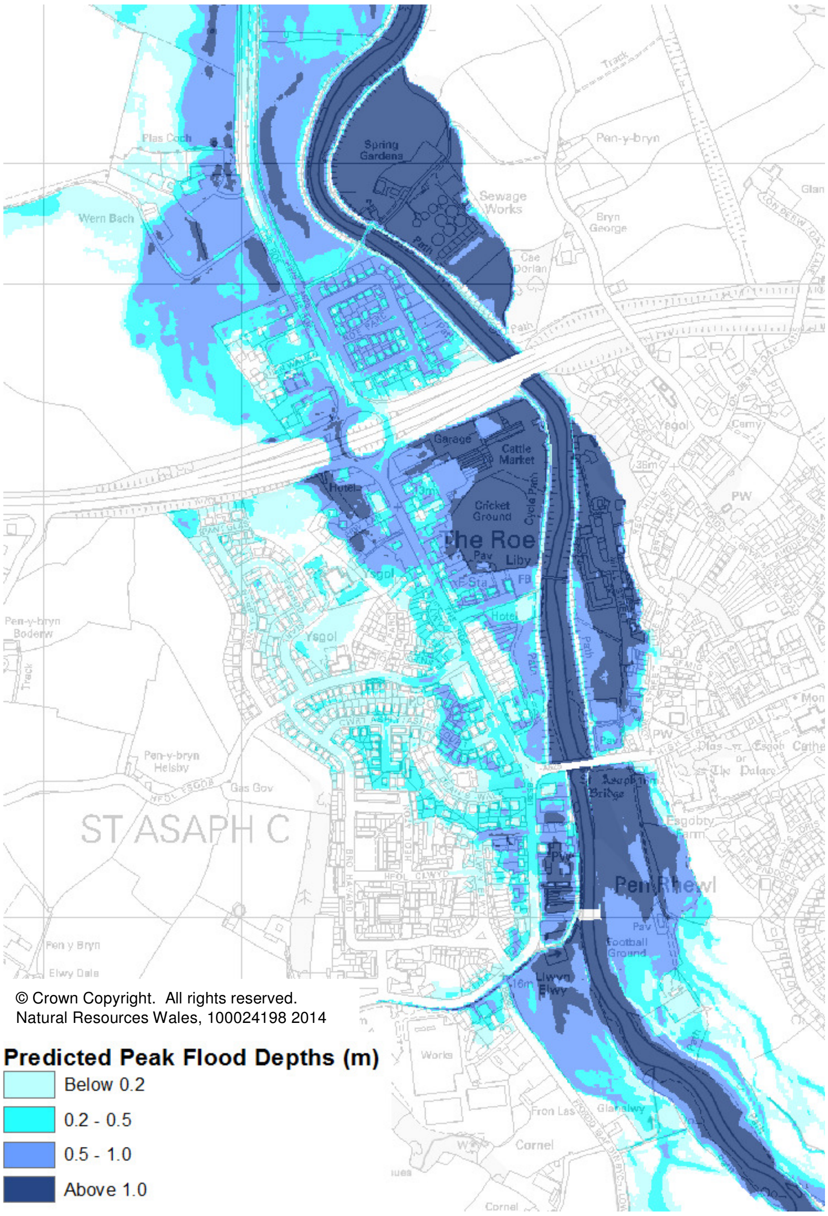


5.7.3 Impact of Climate Change

The 20% increase in flows used to represent the effects of climate change increases flood risk through St Asaph in the defended scenario compared to the 1% AEP event. The largest increase in flood risk is seen to the west of The Roe where a number of additional properties are predicted to flood compared to the 1% AEP event. Figure 5-7 shows the predicted flood depth and extent for the 1% plus climate change defended event.

An additional 404 properties in St Asaph are predicted to flood during the 1% AEP plus climate change event compared to the 1% AEP event with the total number of properties predicted to be affected in the town 800. The 1% AEP plus climate change event flood extent is larger than that predicted for the 0.5% AEP event, 548 properties are predicted as at risk during the 0.5% AEP event.

Figure 5-7 Predicted Flood Depth and Extent in St Asaph for the 1% AEP Event with Climate Change



5.7.4 Velocity Data

Predicted peak velocity data obtained from the 2D model is illustrated in Figures 5-8 and 5-9. Within St Asaph, for the 1% AEP defended event, velocities remain relatively low (<0.2m/s) across a large part of the floodplain. The highest velocities are predicted in the Roe Parc area, particularly along roads that act as flow paths.

During the 0.1% AEP defended event, higher velocities (0.8 - +1.5m/s) are experienced along roads and key flow routes. Particularly high velocities above 1m are experienced along the A525 upstream and downstream of the A55. In general, low velocities are experienced in both the 1% AEP and 0.1% AEP event at the Sewage Works and Spring Gardens caravan park, suggesting flood water ponds here as flow bypasses the meander.

Given the high velocities and depths predicted across the study area for both the 1% and 0.1% AEP events, flood hazard is likely to be high during an event in St Asaph. Hazard is predicted by the hydraulic model and this is discussed further in Appendix E.

Figure 5-8 Predicted Peak Velocity in St Asaph for the 1% AEP Defended Event

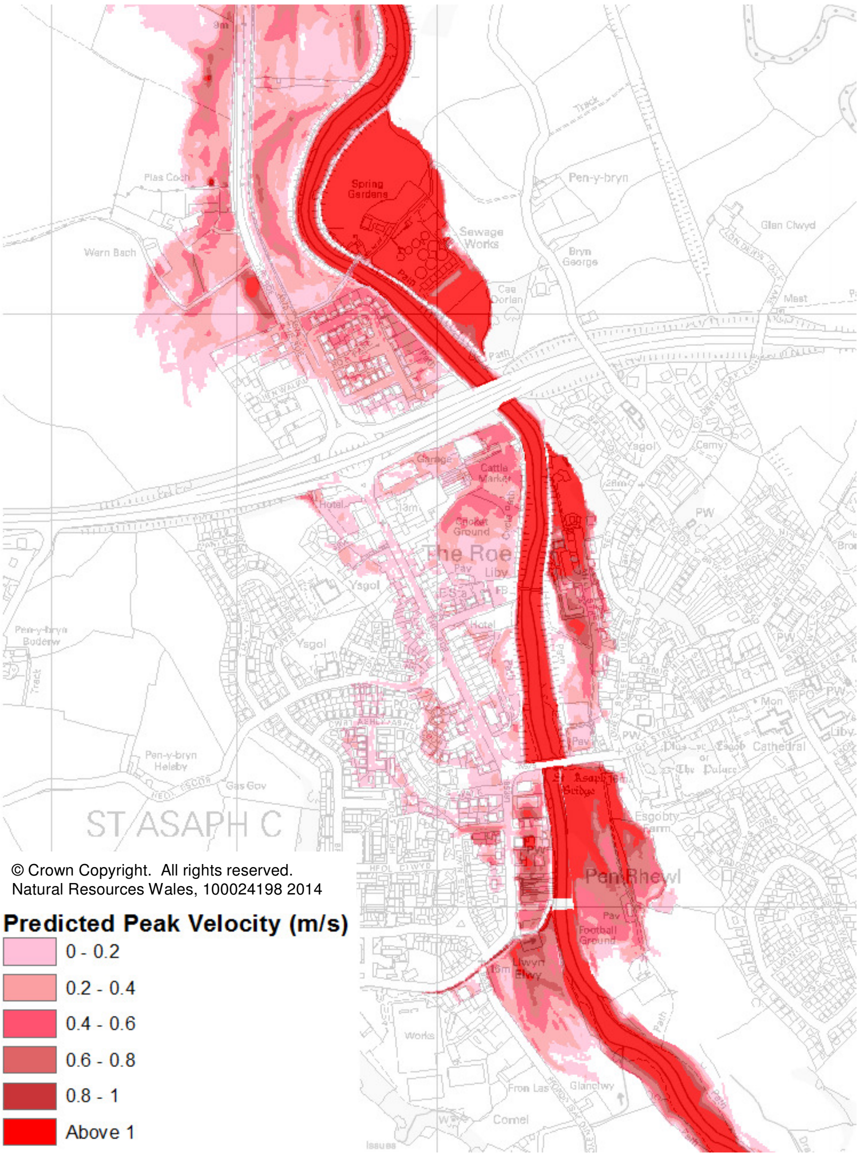
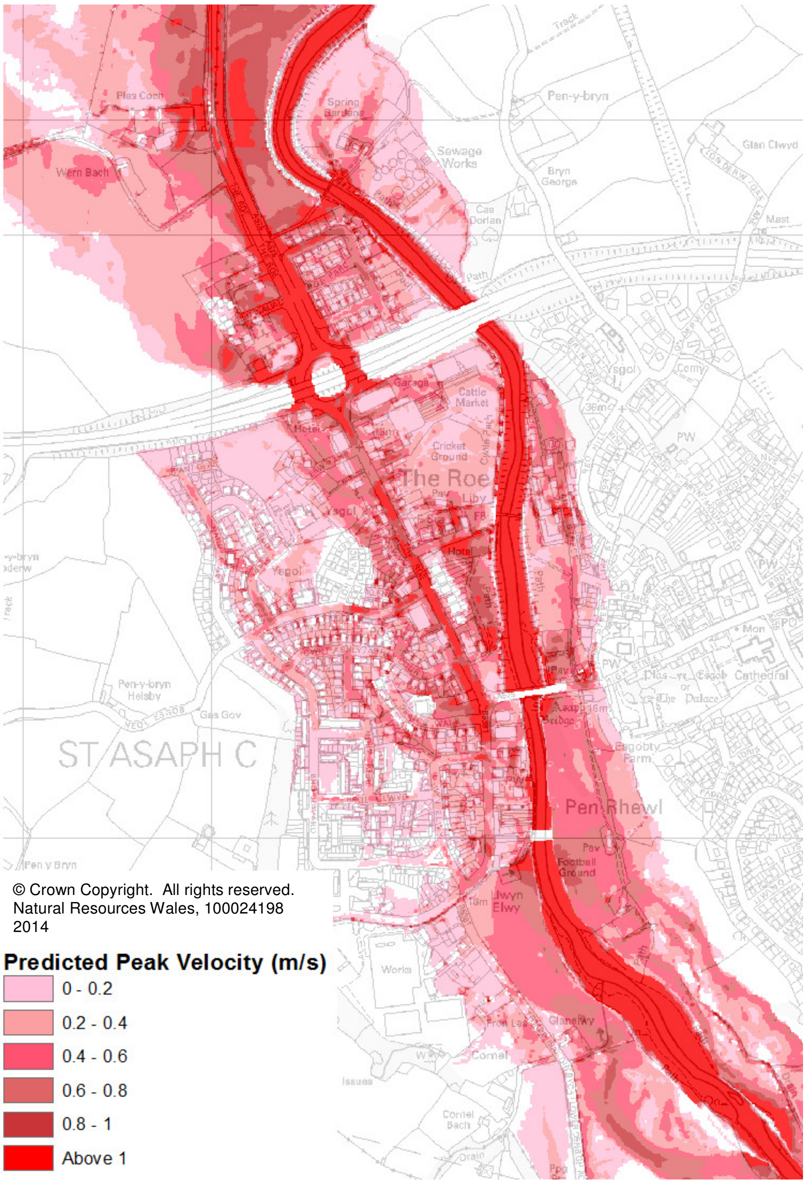


Figure 5-9 Predicted Peak Velocity in St Asaph for the 0.1% AEP Event



5.8 Undefended Scenario and Areas Benefiting from Defences

The undefended flood extent for the 1% AEP event and the subsequent Area Benefiting from Defence (ABD) layer produced for the study are shown in Figure 5-10 (located at the back of the report). These show that there is an increase in flood risk associated with removing the raised defences in the catchment. 438 properties are predicted to be at risk within St Asaph for the 1% AEP undefended event, compared to 396 properties during the 1% AEP defended event. The extent of flooding downstream of St Asaph is greatly increased without the raised defences along the Elwy in place, although there are currently few properties in this area. However, through St Asaph itself upstream of St Asaph Old Bridge, flood risk is reduced in the undefended scenario. This is because with the flood embankments downstream of the A55 removed, a large amount of water spills out of the Elwy channel onto the floodplain downstream of the A55 early on in the design run. This increases conveyance within the

Elwy channel and leads to a reduction in water levels upstream of the A55. It is not uncommon for undefended water levels to be less than those predicted for the defended event because water can come out of bank much earlier and reduce the volume of water within the channel during the undefended scenario.

Figure 5-10 Predicted Area Benefiting from Defences (located at the back of the report)

The Flood Zones developed for this study are larger than the existing ones produced by the previous Flood Map update by JBA in 2011. Flood Zone 3 (1% AEP event) is very similar upstream of St Asaph Old Bridge, it is slightly larger in The Roe area and significantly greater downstream of the A55 compared to the existing Flood Map. The revised Flood Zone 2 outline is similar to the existing throughout the study area with slight increases in various places such as in The Roe area.

Flood maps are included in Appendix D for the 1% and 0.1% AEP events defended and undefended extents. Flood extent, depth, velocity, water level and hazard information for all modelled events have been supplied as GIS deliverables with this report.

6. Impact of Spring Gardens Bridge

6.1 Overview

While the calibration process was being undertaken, the impact of Spring Gardens Bridge on flooding to St Asaph was tested using the model. During the November 2012 flood event, large amounts of debris accumulated at the bridge, particularly on the railings. The railings on the bridge were blocked approximately 300-400mm above the bridge deck level by debris. The bridge is shown in Figure 1-4 of this report.

6.2 Impact of Spring Gardens Bridge on flood risk to St Asaph

To test the impact of the bridge on flood risk to St Asaph, a version of the hydraulic model was configured with the bridge removed. The November 2012 event was then run through this version of the model and the results compared to those obtained using the model with the bridge included. The version of the model used to test the impact of removing Spring Gardens Bridge was not the final calibrated Elwy model as this test was undertaken during the calibration process. However, the version of the model used was very similar to the final calibrated model and represented the flooding that occurred during the November 2012 event well. The outcome of this test would therefore be very similar with the final calibrated model.

The effect of removing the bridge on water levels predicted by the model for the November 2012 event upstream and downstream of the A55 is shown in Figure 6-1. Peak water levels immediately upstream of the Spring Gardens Bridge are elevated by approximately 0.7m by the presence of the bridge. However this increase rapidly diminishes upstream so by the A55 Bridge the water level increase caused by the bridge has reduced to under 0.05m. Upstream of the A55 Bridge the difference diminishes further to essentially nothing.

Water levels downstream of the bridge are actually higher with the bridge removed as more water remains in the river channel and less has gone onto the floodplain.

Figure 6-1 Impact of removal of Spring Gardens Bridge on water levels

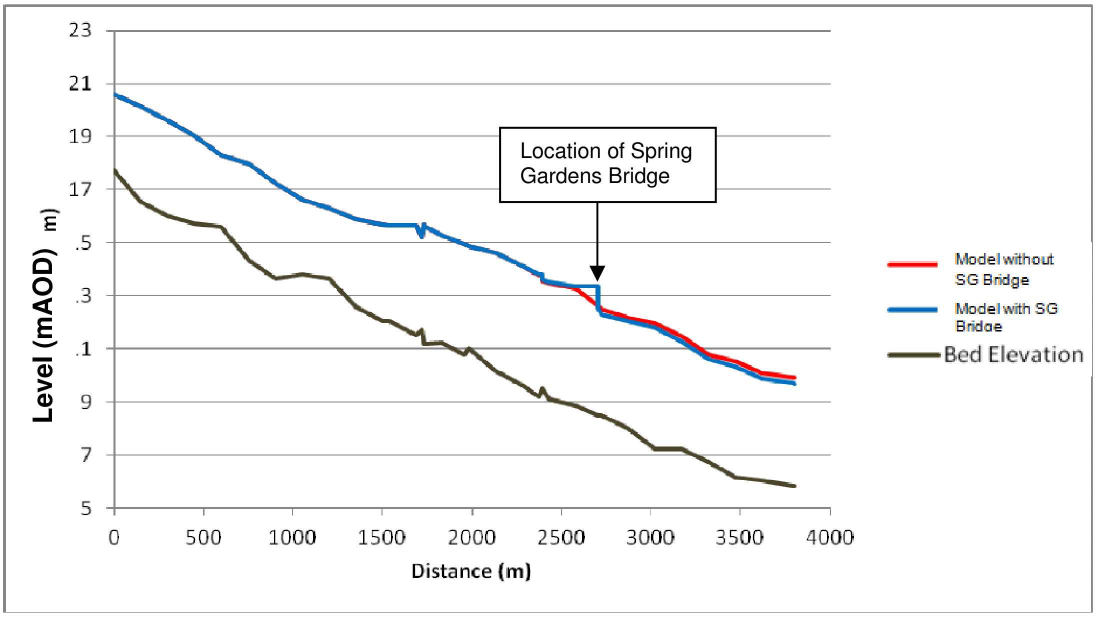
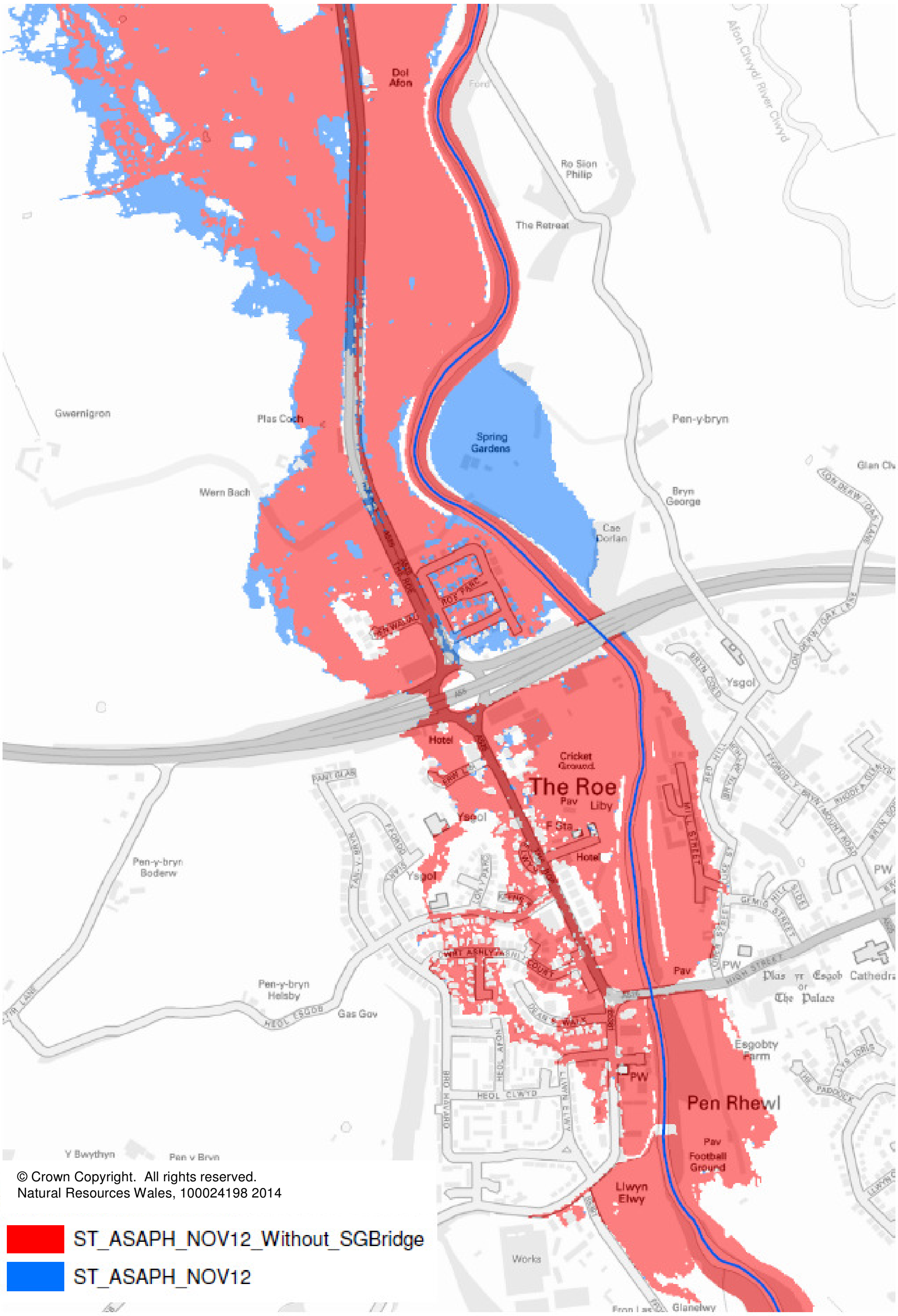


Figure 6-2 shows the difference in flood outlines produced for the November 2012 event with and without the Spring Gardens Bridge. The Roe Park estate is still predicted to flood with the bridge removed, although to a lesser depth. The Spring Gardens Holiday Park and Sewage Works are not predicted to flood without the bridge in place; whereas they are predicted to flood with the bridge in place in the calibrated model. Upstream of the A55 Bridge the flood extents and depths are very similar with and without the Spring Gardens Bridge in the model.

This assessment has shown that the Spring Gardens Bridge has a impact on flood risk to the area of St Asaph downstream of the A55 Bridge, notably Roe Parc and Spring Gardens Holiday Park. However the impact on flood risk upstream of the A55 Bridge is minimal.

The version of the model that this test was undertaken on has been calibrated to improve the representation of the November 2012 event. This was not the final version of the model but only minor amendments to this version were made to create the final calibrated model as presented in Section 4. Therefore, this test is deemed adequate to show the minimal impact on flood risk through St Asaph that removing the bridge would have. It is only the Spring Gardens area local to the bridge that is shown to have reduced flood risk without the structure in place.

Figure 6-2 Flood extents for November 2012 event with and without Spring Gardens Bridge



7. Conclusion

The study has further increased understanding of the flood risk to St Asaph in North Wales. Following the November 2012 flood event within the town, post event analysis has been undertaken and as a result the hydraulic model of the River Elwy through the town has been calibrated using available data for the event. The calibrated hydraulic model has been used to update the flood mapping deliverables for St Asaph.

Using the hydraulic model developed for the study, flood outlines have been developed for a range of defended and undefended events. The outputs from the study highlight that 236 properties are at risk in the 1% AEP defended event, increasing significantly to 691 in the 0.1% AEP event. Flooding to properties is predicted downstream of the A55 for all design events considered. Flooding to properties upstream of the A55 is predicted for events above and including the 1.33% AEP event. The undefended model runs show a large increase in flood extent but the increase in number of properties flooded compared to the defended model runs for a given return period event is not proportional. This is because the main additional flooding is predicted downstream of St Asaph towards the downstream extent of the model where there are few properties. There are 306 properties predicted at flood risk for the 1% AEP undefended event.

The model results also showed that once flow becomes out of bank, it largely remains out of bank and flows downstream along the floodplain towards the River Clwyd. The depth of flooding and velocities highlight a relatively low hazard during the 1% AEP defended event over parts of Roe Parc and at Spring Gardens Leisure Park and significant flood hazard during the 0.1% AEP defended event.

This study has used the latest data and information to update the flood mapping for St Asaph. It is recommended that a rating review at the Pont Y Gwyddel gauge should be undertaken in order to increase confidence in the flows associated with the higher return periods before detailed scheme options are evaluated. This may require some degree of re-calibration of the hydraulic model.