LANGHOLM
Flood Protection Scheme

Hydraulic Analysis Report

MAKING COMPLEX EASY

Dumfries & Galloway COUNCIL

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1 INTRODUCTION

1.1 BACKGROUND

Dumfries and Galloway Council commissioned RPS to undertake a flood risk assessment (FRA) of Langholm in 2011 to investigate the risk of fluvial flooding to the town. The assessment concluded that the only feasible option to mitigate the flood risk in Langholm during the high return periods was the provision of hard defences.

Dumfries and Galloway Council (DGC) have since developed and published the Solway Local Flood Risk Management Plan to comply with the Flood Risk Management (Scotland) Act 2009. This Plan identifies Langholm as a Potentially Vulnerable Area. To address the requirements of the Plan DGC have commissioned a study to produce an outline design of a flood protection scheme. DGC have appointed RPS to revise and update the original FRA hydrology and hydraulic model to inform the development of a scheme.

The hydraulic analysis for the Langholm Flood Protection Scheme (FPS) focuses on the main source of flood risk from the River Esk and its two significant tributaries - the Wauchope Water and Ewes Water. The River Esk and the Ewes Water have their confluence to the north of Langholm, and the Wauchope Water joining the main watercourse, from a south westerly direction, in the centre of the town. Figure 1.1 shows the location of Langholm and Figure 1.2 provides a plan of the study area.

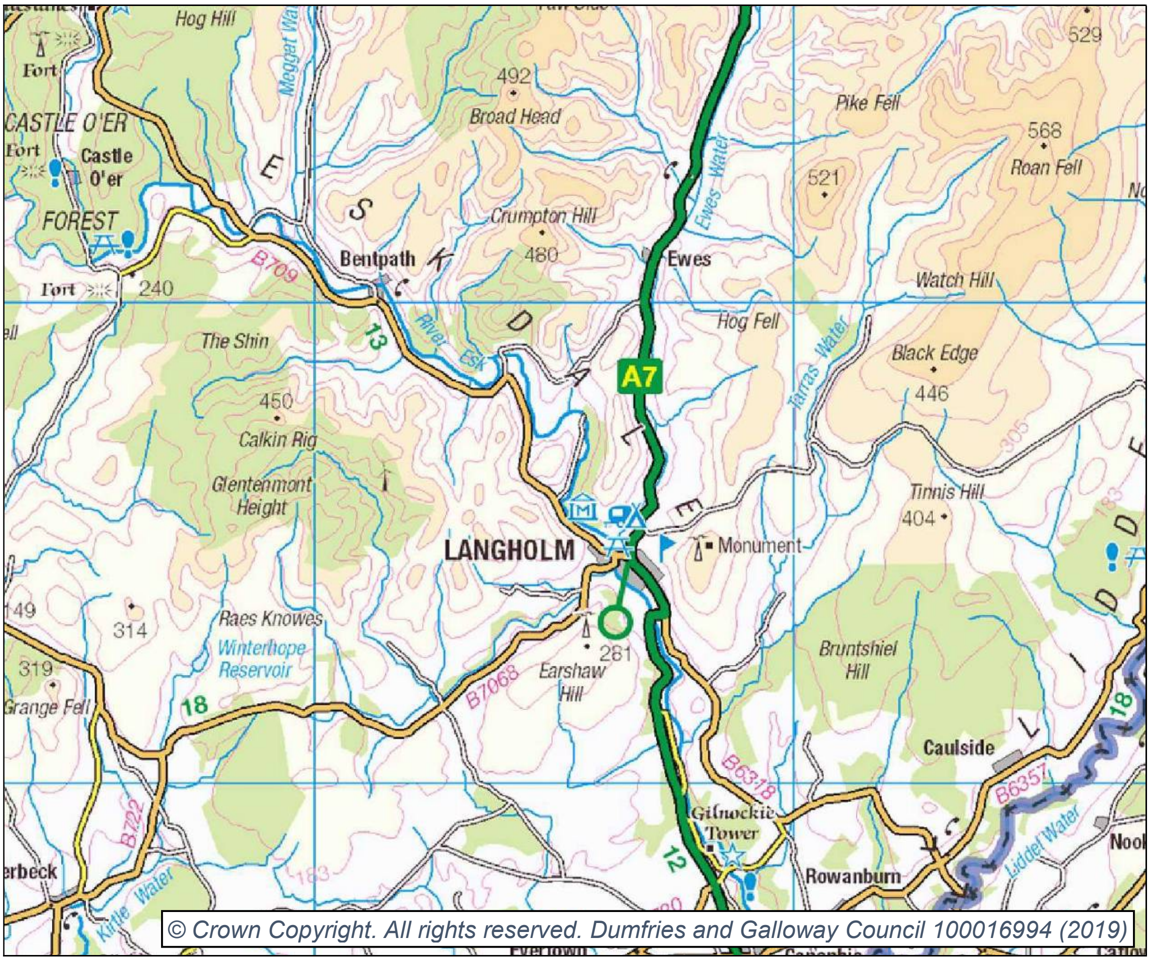

Figure 1.1 Location of Langholm

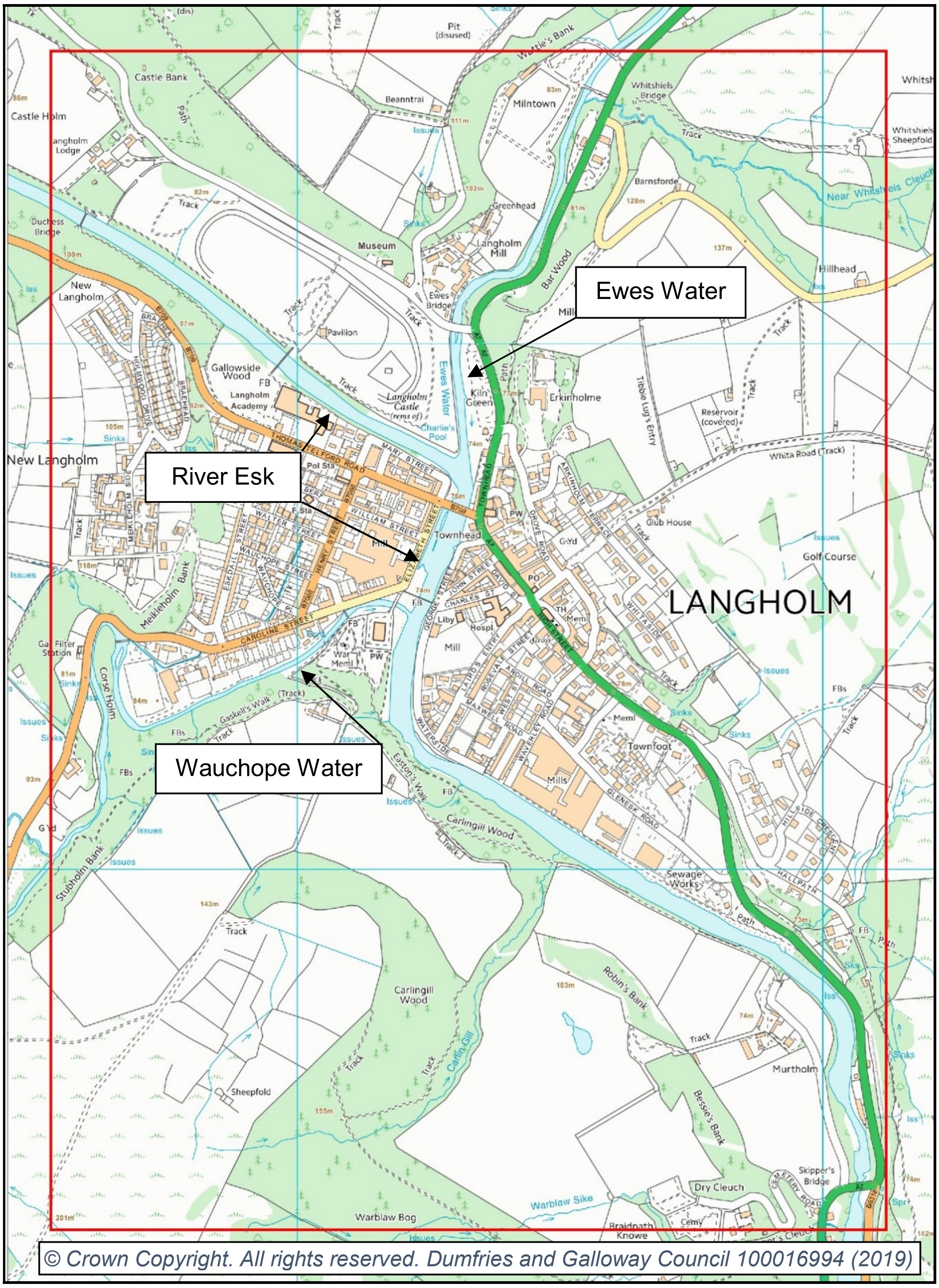

Figure 1.2 Study Area

1.2 OBJECTIVES OF THE STUDY

The aims of the study are summarised below:

- Hydrological assessment to include and update of the hydrology for the three watercourses and completion of hydrological analysis to determine the design flows at Langholm. Also to derive inflows for 50%, 20%, 10%, 3.33%, 2%, 1%, 0.5%, 0.1% and 0.5% plus climate change fluvial annual exceedance probabilities (AEP).
- Update the existing hydraulic model.
- Environmental considerations including completion of an environmental walk-over of the site, scoping of environmental impacts and completion of an environmental survey.
- Produce flood mapping for a number of design events - 50%, 20%, 10%, 3.33%, 2%, 1%, 0.5%, 0.1%, and 0.5% plus climate change fluvial AEPs.
- Develop options to manage flood risk and provide recommendations for the most sustainable option.

The purpose of this report is to provide details on the hydraulic analysis and flood mapping, with details of the work undertaken to fulfil the other objectives located in separate reports.

2 DATA COLLECTION

2.1 HISTORIC FLOOD EVENTS

2.1.1 Overview

As part of this study, RPS has reviewed historic flood records to fluvial and pluvial flooding in the Langholm area. Sources of information on events include internet searches, community magazines, consideration of SEPA hydrometric data, a review of the Chronology of British Hydrological Events and information provided by Dumfries and Galloway Council. Further information on the calibration/validation data recorded in relation to these events is provided within the hydraulic modelling chapter.

The most recent notable flood event for which records can be found in relation to the Langholm area occurred in December 2015 (Storm Desmond), when the River Esk at Langholm burst its banks and homes within George Street in the town were evacuated by the Police. A summary of the historic event records is shown in Table 2.1.

Table 2.1 - Summary of historic flood records in the Langholm Area

Date	Scale or Magnitude	Source
1990	A7 road, local businesses and properties were flooded.	SEPA
Aug 1994	Surface water flooding contributed to disruption along A7 in Langholm.	SEPA
Oct 2005	After heavy rainfall a landslide caused the B709 road between Eskdalemuir and Langholm to be closed.	BBC News/SEPA
Nov 2009	Record rainfall (an expected maximum of 75mm) prompted rivers to overflow, resulting in numerous road closures.	BBC News
Aug 2012	A number of small watercourses in Langholm flooded in 2012 affecting private properties and the A7 Trunk Road	SEPA / Dumfries and Galloway Council
Dec 2015	The River Esk at Langholm burst its banks and homes within George Street in the town were evacuated by the Police and a care centre was established	ITV News / Dumfries and Galloway Council

SEPA hydrometric was consulted with regards to the available hydrometric data within the River Esk catchment. The gauge Esk at Canonbie was identified as a suitable flow gauge. The Hydrological

Analysis can be seen for more detail on this. The five largest events recorded at the Canonbie gauge station are presented in Table 2.2.

Table 2.2 The five largest AMAX Events recorded at Canonbie

Hydrological Year	Flow (m^3/s)
1967	570.798
2005	567.346
1977	548.934
1964	538.677
2015	522.225

Of the highest flows at Canonbie gauging station, there are a number of records for which no information on flooding or near-flooding can be found at Langholm. Most notably is the highest flow during October 1967. One of the reasons could be that the Canonbie gauging station is located 12.5km downstream of Langholm with one additional (major) tributary confluence with the River Esk downstream of Langholm. Therefore river flows at Langholm could have been lower than some other events for which a flood incident was recorded at the flow gauge.

SEPA also provided data from the level gauge at the Thomas Telford Bridge. This gauge was installed in 2015 to inform the SEPA Flood Early Warning System.

2.1.2 20th Century Flood Events

Flooding occurred in Langholm on 31st October 1977. It was the most significant event experienced in Langholm and the third largest on record at the Canonbie gauging station 12km downstream of Langholm. It was before the level gauge was installed at the Thomas Telford Bridge, therefore there is no recorded level data in Langholm.

The Esk overtopped its banks through the town and there are a number of photos which can be seen in Appendix A. The photos are not timestamped and the extent of the flooding is not known.

2.1.3 5th December 2015 Flood Event

Storm Desmond brought strong winds and heavy rain to many parts of Scotland on the 5th December 2015. There was also widespread travel disruption with a number of roads around Langholm closed due to landslides. Weather warnings for wind and rain across the South West of Scotland were issued by the Met Office.

Dumfries and Galloway Council deployed the Flood Pod to Langholm with officers from the Flood Risk Management Team assisting with the installation of property level protection. Homes in George Street were evacuated however there was no significant internal property flooding reported. A basement in Caroline Street and one in Laird’s Entry did flood and the Fire and Rescue Service pumped them out.

This event was recorded as the fifth largest at the Canonbie gauging station. The peak at the Canonbie gauging station was recorded at 6.45pm. The level gauge in Langholm recorded a peak level of 74.22mAOD at 6.15pm. A direct correlation cannot be made between the flow gauge and the flooding in Langholm as the gauge is 12km downstream of Langholm however the level gauge was used to compare recorded and modelled peak water levels. A number of timestamped photos were taken throughout the day. Figure 2.1 to Figure 2.3 show the water level in the River Esk in the town and the extent of flooding at Waterside.

Figure 2.1 Photo taken from Thomas Telford Bridge (at 2.10pm) showing flooding at the confluence on 05/12/15

Figure 2.2 Photo taken at Waterside (14.47pm) looking downstream on 05/12/15

Figure 2.3 Photo taken from George Street (16.37pm) looking to the river steps on 05/12/15

2.2 EXISTING INFORMATION

2.2.1 Surface and Terrain Model

LiDAR was downloaded from the Scottish Remote Sensing Portal. The Scottish Public Sector LiDAR (Phase I) digital terrain model (DTM) dataset was used. This was collected between March 2011 and May 2012 and has a minimum point density of 1 point/sqm. Tile NY38 was used which covers the entire study area.

2.2.2 Langholm Flood Risk Assessment

RPS produced a Flood Risk Assessment for Langholm; the final revision was issued in April 2017. The report describes the hydrological and hydraulic analysis that was undertaken. RPS considered possible flood management options for Langholm and concluded that hard defences were the only feasible option. Hard defence schemes were developed for three standards of protection; 0.5%, 2% and 4% AEP. A cost benefit analysis was carried out on three schemes and the option that produced the highest cost/benefit ratio was the 0.5% AEP scheme. As part of the study RPS also considered the development of a flood warning scheme. Resilience improvements were also highlighted.

RPS sub-contracted cbec to undertake an assessment of impacts to water levels and velocities from the removal of gravel bars in the study area. The assessment concluded that there would be minimal flood risk benefit gained by the removal of the existing gravel bars which are likely to reform due to the sediment from the Ewes Water.

2.2.3 Existing Hydraulic Model

RPS constructed a 1D-2D InfoWorks ICM hydraulic model for the original FRA which was used to assess the fluvial flood risk to Langholm. This model was reviewed to ascertain if it could be wholly or partially used as a basis for the hydraulic modelling to be undertaken in this study. The existing model was deemed to be adequate to use as a base however there were uncertainties over the downstream boundary. Additional survey information was required to extend the downstream boundary of the model.

2.3 TOPOGRAPHICAL SURVEYS

The existing Langholm model was built using channel data surveyed in 2011. A review of the existing model identified that additional survey data was required to develop the model for this study. To allow the model to replicate the flooding mechanisms within Langholm the downstream boundary should be a sufficient distance downstream of the town. Therefore the downstream boundary was extended approximately 600m downstream of Skipper's Bridge, which required additional channel cross sections. The footbridge on the Wauchope Water was also surveyed as it had the potential to impact the flow. A number of channel cross sections were also surveyed on the River Esk between the Thomas Telford Bridge and the Footbridge. This was to allow a comparison of the gravel bars along the River Esk and to highlight any change in channel profile from 2011.

Following consultation with Dumfries and Galloway Council RPS procured the additional survey information. The surveys were undertaken by Six West (September 2018) and Aspect (February 2019) respectively and included the following information:

Six West (Sept 18):

- Topographic river cross-section survey of 7no. locations on the River Esk (Figure 2.4)
- Elevation/structure survey of the footbridge at Caroline Street on the Wauchope Water (Figure 2.4)

Aspect (Feb 19):

- Topographic river cross-section survey of 17no. locations on the River Esk (Figure 2.5)
- Elevation/structure survey of the Skipper Bridge on the River Esk, downstream of Langholm (Figure 2.5)

The survey information is included in Appendix B.

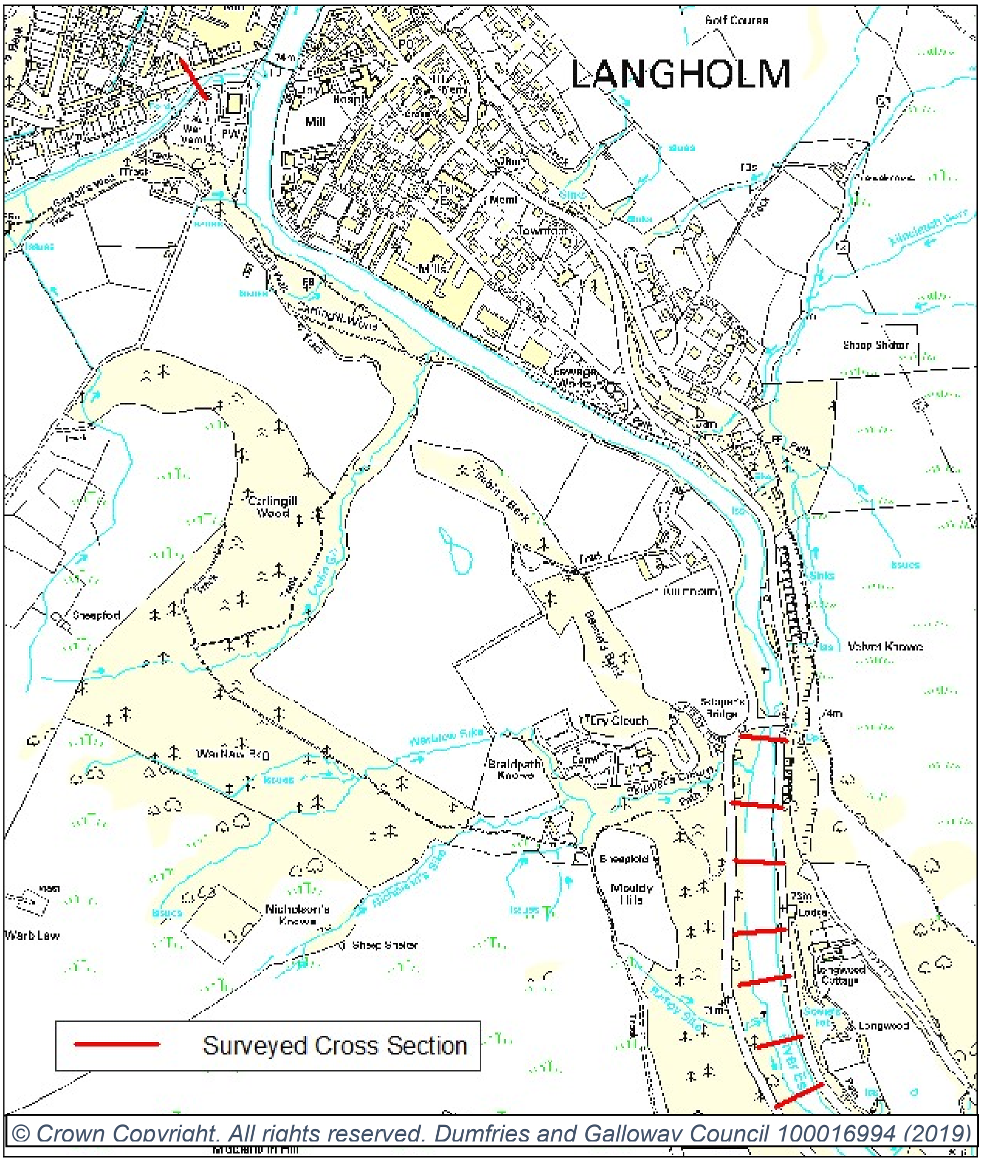

Figure 2.4: Location of Sept18 Survey Cross Sections

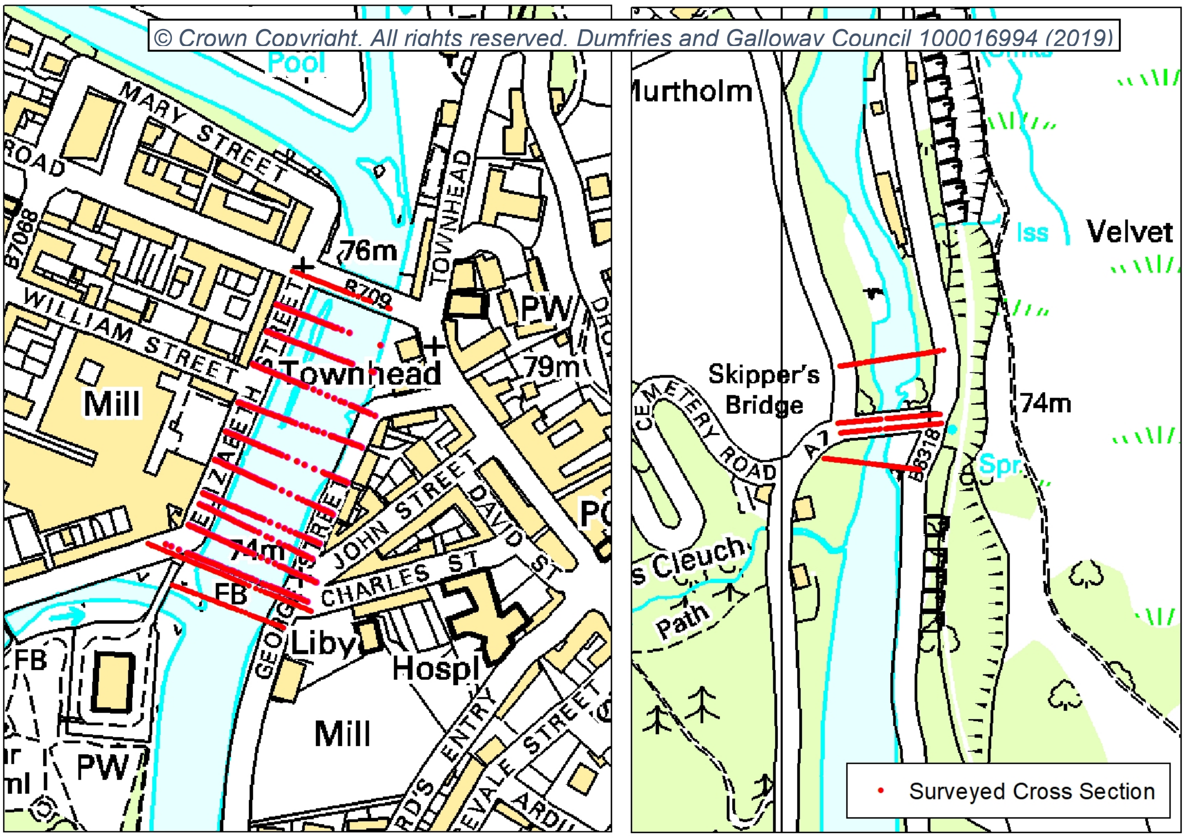

Figure 2.5: Extent of the Topographical Survey undertaken during February 2019

2.4 WALKOVER SURVEY

RPS conducted a walkover survey in conjunction with Dumfries and Galloway Council on the 5th September 2018. Completion of the walkover survey allowed RPS to review the area in the context of historical flooding mechanisms and collect information to facilitate the hydraulic modelling.

3 HYDRAULIC MODELLING AND MAPPING

3.1 MODEL CONCEPTUALISATION

Following a review of the existing model RPS considered it to be adequate to be used as a basis for the hydraulic modelling to be undertaken in this study. However due to the uncertainties of the downstream boundary additional survey information was required to extend the downstream extent.

RPS used InfoWorks ICM to undertake the numerical modelling of the River Esk, Ewes Water and Wauchope Water. InfoWorks ICM is an integrated hydrological and hydraulic modelling package developed by Innovyze. InfoWorks ICM includes full solution modelling of open channels, floodplains, embankments and hydraulic structures. Additionally, the 2-dimensional areas within InfoWorks ICM are modelled through a triangular flexible mesh which allows for high levels of detail in specific areas (for example at river banks and around buildings) and a broader approach in other areas (for example open floodplains). This can give better results compared with a rectangular grid approach utilised in some other modelling packages.

The location of the model boundaries were selected at sufficient distances both upstream and downstream of Langholm to allow the model to replicate the flooding mechanisms within the town. The upstream extents were not changed from the original model. The downstream boundary was extended approximately 600m downstream beyond the original. The extent of the modelled watercourses are shown in Figure 3.1 and defined as:

- Wauchope Water – Springhill through to the Esk
- Ewes Water - Highmill Bridge to the Esk
- River Esk- Duchess Bridge through to 600m downstream of Skipper's Bridge

Each river is modelled as 1D-2D, with the river channel modelled as 1D and its floodplain as 2D. The 1D channel model is connected to the 2D flood plain by banklines. The banklines are created using the levels at either end of the river cross sections. Levels between cross sections are either interpolated from the cross sections or created from the DTM. 450m of the upstream extent of the Ewes Water is 1D only as there is no out of bank flooding here.

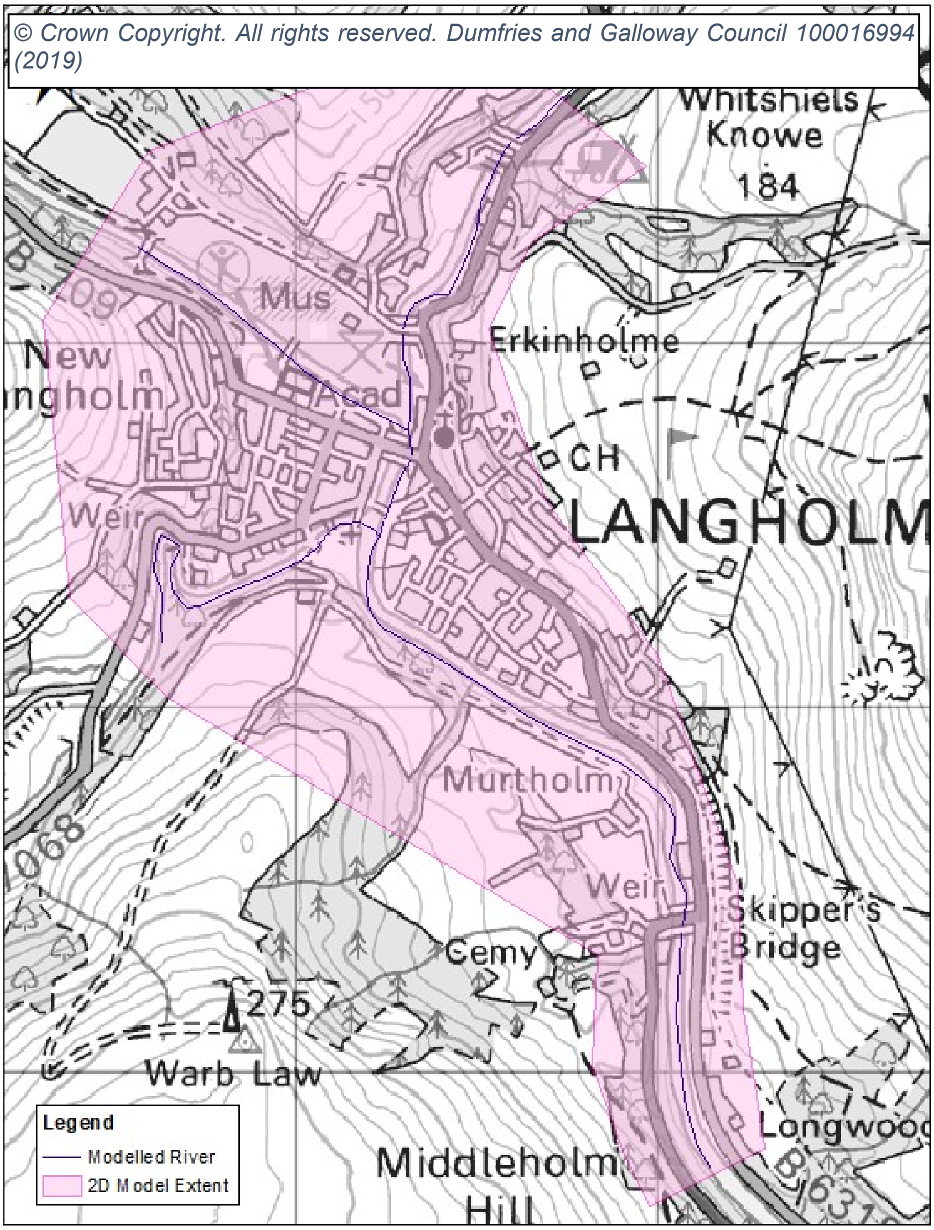

Figure 3.1 Extent of Hydraulic Model

3.2 HYDRAULIC MODEL CONSTRUCTION

3.2.1 1D Model Domain

The in-bank portion of the river model (1D) was created using the cross sections from the original model and cross section survey information from the September 2018 survey. There were 7 no. bridges in the original model; the footbridge on the Wauchope Water was built into the model using the September 2018 survey. Details of all the bridges can be found in Appendix C. The existing river walls along the River Esk on Elizabeth and George Streets have not been included in the model as they are not formal flood defences and therefore cannot be relied upon during an event as they have not been designed for that purpose.

3.2.1.1 Channel Profile Comparison

The watercourses influencing the study area are known to be active. Sediment is transported from the Ewes Water and deposited along the River Esk, creating gravel bars from the Thomas Telford Bridge to the Footbridge. A comparison was carried out between the survey data from the existing model, surveyed in 2011 and the February 2019 Aspect survey. It was identified that there was no significant change in bed levels between the two surveys, therefore confirming that the survey data used is representative of the existing situation and appropriate to use.

3.2.2 2D Model Domain

The LiDAR data was used to model the floodplain. For an accurate assessment of 2D flow paths, the bare earth DTM data was used within the modelling package to generate the computational mesh; the mesh was then augmented to include buildings which will affect flow paths. Building footprints were defined by a GIS shape file which was extracted from the OS Master Map geodatabase supplied by Dumfries and Galloway Council. The building footprints were then imported into the model as porous polygons and designated as having a porosity of 0.01 to enable buildings to store some water. The building footprints were also imported to the model as mesh zones with the *Ground level modification* set to +300mm. Boundary walls were incorporated into the 2D model domain where they may have a substantial impact on flowpaths. All flood receptors were contained within the 2D modelling domain.

The maximum mesh size used in the model was 25m^2 (generally this gives an element size of 15m^2) which was considered sufficient for modelling the larger open spaces. In areas where there are known flowpaths and historic flooding has been reported, the mesh was refined with a maximum mesh size of 5m^2 (generally giving an element size of 3m^2). Terrain sensitive meshing was used which increases the resolution of the mesh in areas that have a large variation in height.

3.2.3 Model Boundaries

Upstream boundary conditions and input hydrographs for the model were provided from the hydrological analysis and have been introduced directly to the 1D domain as point or lateral inflows. The details of the hydrological analysis are available in a separate report – IBE1511Rp04. An input hydrograph was applied as a point flow at each upstream boundary (for the River Esk, Wauchope Water and Ewes Water). Lateral inflows were also applied along the length of each river. The lateral inflows were disaggregated between hydrology nodes and distributed pro-rata, based on length, and applied to each link (river reach) along the length of the river.

Downstream boundary conditions for the River Esk were defined by an outfall node located at a sufficient distance downstream of Langholm thereby ensuring that any backwater effect was accounted for in the model. The downstream boundary conditions for the Wauchope Water and Ewes Water were defined by the River Esk at their confluence. All watercourses within each simulation were modelled with the same return period. For example, in the 50% AEP simulation, a 50% AEP event was applied to all the watercourses. Therefore the downstream boundaries for the Wauchope Water and Ewes Water were the level in the River Esk during a 50% AEP (1 in 2 year return period) event. The modelled flows from the design events are compared with the estimated flow at each Hydrological Assessment Point (HAP) in Table 3.2.

3.2.4 Model Roughness

The roughness values were determined using the tables from Chow (1959) and based on information collected during the walkover survey in September 2018 and photographs provided along with the survey information. Within the 1D domain the in-bank roughness was given a Manning's n value of between 0.040 – 0.080. These figures were employed as the reaches vary from clean, winding watercourses to active mountainous watercourses with cobble beds and large boulders.

The out-of-bank 1D roughness varies from a minimum of 0.04 to a maximum of 0.08 as the banks vary from scattered brush to medium/dense brush. The 2D model domain was split into different land uses based on the Ordinance Survey MasterMap topography layer. Roughness values were assigned to the different land classes as per Table 3.1.

Table 3.1 Land Class Roughness Values

Class	Manning's n
General Surface	0.040
Glasshouse	1.000
Inland Water	0.030
Landform	0.035
Natural Environment	0.100
Path	0.016
Rail	0.020
Road Or Track	0.014
Roadside	0.015
Tidal Water	0.020
Unclassified	0.050
Building	1.000
Rough Grassland	0.035
Natural Environment Scrub	0.043
Non-coniferous Trees	0.05
Non-coniferous Trees (Scattered),Rough Grassland	0.055
Natural Environment Coniferous Trees	0.08
Structure_	0.1

3.2.5 Other Model Information

The selection of the timestep has been set at 1 second to ensure model convergence. Version 8.5 of the ICM software has been used for the model. Further details on model construction can be found within the Model Log in Appendix D.

3.3 MODEL CALIBRATION AND VERIFICATION

The computational river model was calibrated by the undertaking the tasks below. Further details are provided in 3.3.1 to Section 3.3.2.

- Comparison of modelled and design flows;
- Comparing recorded and predicted water levels at a SEPA level gauge located just downstream of the Thomas Telford Bridge, comparing flood extents with field observations. Historical data including photographs and recorded flood data was used, where available (as outlined in Section 2.1);

Model calibration for Langholm was an iterative process. In order to ensure the model was calibrated satisfactorily, a series of changes to the channel Manning's roughness were made. All model parameters used in the Langholm model were within acceptable limits.

3.3.1 Comparison of hydrological flow estimates and modelled flows

Table 3.2 provides a comparison between the hydrological flow estimates (as detailed in the Hydrological Analysis IBE1511/Rp04) and those extracted from the model at the HAP check point locations (Figure 3.2) to determine if the model is well anchored to the hydrological estimates (i.e. that there is a good correlation between modelled flows and hydrological flow estimates at each HAP). The comparisons indicate that the model is well anchored to the hydrological estimates as there is a very good correlation during the high frequency events where little flow is lost to overland flow.

At HAP06, the modelled figures take into account both the 1D and 2D flow at this point. At HAP06 there is a very good correlation (1% difference) across all return periods.

At HAP07, which is located at the downstream extent of the model all of the flow is within the 1D. There is a very good correlation (maximum 1% difference) across all return periods at this point.

At HAP03, the correlation is very good during the high frequency events where little flow is lost to overland flow. However, the modelled figures only show the 1D flows at this point as the 2D flow cannot be accurately separated between the River Esk and the Ewes Water. Divergence of model flows from the hydrological estimates during the medium and low frequency events can be attributed to the loss of flow from the watercourse to the floodplain.

At HAP05 the correlation is good during the high frequency events. Divergence of the modelled flows from the hydrological estimates during the medium and low frequency events can be attributed to the loss of flow from the watercourse to the floodplain between the confluence of the Wauchope Water and the River Esk where the flow cannot be accurately separated. The model is considered to be providing a good estimation of the flow continuity along the modelled reaches.

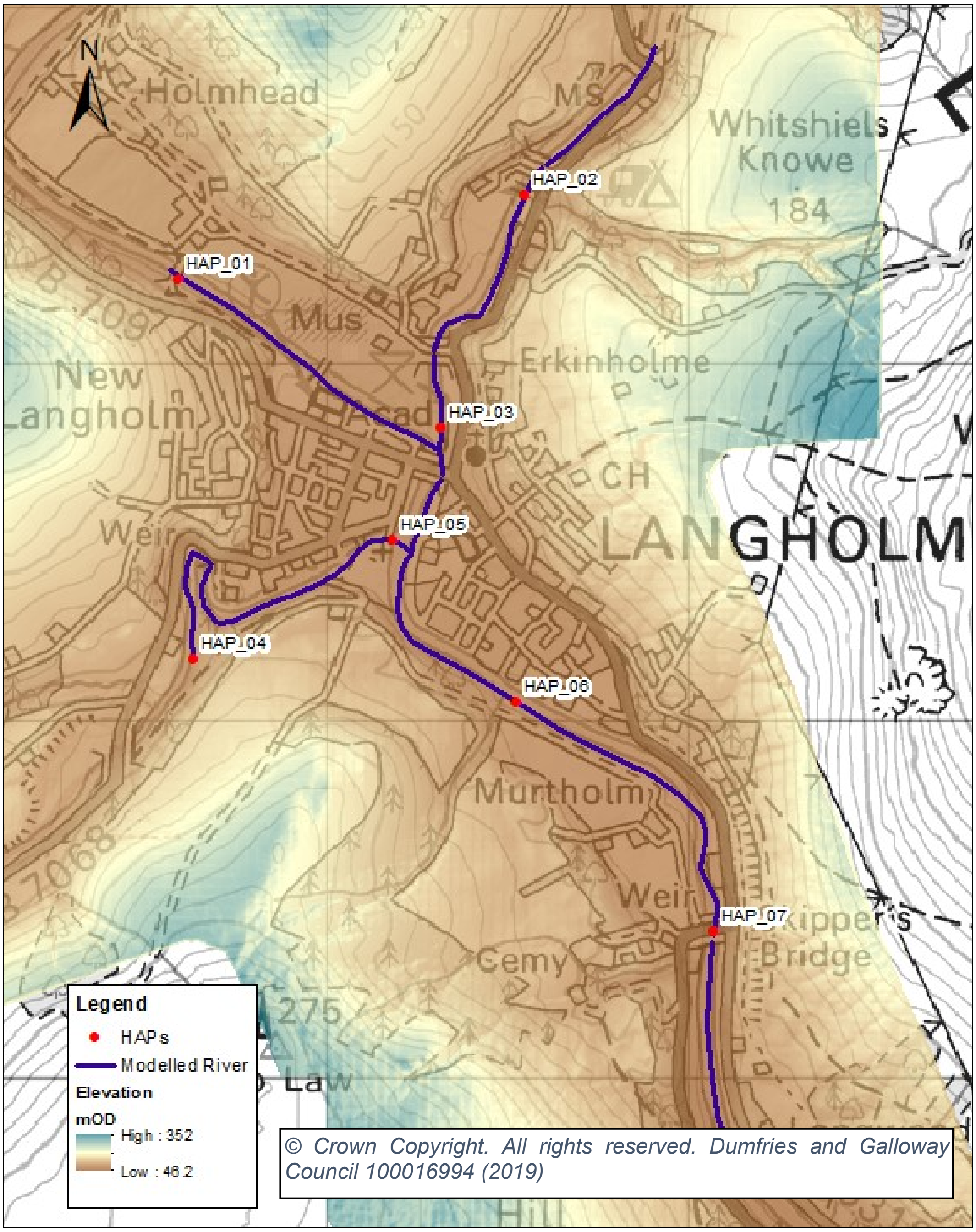

Figure 3.2 Location of HAP's

Table 3.2 Peak Flow Comparison

HAP Check Point (Sum of Inflows)		HAP03	HAP05	HAP06	HAP07
Corresponding Model Section		EW_1347 (1D only)	WW_BR_US (1D only)	RE_1897 (1D & 2D)	RE_2842_US (1D only)
2yr (m^3/s)	Calculated	68	46	301	302
	Model Flow	64	45	300	301
	% Difference	5%	1%	0%	0%
5yr (m^3/s)	Calculated	89	60	386	388
	Modelled	82	60	386	386
	% Difference	7%	0%	0%	0%
10yr (m^3/s)	Calculated	103	71	443	444
	Modelled	94	69	441	441
	% Difference	8%	3%	0%	1%
30yr (m^3/s)	Calculated	124	89	529	531
	Modelled	113	83	529	527
	% Difference	9%	7%	0%	1%
50yr (m^3/s)	Calculated	134	99	568	571
	Modelled	123	88	571	567
	% Difference	8%	11%	0%	1%
100yr (m^3/s)	Calculated	148	114	623	625
	Modelled	134	96	623	618
	% Difference	9%	16%	0%	1%
200yr (m^3/s)	Calculated	162	131	678	681
	Modelled	144	103	684	676
	% Difference	11%	21%	-1%	1%
1000yr (m^3/s)	Calculated	194	180	812	814
	Modelled	172	128	823	808
	% Difference	11%	29%	-1%	1%

3.3.2 Key Historical Flood Events

Of the highest flows at Canonbie gauging station, there are a number of records for which no information on flooding or near-flooding can be found at Langholm. One of the reasons could be that the Canonbie gauging station is located 12.5km downstream of Langholm with one additional, major tributary confluence with the River Esk downstream of Langholm. Therefore river flows at Langholm could have been lower than some other events for which a flood incident was reported.

The two largest events to impact Langholm were December 2015 and October 1977. These were estimated as a 1 in 12 year and 1 in 21 year return period respectively, see the Hydrology Analysis IBE1511/Rp04 for further detail. The model was run to simulate these events in order to compare predicted flood extents with recorded data available and field observations from these events. The modelled extents in the area were seen to generally reproduce the observed flood extents in Langholm for these events as shown below.

3.3.2.1 Storm Desmond 5th December 2015

The most recent significant flood event in Langholm occurred on 5th December 2015. This event is the fifth largest on record at the Canonbie gauging station. The River Esk overtopped its banks, and homes in George Street were evacuated. A basement in Caroline Street and one in Laird's Entry were flooded, the Fire and Rescue Service pumped them out.

SEPA have a level gauge just downstream of the Thomas Telford Bridge which has been used to calibrate the model. The extent of the flooding was not recorded and there are no recorded flood markers from this event. A number of timestamped photos were taken and these have been used to support the calibration. The flow gauge is a significant distance downstream from Langholm, therefore a direct correlation cannot be made between the flow gauge and the flooding in Langholm; neither in regard to the timing of the peak nor with the volumes between the two.

Through the hydrological analysis Storm Desmond has been calculated as a 1 in 12 year return period at the Canonbie gauge. An inflow file was set up for the 1 in 12 year estimated flows in all three watercourses based on the design hydrograph which has been calculated in the hydrological analysis. The model was run with this inflow file and the peak modelled water level downstream of the Thomas Telford Bridge was compared to the peak level recorded for this event. The modelled flood extents were then compared to the photos taken during the event. See the Model Log for further detail on the model construction.

The peak level recorded was at 18.15 on 05/12/15 was 2.89m. With a gauge datum of 71.33mAOD this gives a peak recorded water level as 74.22mAOD. The maximum water level at the cross section downstream of the Thomas Telford Bridge (RE_1017) exported from the model is 74.479m, a level difference of 259mm. Given that this model is to be used to develop an outline Scheme this accuracy is adequate.

There were a number of photos taken throughout the day timestamped from 13.37 – 17.52. The peak at the level gauge at Thomas Telford Bridge was at approx. 18.15. The photos and the simulated results at the equivalent times were compared:

- Figure 3.3: The photograph shows flooding between the confluence of the River Esk and the Ewes Water, the simulated extent from the equivalent time shows a similar extent.

- Figure 3.4: The photograph shows flooding from the River Esk downstream of Waterside; the simulated extent from the equivalent time shows a similar extent.

Figure 3.3 Left: Photo taken at 14.10 from Thomas Telford Bridge in Langholm on 05/12/15 Right: Model output at corresponding time superimposed onto Google Earth

Figure 3.4 Left: Photo taken at 17.12 at Waterside in Langholm on 05/12/15 Right: Model output at corresponding time superimposed onto Google Earth

From the information available, the source of the flooding to the basements in Caroline Street and Laird’s Entry is unclear. It is possible that this has been caused by surface water flooding, drainage systems being overwhelmed or via groundwater through the basement walls. There are no reports or evidence of ground level flooding at either location, which is supported by the 2015 flood extent map.

The simulated flood extent for the 2015 event can be seen in Appendix E. Based on the evidence available it is considered that there is a good correlation between the modelled flood extent and the actual flood extent for the 2015 event.

3.3.2.2 31st October 1977

The most significant flood event recorded in Langholm occurred on 31st October 1977. This event is the third largest on record at the Canonbie gauging station 12km downstream of Langholm. The River Esk overtopped its banks.

The SEPA level gauge started recording data in June 2015; therefore there is no recorded level data at Thomas Telford Bridge for this event. The extent of the flooding was not recorded and there are no recorded flood markers from this event. A number of photos were taken however they are not timestamped. Therefore, as the photos carry significant uncertainty, they will be used more as a guide than calibration data. The photos can be seen in Appendix A.

Using the topographic survey and the photos the water level is estimated to be approximately 74.291m at the steps on George Street and 74.420m upstream of the footbridge. Note the photos are believed to have been taken some time after peak river levels had been reached.

Figure 3.5 Photos taken looking at the steps on George Street and looking downstream from George Street on 31/10/77

Through the hydrological analysis this event has been calculated as a 1 in 21 year return period at the Canonbie gauge. An inflow file was set up for the 1 in 21 year estimated flows in all three watercourses based on the design hydrograph which has been calculated in the hydrological analysis. The model was run with this inflow file and the modelled extents and water extents in the area were compared to the photos.

The maximum simulated water level at the steps on George Street (Section RE_1085) is 74.594m and upstream of the footbridge (Section RE_1133) is 74.527m.

The photos and the simulated results were compared:

- Figure 3.6: The photograph shows flooding between the confluence of the River Esk and the Ewes Water, the simulated extent from the equivalent time shows a similar extent.

- Figure 3.7: The photograph shows the water level in the River Esk along George Street, with the water level above the top step and overtopping the river wall at the foot bridge. The equivalent levels extracted from the model give an approximate difference of 303mm and 107mm respectively. As both these water levels are recorded during the peak, the difference between the levels estimated from the 1977 photographs, (after the peak) and the modelled level (during the peak), is considered acceptable.

Figure 3.6 Looking upstream from Thomas Telford Bridge. Left: Photo taken on 31/10/77 Right: 1 in 21 year model output superimposed onto Google Earth

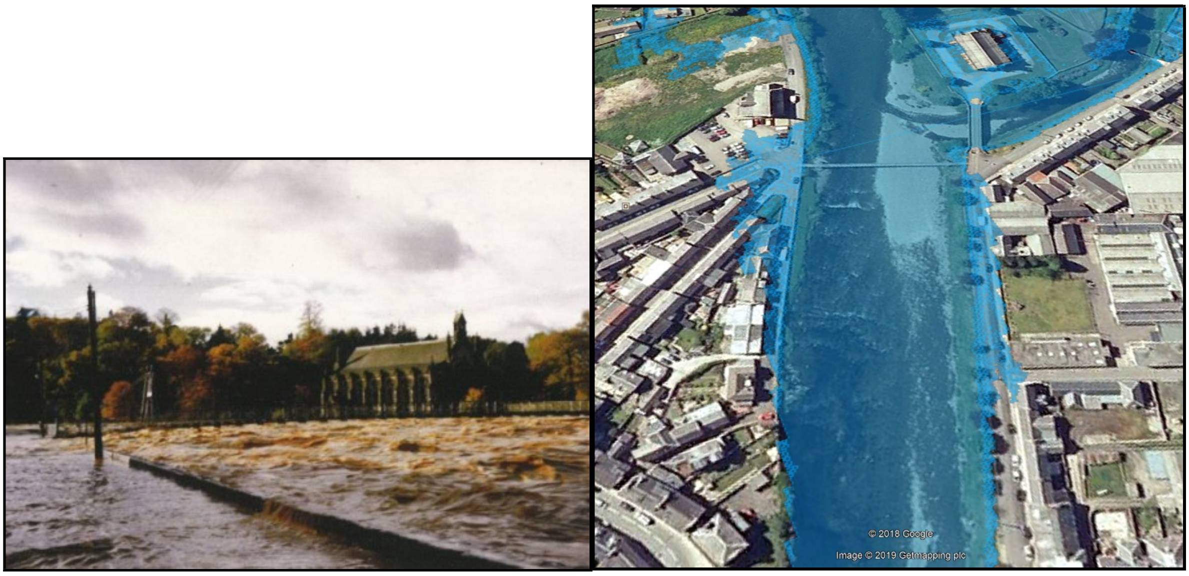

Figure 3.7 Looking downstream from George Street. Left: Photo taken on 31/10/77. Right: 1 in 21 year model output superimposed onto Google Earth

3.3.2.3 Calibration Summary

The flow gauge at Canonbie is a significant distance downstream from Langholm therefore a direct correlation cannot be made between the flow gauge and the flooding in Langholm. For the December 2015 event, an approximate 1 in 12 year return period, there is a difference of 259mm between the peak recorded and modelled water levels at the Thomas Telford Bridge. This is supported by the anecdotal evidence which shows the modelled flood extents similar to those in the observed in the photos.

While there is little confidence in the information available for the 1977 event, the modelled flood extents are similar to those observed in the photos which would further increase the confidence in the model.

RPS consider that the model has been calibrated to best represent the flooding mechanisms in Langholm and is suitable to be used in sensitivity analysis simulations and design model simulations.

3.4 HYDRAULIC MODEL SENSITIVITY

A sensitivity test was carried out to assess the impact of changes to various inputs and parameters on the flood levels in the model. The testing was carried out on the 0.5%AEP (1 in 200 year return period) design model and the following parameters and inputs were adjusted;

1. Floodplain and channel roughness - increased by 40%
2. Input flow - increased by 20%
3. 2D Resolution – 2D resolution increased: max triangle area reduced from 25m^2 to 5m^2, mesh zone max triangle area reduced from 5m^2 to 1m^2

Tables showing the predicted water levels at the modelled cross sections for the sensitivity tests can be seen in Appendix F.

3.4.1 Roughness

Adjusting the floodplain and channel roughness had the greatest impact on the river levels affecting them by a maximum of +1140mm. Figure 3.8 shows the study area indicating that the model has a high sensitivity to change in roughness values. It is estimated that there is an increase of 36% in the number of properties affected due to the increase in roughness, showing that there is a high impact to the number of properties affected when roughness is increased.

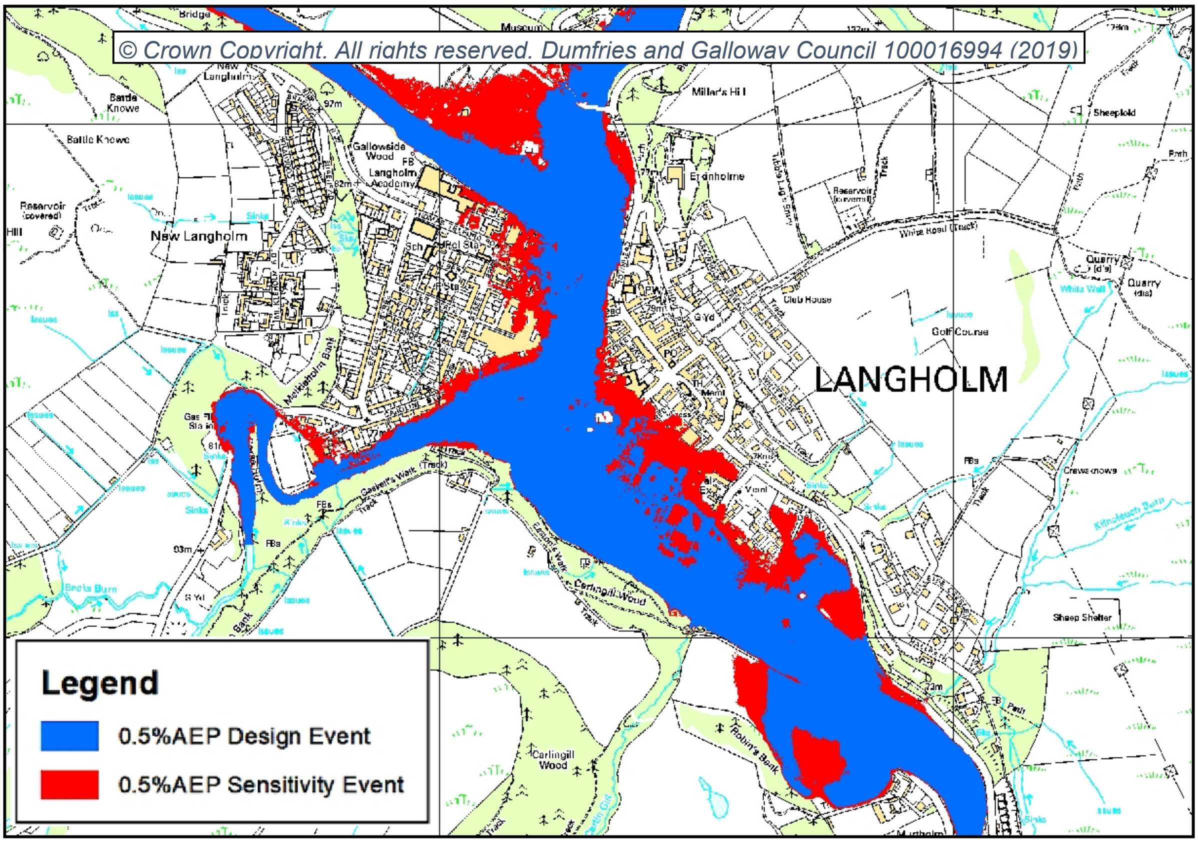

Figure 3.8 Comparison between 0.5% AEP Design Event and 0.5% AEP Sensitivity Roughness Increase Event

3.4.2 Input flow

The model inflows had generally less of an impact on river levels in the model than changes in roughness coefficients. When the inflows were increased by 20%, the maximum impact on the river levels was +600mm. shows the study area indicating that the model has a moderate sensitivity to flow parameters with a moderate impact to properties across the study area. It is estimated that there is an increase of 27% in the number of properties affected due to the increase in flow.

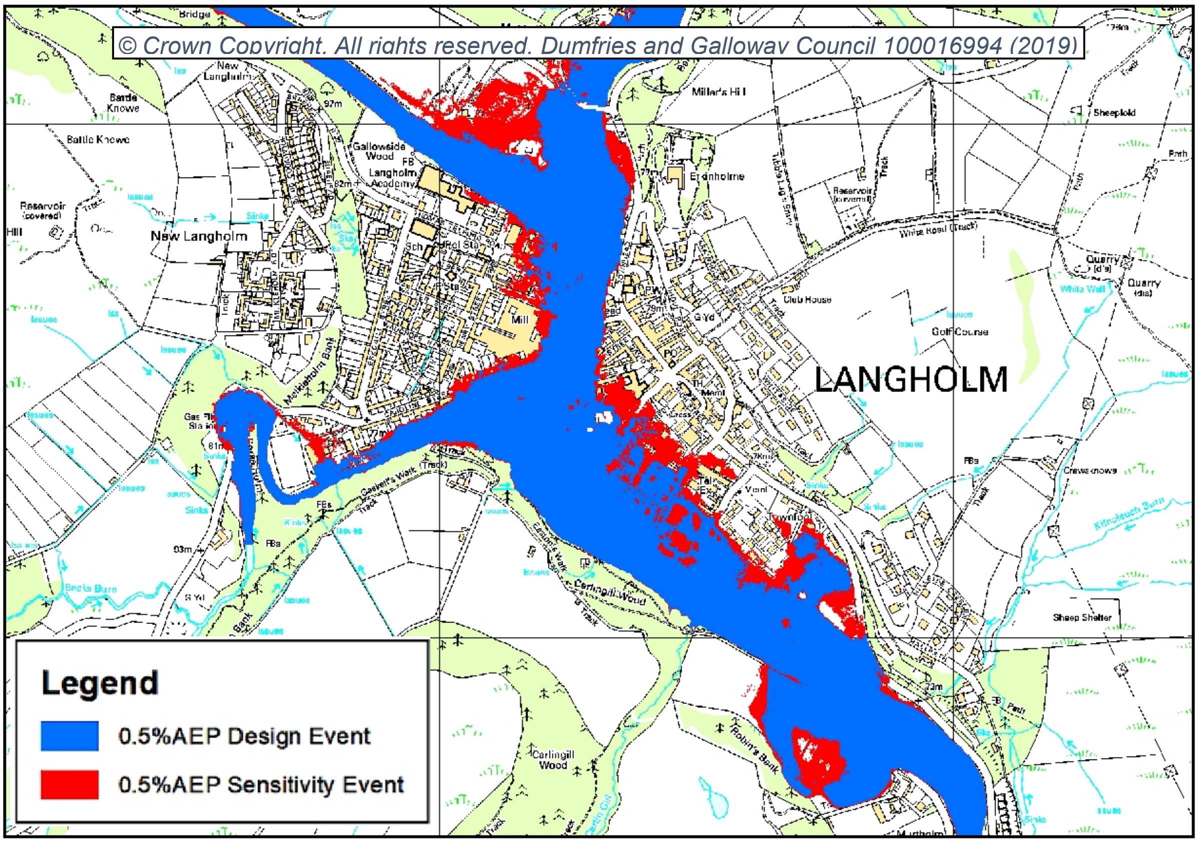

Figure 3.9: Comparison between 0.5% AEP Design Event and 0.5% AEP Sensitivity Flow Increase Event

3.4.3 Resolution

The resolution of the 2D was increased however the impact is negligible. It made no significant difference to the river levels or flood extents, and had little impact on the number of properties affected (3%). The slight differences can be seen in Figure 3.10. Therefore the model can be considered to have a low sensitivity to the model resolution, with a low impact on the number of properties affected.

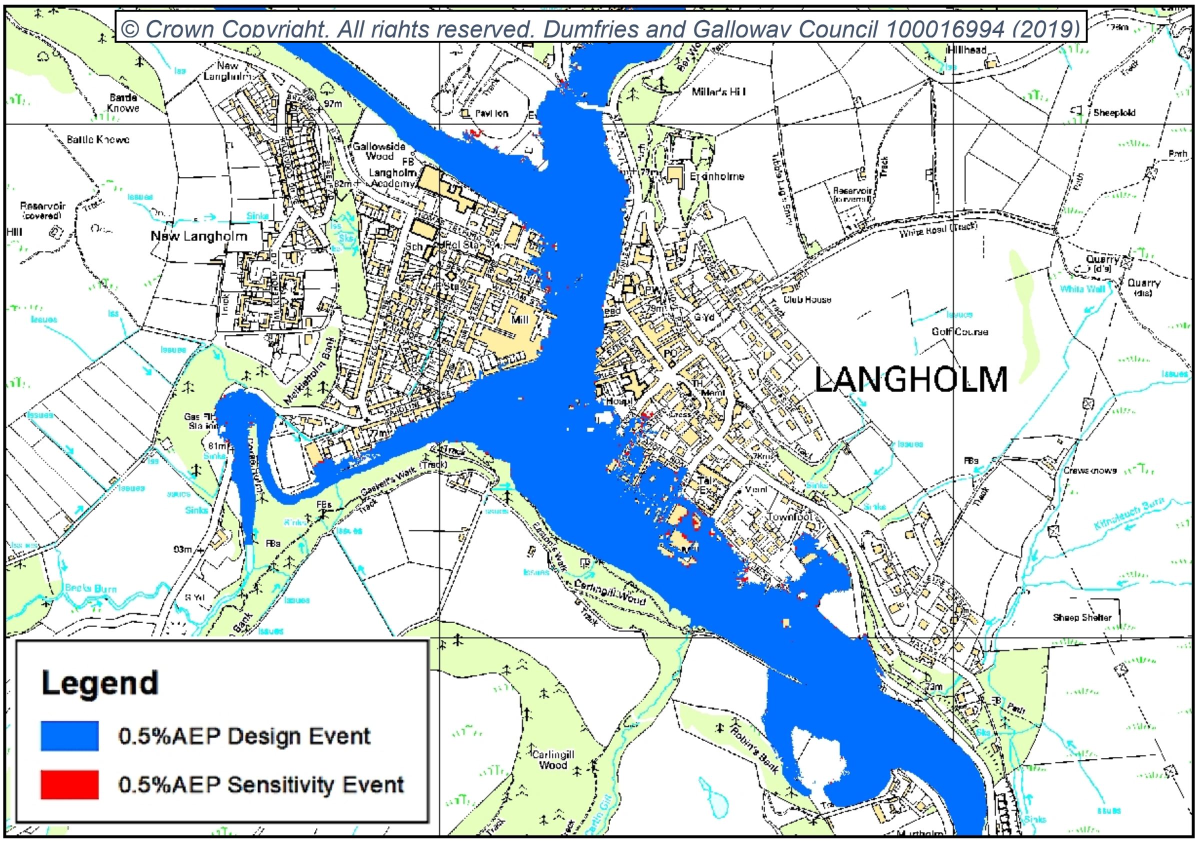

Figure 3.10: Comparison between 0.5% AEP Design Event and 0.5% AEP Sensitivity Resolution Event

3.4.4 Summary

The largest negative effect on the river levels was an increase in level by 1140mm when the roughness was increased by 40%. This indicates that the model is sensitive to changes in the roughness coefficients. The model is considered to have a moderate sensitivity to increases in the flow and a low sensitivity to changes to the model resolution.

3.5 HYDRAULIC MODEL PERFORMANCE

A mass balance check has been carried out on the 0.5% AEP (1 in 200 year return period) model to ensure that the total volume of water entering and leaving the model at the upstream and downstream boundaries balances the quantity of water remaining in the model domain at the end of a simulation. As a general rule of thumb, mass errors should be less than 2%. If the mass error is greater than 2%, the cause and location of the mass error within the model schematisation should be identified and the consequence of this error assessed and improvements to the model considered. If the mass error is greater than 5%, then it suggests that the model schematisation is not robust and needs to be reviewed (Environment Agency, 2010). The mass balance assessment of the model is within acceptable bounds with a Volume Balance Error of 0.2% during the 0.5% AEP (1 in 200 year return period) flood event.

3.6 MODEL SIMULATIONS

3.6.1 Design Scenarios

The calibrated river model was simulated to determine water levels for a range of flood events. Flood maps have been generated for the following range of return periods:

1. 50% AEP (1 in 2 year return period)
2. 20% AEP (1 in 5 year return period)
3. 10% AEP (1 in 10 year return period)
4. 3.33% AEP (1 in 30 year return period)
5. 2% AEP (1 in 50 year return period)
6. 1% AEP (1 in 100 year return period)
7. 0.5% AEP (1 in 200 year return period)
8. 0.1% AEP (1 in 1000 year return period)
9. 0.5% AEP plus 44% for climate change (1 in 200 year return period plus climate change)

The flood maps are presented in Appendix G. Further detail on the model can be seen in the model log in Appendix D.

3.6.2 Comparison with SEPA Strategic Flood Maps

The 0.5% AEP (1 in 200 year return period) event was compared with the SEPA Fluvial Medium Likelihood flood mapping. The extents are not expected to be the identical as different survey, hydrological analysis and hydraulic modelling analysis were used in the two studies, with the SEPA study being undertaken at a higher, strategic level. However, the extents are generally similar as can been seen in Figure 3.11 and Figure 3.12. An in-depth comparison of the two sets of extents is outwith the scope of this study.

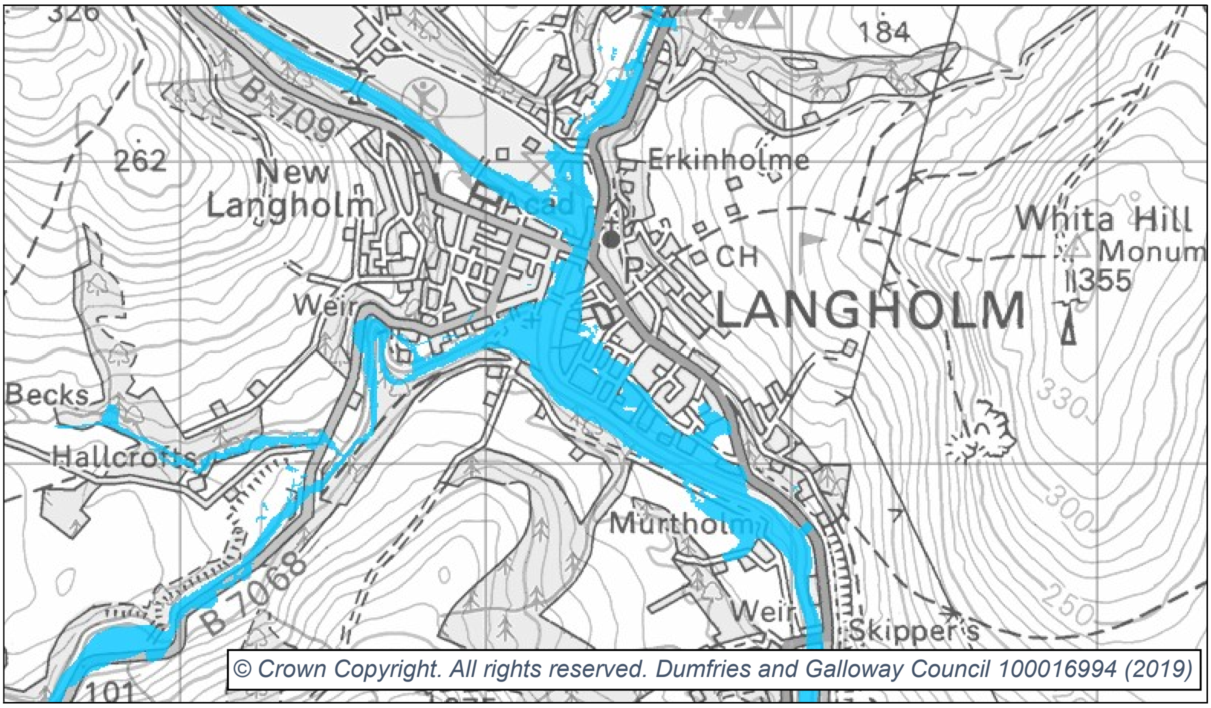

Figure 3.11 SEPA Medium Likelihood Fluvial Flooding (0.5% AEP, 1 in 200 year return period)

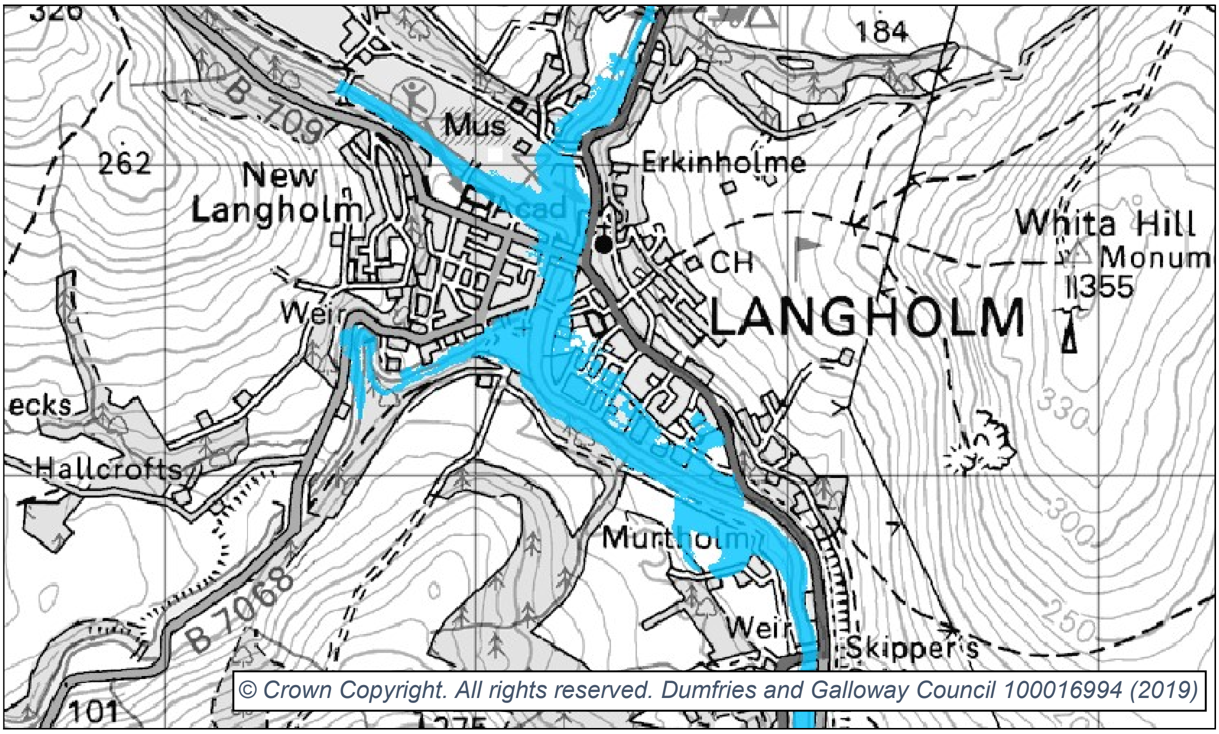

Figure 3.12 Modelled Langholm Flood Protection Study 0.5% AEP Design Event (1 in 200 year return period)

3.7 CONFIDENCE TRACKING

SEPA has considered how confidence is assessed and recorded in support of Flood Risk Management (Scotland) Act (FRM Act) hazard map outputs. An approach to assessing and tracking uncertainty in models and modelled outputs has been established through the development of a confidence framework for FRM Act outputs. The framework is based on the key principles of proportionality, alignment with modelling strategy, data availability and simplicity of approach and use. This approach has been applied to the Langholm Flood Study outputs. The tables below detail the confidence scores for various categories. The total score for the entire modelled reach is 14. Calibration/verification and Hydrology scored as ‘Good’, whereas Topography and Method scored as ‘Excellent’.

Table 3.3 Summary of confidence categories and scoring requirement for each category

Hydrology	Relative confidence (5 = higher confidence, 1 = lower confidence)	Confidence score for this domain.
Detailed hydrological analysis using gauging station data. Well gauged catchment (record length, and proximity of gauge to site) Expect unsteady inflows or justification why not used.	5	
Domain containing gauging station where flow grid updated using that gauging stations data. Or detailed hydrological analysis where the catchment is not well gauged.	4	
Catchments/reaches where design flows derived by catchment weighting based on flood frequency analysis (FEH statistical method) using SEPA gauging station data. Station within the catchment but may be some distance from this domain. **OR** locations where design flows from the flow grid have been used, but they do not differ by more than 25% relative to estimates produced at the gauge using station data - FEH Statistical method.	3	x
Catchments/reaches where the design flows have been adopted directly from the flow grid (automated FEH statistical method) with no comparison to local data.	2	
Hydrological approach taken is not the preferred approach or not considered suitable for the site in question.	1	

Topography	Relative confidence (5 = higher confidence, 1 = lower confidence)	Confidence score for this domain.
Survey	5	
LiDAR (more than 70% over the floodplain in the study area)	4	X
Combination of LiDAR and NextMap in domain (10-70% LiDAR over floodplain in the study area)	2.5	
NextMap (less than 10% LiDAR over the floodplain in the study area)	1	

Modelling	**Relative confidence (5 = higher confidence, 1 = lower confidence)**	**Confidence score for this domain.**
Detailed model, considered representative of hydraulic processes. Generally a 1D-2D model expected, or a 1D model if very well defined flow routes and limited floodplain flow. - detailed representation of hydraulic structures including weirs, culverts and flood defences. - out of bank flow paths well resolved - combined source modelling where appropriate	5	X
2D modelling where the channel is well resolved and there are either no significant hydraulic structures or structures/defences are well represented. **OR** 1D modelling where there is limited out of bank flow e.g. for a narrow incised channel.	4	
2D modelling where either: the channel is not well resolved and there are no structures **OR** there are structures/defences that are not well represented and the channel is well defined **OR** there are structures/defences that are represented using some local information. **OR** 1D modelling where there is significant out of bank flow.	2	
Simplified approach e.g. RFSM (irrespective of whether structures/defences represented)	1	

Calibration/ Verification	**Relative confidence (5 = higher confidence, 1 = lower confidence)**	**Confidence score for this domain.**
Model results compare well with higher quality historical information e.g. levels at gauge or historic flood extent from survey for MULTIPLE events. Model calibrated.	5	
Model results compare well with higher quality historical information e.g. levels at gauge or historic flood extent from survey Model calibrated.	4	
Model results compare well with results of other independent accepted studies.	3	
Model results compare well with anecdotal evidence (e.g. LA understanding) or lower quality historical information.	2	X
Model not calibrated or validated at present	1	

Summary	
Total Score (Hydrology + Topography + Method + Calibration/Verification)	14
Confidence Category (Assigned based on the score achieved for each of the elements - see table below for summary of confidence categories and scoring requirements for the different categories)	Good

Confidence category	General description	Scoring Requirements for assigning to this category: Hydrology	Topography	Method	Calibration/Verification
Excellent	*A relatively high confidence is given to this information. This is provided by the use of calibrated and/or validated detailed models using local hydrological analysis. The method of modelling sufficiently represents hydraulic processes and uses LIDAR DTM or survey information.* *The data represents local conditions well and reflects real flood events or compares well with other supporting information such as other accepted detailed studies.*	≥ 4	≥ 4	≥ 4	≥ 3
Good	*Reasonable confidence in hydrology, topography and method. Reflects real flood events and scenarios or compares well with other supporting information such as other accepted detailed studies or anecdotal evidence from partners.*	≥ 3	≥ 3	≥ 3	≥ 2
Intermediate	*Varied level of confidence in this data.* *There is a reasonable level of confidence in at least one of the elements (topography, hydrology, method) but not all elements have an appropriate level of confidence to be included in the "Good" category.* *Developing some elements of the data would improve the level of confidence to good.*	At least one element with score ≥ 3			If at least one of Topography, Hydrology and Method are < 3 than CV score can be any value. If Hydrology, Topography and Method are ≥ 3 then CV score must be 1 to remain in this category.
Acceptable to meet statutory requirements	*This data is acceptable for use at a strategic level and meets the requirement of the FRM Act.* *The data supports national, strategic modelling and mapping but is not suitable for more detailed assessments, given the lower relative confidence in this data.*	< 3	< 3	< 3	Any, although typically score = 1.

4 SUMMARY AND RECOMMENDATIONS

Langholm is located at the confluences of the Ewes Water and the Wauchope Water with the River Esk in Dumfries and Galloway. The town has a history of flooding with the most recent flood event occurring in December 2015, when residents had to be evacuated and two basements were flooded.

RPS have undertaken a comprehensive review of existing information including historical flood event data, survey information, existing models and reports in addition to procuring additional topographical survey information for the purposes of this study. Following walkover surveys, RPS used InfoWorks ICM to undertake the numerical modelling of the River Esk, Ewes Water and Wauchope Water within the study area. RPS constructed a 1D in channel model, incorporating all significant hydraulic structures, combined with a 2D flood plain model to provide an accurate assessment of both the in channel flow regime and floodplain flow paths.

Langholm has suffered flooding in the past however there is limited recorded information available of the historic events which can be used to facilitate model calibration and verification. The only gauging station in the area is 12.5km downstream of Langholm with one additional, major tributary confluence with the River Esk downstream of Langholm. Therefore high flows at Langholm do not directly correlate to high flows at the gauge. However data from the gauge during the two largest events witnessed in Langholm (December 2015 and October 1977) was used to create modelled flood extents for each historical event. RPS have used the anecdotal evidence that is available to achieve model calibration.

The calibrated river model has been simulated to determine water levels for a range of flood events, with flood extent and depth maps being generated for each return period. Sensitivity analysis simulations were undertaken. This indicated that the model is sensitive to changes in the roughness coefficients. It is recommended that the model is reviewed and updated prior to the detailed design of the flood alleviation scheme with more detailed information on the roughness coefficients, to provide increased confidence in the model outputs. The model is considered to have a moderate sensitivity to changes to input flows and a low sensitivity to changes in the model resolution.

RPS consider that the model has been calibrated to best represent the flooding mechanisms in Langholm and is suitable to be used as a basis for identifying flood alleviation options in Langholm. It is recommended that extensive data collection is undertaken during and after any future flood events, which would provide information to further improve confidence in the hydraulic model. It is also recommended that, due to dynamic nature of the River Esk, the model is reviewed and updated prior to the detailed design and construction of a flood protection scheme.