Appendix A11.4: Hydraulic Modelling Report

1 Introduction

Purpose of the Hydraulic Modelling

1.1.1 This Hydraulic Modelling Report provides detailed information on the hydraulic model build process undertaken to assess the risk of fluvial flooding from the River Garry to the proposed scheme between Killiecrankie and Glen Garry.

1.1.2 The report supports the hydraulic modelling results presented in Appendix A11.3 (Flood Risk Assessment) in Chapter 11 Road Drainage and the Water Environment (RDWE) of the Environmental Statement.

1.1.3 The main body of this report covers the hydraulic modelling of the main rivers (i.e. River Garry and two tributaries). Annex A (Minor Watercourse Modelling) presents additional hydraulic modelling undertaken for a number of minor watercourses outside of the main modelling area.

1.1.4 In accordance with the DMRB, the proposed scheme development is currently at DMRB Stage 3 'Detailed Assessment'. This report documents the modelling undertaken on the DMRB Stage 3 only.

Modelling Approach

1.1.5 The hydraulic model was built using a linked One-Dimensional/Two-Dimensional (1D/2D) technique, where the river channel is represented as a 1D component using Flood Modeller Pro (FM) version 4.1 software and the floodplain is represented using TUFLOW 2016 software. The linked 1D/2D modelling approach means that the model dynamically transfers the water between the watercourses and the floodplain. The flow exchange at the link in this approach is controlled by the bank crest levels, which were informed by Digital Terrain Model (DTM) data along the channel banks.

1.1.6 The hydraulic modelling aimed to predict the peak water level within the modelled river reach and the floodplain for the 50% Annual Exceedance Probability (AEP), 3.33% AEP (30-year), 0.5% AEP (200-year) and 0.5% AEP (200-year) plus an allowance for climate change (plus CC) flood events for both the baseline and proposed scheme scenarios. These were then used to understand the existing fluvial flood risk and assess the potential impacts of the proposed scheme on flooding.

Modelled Area

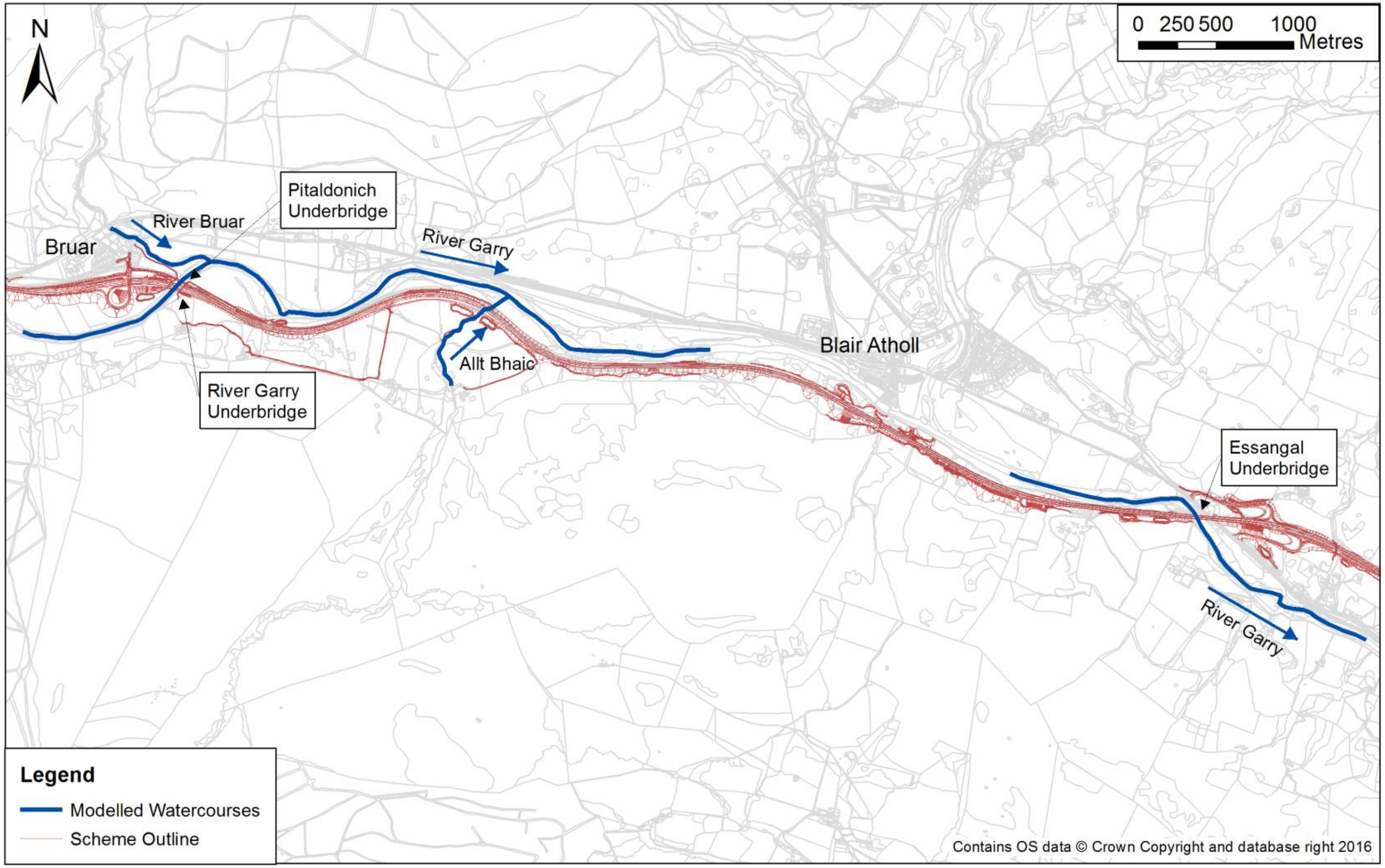
1.1.7 Diagram 1 illustrates the extent of the modelling work undertaken for the proposed scheme.

1.1.8 Two independent hydraulic models were constructed to understand the flood risk from the River Garry to the existing A9.

- The first model (Model V/VI) covers a 5,000m long reach of River Garry around the proposed River Garry Underbridge at Pitaldonich, including parts of its tributaries, namely the River Bruar and Allt Bhaic. The upstream end of this model is approximately 1,145m upstream of the proposed River Garry Underbridge.
- The second model (Model V) covers a 2,730m reach of River Garry around Essangal Underbridge. The upstream end of this model is approximately 1,280m upstream of Essangal Underbridge.

1.1.9 The model extents were chosen based on the key locations where the River Garry and its tributaries are close to the existing A9, and could potentially influence the flood risk to and from the road in both baseline and proposed scheme scenarios.

Diagram 1: Modelled area



2 Input Data

2.1.1 The data used to construct the hydraulic models are summarised in Table 1.

Table 1: Data used to build the hydraulic models

Data	Description	Source
Digital Terrain Model (DTM)	5m horizontal resolution DTM derived from photogrammetry (2013)	Transport Scotland
OS maps	Background maps and Master Map data	Ordnance Survey
BLOM topographic survey	Detailed topographic survey of an approximately 200m corridor along the A9. This had already been integrated into the above DTM	BLOM
Channel survey	In-channel cross sections and hydraulic structures	Jacobs Site survey 2015
Watercourse photographs	Site visit in-channel watercourse photographs	Jacobs Site survey 2015 Site inspection 2015/2016
Hydrological analysis	Hydrological analysis carried out as discussed in Section 3	Jacobs 2015
Scottish Environment Protection Agency (SEPA) Flood Maps	Flood maps showing the fluvial flood extent for different likelihoods of flooding (high, medium and low)	SEPA
Proposed Scheme Topography	MXROAD ASCII grids	Jacobs 2017
Proposed Scheme Structure Details	Design drawings for proposed structure modifications	Jacobs 2017

3 Hydrology

3.1.1 The details of the analysis carried out to produce design inflows for the hydraulic model are provided in Appendix A11.2 (Surface Water Hydrology). Inflows have been provided for the 50% AEP (2-year), 3.33% AEP (30-year), 0.5% AEP (200-year) and 0.5% AEP (200-year) plus CC flood events.

3.1.2 As discussed in Appendix 11.2 (Surface Water Hydrology), for Model V/VI two sets of hydrological inflows were simulated, referred to as Run 1 and Run 2. Run 1 used the critical storm duration of the River Garry for all inflows in order to assess the flood risk from the main stem, whereas Run 2 combined the critical storm durations for the River Bruar and Allt Bhaic tributaries with the QMED flow in the River Garry. Run 1 was found to be the critical scenario; therefore, these flows were used in the analysis.

3.1.3 The peak flows for the modelled watercourses are shown in Table 2 for Model V and Table 3 for Model V/VI along with the locations where they were estimated. The flow hydrographs are shown in Diagram 2 and Diagram 3.

Table 2: Hydrological inflow peak values and locations for Model V

Inflow	Description	Peak Flow (m^3/s)			
		AEP 50% (2-year)	AEP 3.33% (30-year)	AEP 0.5% (200-year)	AEP 0.5% (200-year) + CC
River Garry at Essangal Underbridge	Inflow estimated at Essangal Underbridge and applied in the model about 1280m upstream on River Garry	404.1	677.4	973.7	1168.5
Residual catchment	Flow distributed laterally along the River Garry between Essangal Underbridge and the downstream end of the model	3.1	6.4	8.5	10.2
River Garry at downstream extent of Mode V	Peak flow at the downstream end of the model, used for reconciliation of routed flows through the model.	405	679	976	1171

Table 3: Hydrological inflow peak values and locations for Model V/VI

Inflow	Description	Peak Flow (m³/s)			
		AEP 50% (2-year)	AEP 3.33% (30-year)	AEP 0.5% (200-year)	AEP 0.5% (200-year) + CC
River Garry at the Garry / Bruar confluence	Inflow estimated at the confluence and applied in the model about 1340m upstream near East Kindrochit	184.5*	317.4*	432.8	519.4
River Bruar at the Garry / Bruar confluence	Inflow estimated at the confluence and applied in the model about 750m upstream at the Highland Main Line railway on River Bruar	46.8*	80.6*	109.9	131.9
Allt Bhaic	Inflow applied about 850m upstream of Allt Bhaic/River Garry confluence	4.36	7.59	11.03	13.24
Residual catchment between Garry/Bruar confluence and d/s end of the model	Flow distributed laterally along the River Garry from A9 bridge on River Garry to the downstream end of the model	4.36	7.59	11.03	13.24
River Garry at downstream extent of model	Peak flow at the downstream end of the model, used for reconciliation of routed flows through the model.	227	391	545	654

*A scaling factor of 0.95 was applied to these inflows to reconcile the routed flows to the target flows at the downstream end of the model.

Diagram 2: Inflow hydrographs for Model V

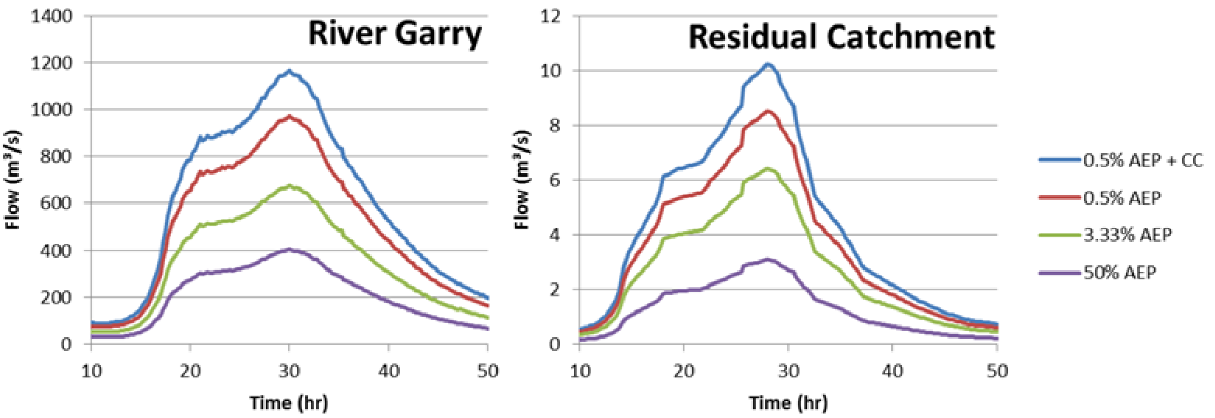
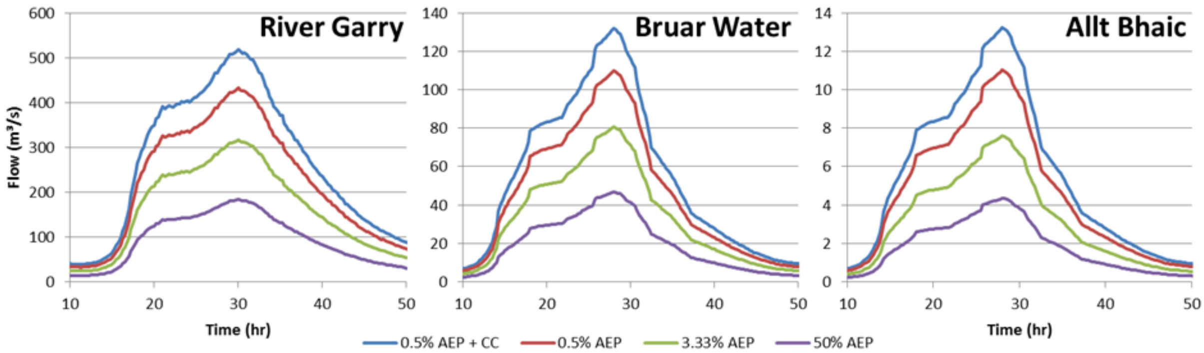


Diagram 3: Inflow hydrographs for Model V/VI



4 Baseline Modelling

Watercourse Schematisation – 1D Domain

In-Channel Geometry

4.1.1 Surveyed river cross section data has been used to inform the in-channel geometry of the modelled watercourses. The locations of the surveyed river cross sections are shown in Diagram 8 and Diagram 9 for Model V and Model V/VI respectively. To aid model performance interpolated cross sections were added between the surveyed cross sections where needed.

4.1.2 Table 4 shows the Flood Modeller nodes associated with the modelled watercourses. Node labels are provided on Diagram 10 and Diagram 11.

Table 4: Flood Modeller nodes

Model	Reach	Upstream Node	Downstream Node
Model V	River Garry	GAR01_2734	GAR01_0000
Model V/VI	River Garry	GAR02_5002	GAR02_0000
Model V/VI	River Bruar	BRU01_0700	BRU01_0000
Model V/VI	Allt Bhaic	ALB01_0783	ALB01_0000

In-Channel Hydraulic Friction

4.1.3 Hydraulic roughness (Manning's 'n' coefficient) values were determined primarily using the photographs taken during the survey. The values have been applied using a general impression of the reach rather than looking at individual cross section locations. Photographs of the typical channel material for the watercourses are shown in Diagram 4 and Diagram 5. The in-channel roughness coefficients used are shown in Table 5 and these values were taken from standard guidance (Chow 1959).

4.1.4 In some locations the 1D cross sections extend into the floodplain and roughness coefficients have been used as discussed in the section on floodplain hydraulic friction below, and shown in Table 8.

Table 5: In-channel Manning's 'n' coefficients

Watercourse	Manning's 'n'	Bed Material
River Garry	0.04	Large river with straight reaches. River bed with gravels, cobbles, and few boulders.
River Bruar	0.07	Mountain stream, brush along banks. River bed with cobbles and large boulders.
Allt Bhaic	0.05	Mountain stream, no vegetation in channel, banks usually steep. River bed with gravels and few boulders.

Diagram 4: River Garry channel material near Pitaldonich Underbridge (left) and 1200m downstream of the bridge (right)

Diagram 5: Channel material for the River Bruar (left) and Allt Bhaic (right)

In-Channel Hydraulic Structures

4.1.5 The in-channel hydraulic structures included in the 1D model extent are specified in Table 6 and locations are shown in Diagram 8 and Diagram 9. Cross sections for the bridge units for the two models are shown in Diagram 6 and Diagram 7.

4.1.6 The Essangal Underbridge in Model V has been included in the 1D model, except for the span on the left bank (east) covering B8079 and the Highland Main Line railway. This span has been included in the 2D model to allow a better representation of the flow connectivity at this location.

Table 6: In-channel hydraulic structures (represented in Flood Modeller)

Model	Watercourse	Existing Structure	Flood Modeller Node	Specification
Model V	River Garry	A9 Essangal Underbridge	GAR01_1452bu	Type: USBPR Spans: 3 Total Width: 129.0m Upstream Bed Level: 115.833mAOD Downstream Bed Level: 115.407mAOD Maximum Height: 8.4m Skew Angle: 30°
Model V/VI	River Garry	A9 Pitaldonich Underbridge	GAR02_3857bu	Type: USBPR Spans: 3 Total Width: 78.6m Upstream Bed Level: 143.617mAOD Downstream Bed Level: 143.640mAOD Maximum Height: 5.4m
Model V/VI	Allt Bhaic	A9 crossing	ALB01_0110c	Type: Rectangular Conduit Inlet: 90° Headwall Length: 16m Width: 11.1m Height: 2.79m Upstream Invert Level: 135.970mAOD Downstream Invert Level: 135.700mAOD
Model V/VI	River Bruar	B8079 crossing	BRU01_0505	The bridge has been represented by a spill unit with lateral extents limited to the bridge abutments, as a steep drop in bed level occurs under the B8079 bridge and flow is unlikely to be constrained by the bridge soffit at 157.170mAOD. Spill Coefficient: 1.2

Diagram 6: Essangal Underbridge 1D schematisation in Flood Modeller

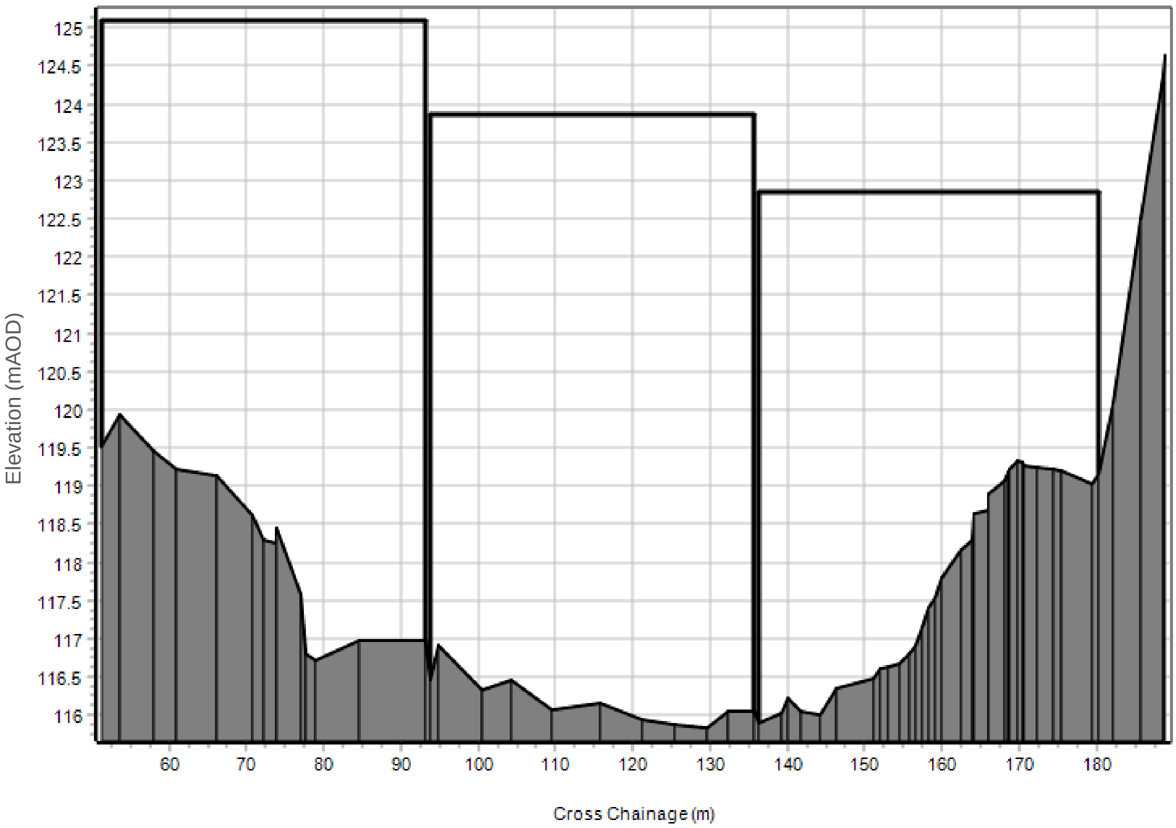
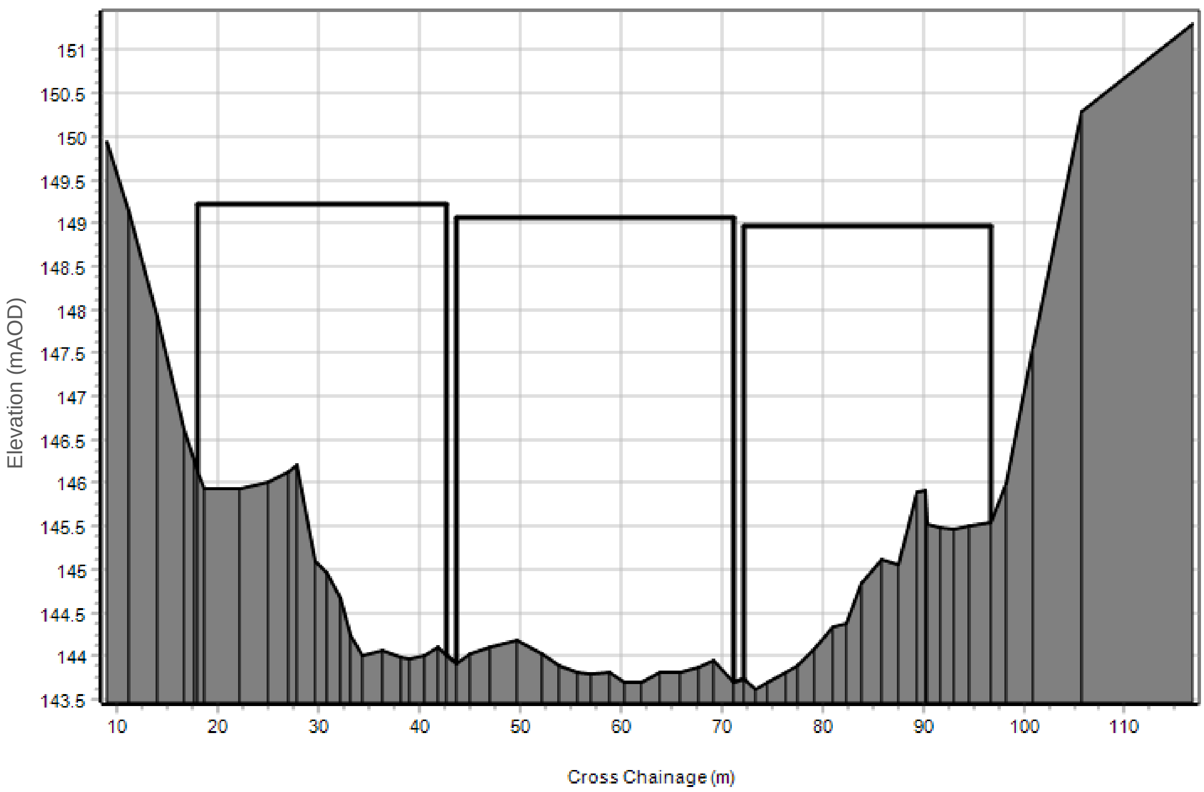


Diagram 7: Pitaldonich Underbridge 1D schematisation in Flood Modeller



Boundary Conditions – 1D Domain

4.1.7 The upstream and downstream boundary conditions applied to the 1D domain for each model are described in Table 7. Locations are shown in Diagram 8 and Diagram 9.

Table 7: 1D boundary conditions

Model	Type of Boundary	Flood Modeller Node	Description
Model V	Flow-Time Boundary	GAR01_2734	Hydrological inflow applied at the upstream end of the model.
Model V	Flow-Time Boundary	Lat	Hydrological inflow distributed laterally between nodes GAR01_1442 and the downstream end of the model.
Model V	Normal Depth Boundary	GAR01_0000	Normal depth boundary condition applied at the downstream end of the model on River Garry.
Model V/VI	Flow-Time Boundary	GAR02_5002	Hydrological inflow applied at the upstream end of the model on the River Garry.
Model V/VI	Flow-Time Boundary	Lat	Hydrological inflow distributed laterally between the confluence with River Bruar and the downstream end of the model.
Model V/VI	Flow-Time Boundary	BRU01_0700	Hydrological inflow applied at the upstream end of River Bruar.
Model V/VI	Flow-Time Boundary	ALB01_0783	Hydrological inflow applied at the upstream end of Allt Bhaic.
Model V/VI	Normal Depth Boundary	GAR02_0000	Normal depth boundary condition applied at the downstream end of the model on River Garry.

Diagram 8: Model V baseline schematisation

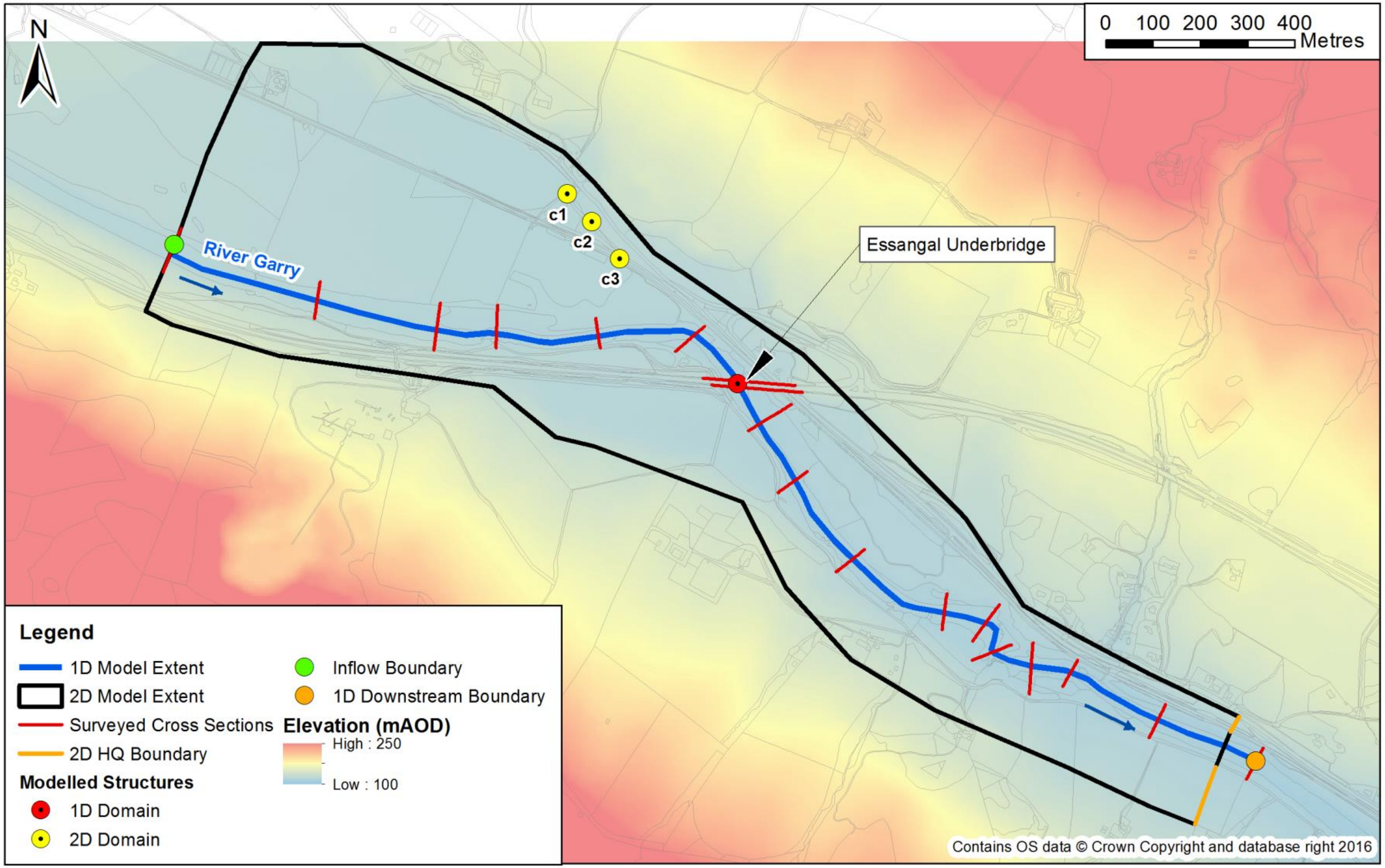


Diagram 9: Model V/VI baseline schematisation

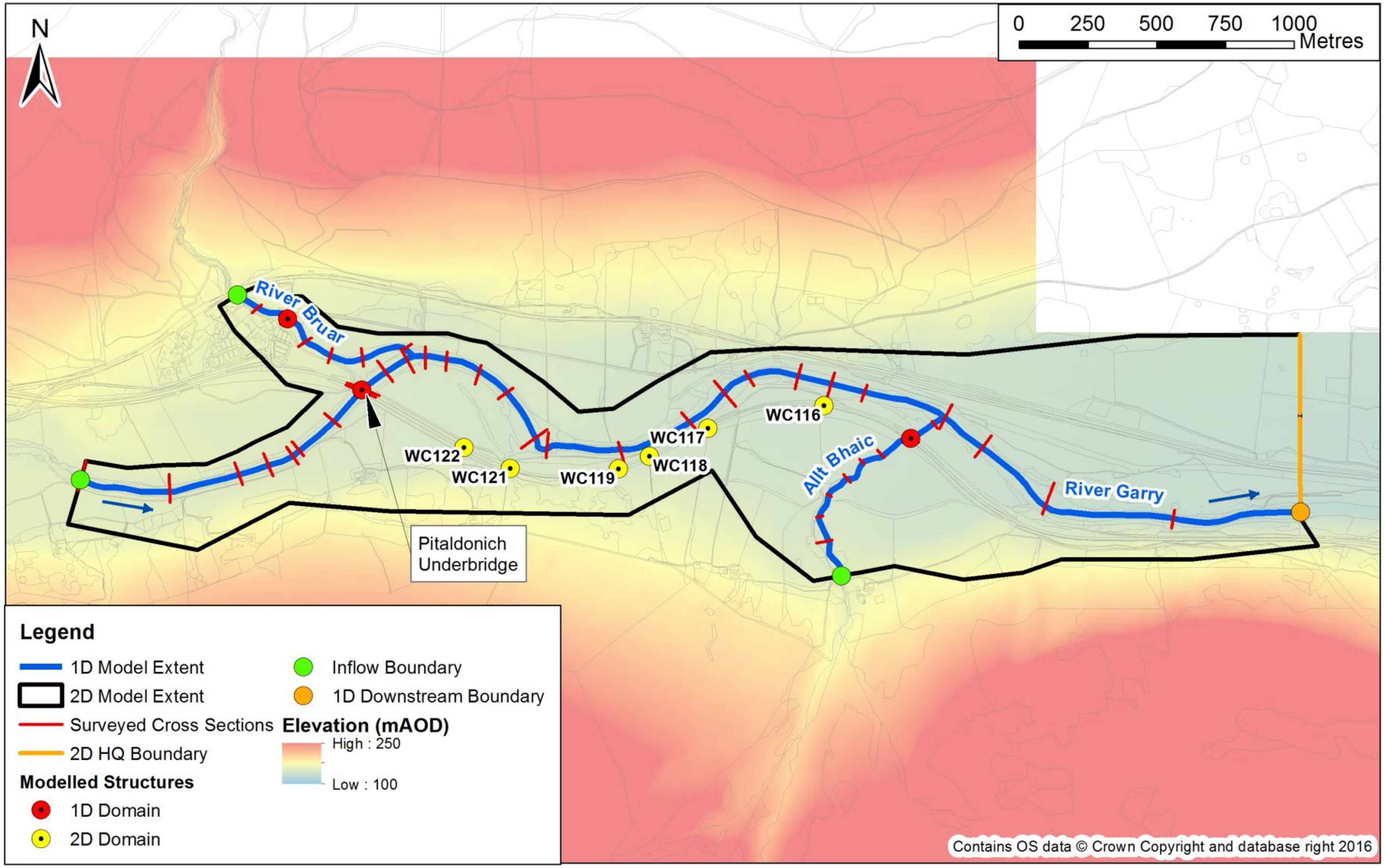


Diagram 10: Model V flood modelled nodes

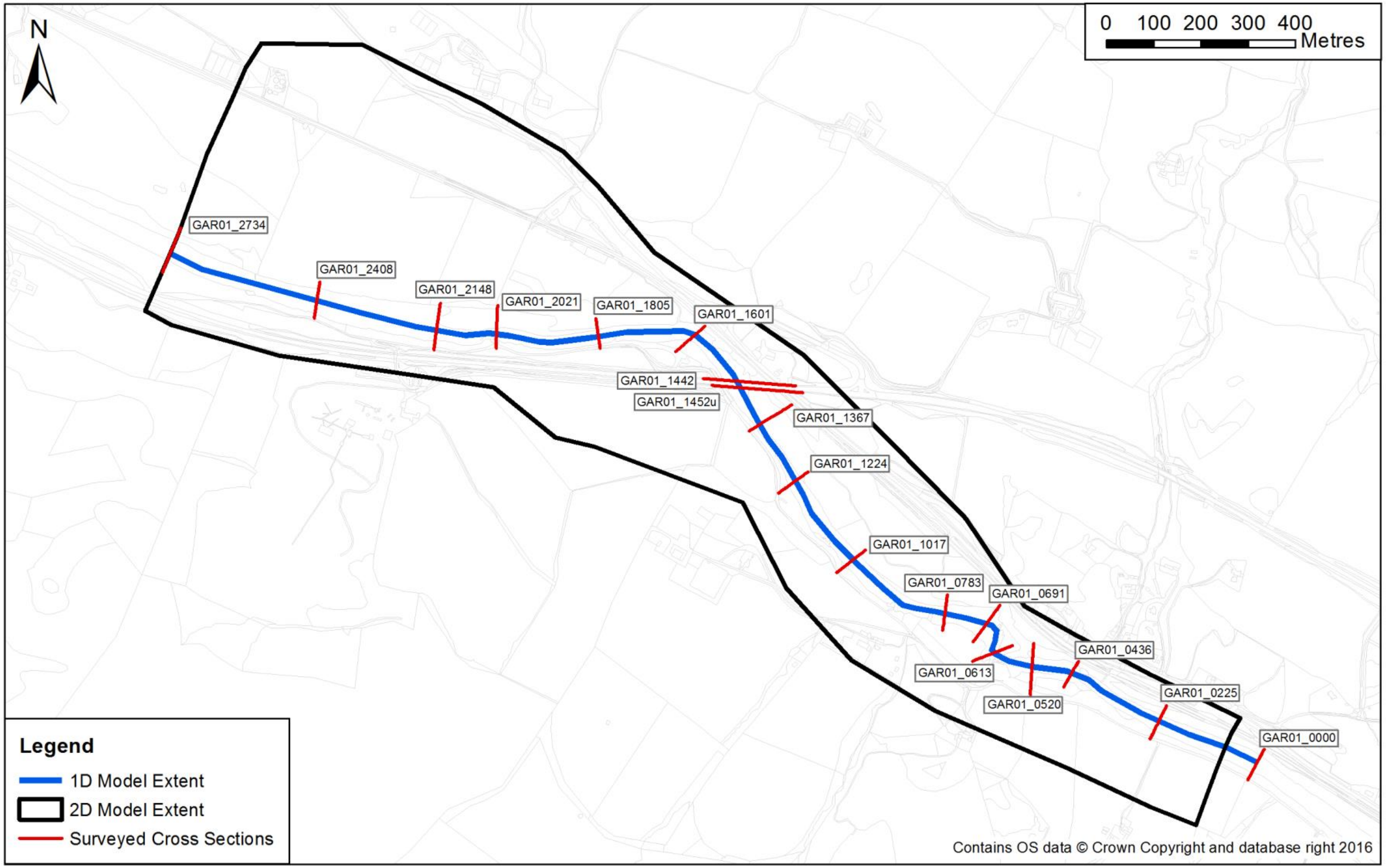
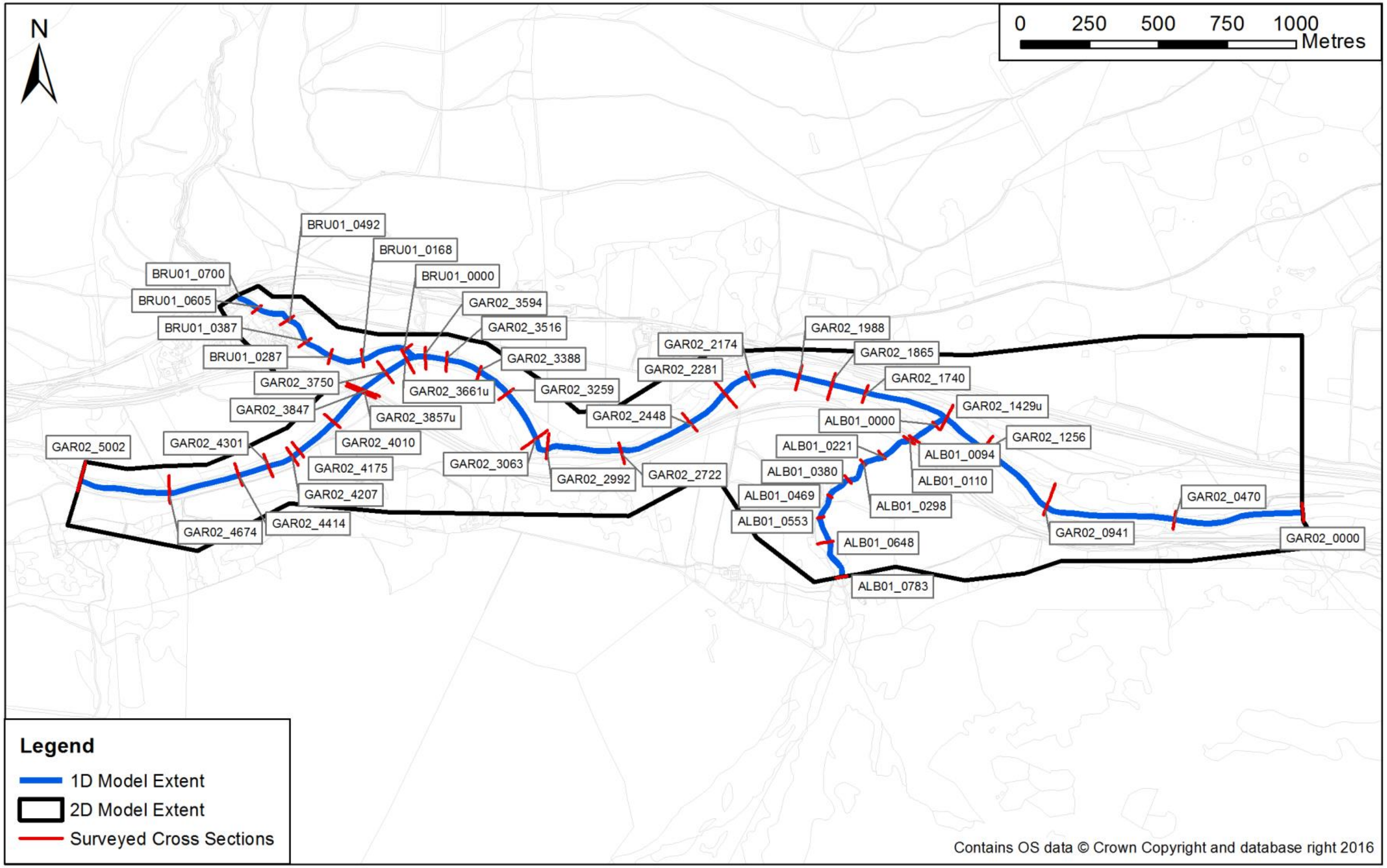


Diagram 11: Model V/VI flood modelled nodes



Floodplain Schematisation – 2D Domain

Floodplain Topography

4.1.8 The 2D domain covers an area of 1.07km² for Model V and an area of 2.76km² for Model VI. The topography is represented using a 5m resolution square grid. The levels for the grid cells are based on a 5m resolution Digital Terrain Model (DTM) derived from photogrammetry.

4.1.9 Appropriate use has been made of 2D breaklines and elevation polygons (z-shapes) to accurately represent roads, drains and ridges where they have a significant impact on flow across the floodplain. Elevations for these topographic features were informed by the DTM data.

4.1.10 Model V includes z-shapes to model the road and Highland Main Line railway elevations beneath the eastern span of the Essangal Underbridge, as well as breaklines along the river banks, the Highland Main Line railway, a nearby track, and a minor watercourse in the Essangal area.

4.1.11 In Model V/VI no modifications to the DTM have been made apart from river bank lines, these are discussed further in the section on 1D/2D linking below.

Floodplain Hydraulic Friction

4.1.12 Hydraulic roughness coefficients are applied across each cell of the 2D domain as shown in Table 8, depending on land use taken from OS Mastermap data. Roughness values adopted were taken from standard guidance.

Table 8: Manning's 'n' coefficients - 2D domain

Land Use	Manning’s ‘n’
Water bodies	0.02
Roads, tracks and paths	0.025
Short grass	0.035
Gardens	0.05
Railway	0.05
Embankments	0.05
General green areas	0.055
Trees	0.1
Buildings and glasshouses	1

Floodplain Hydraulic Structures

4.1.13 Hydraulic structures in the floodplain (2D) were included, using invert levels from the DTM, where they were considered important for flow connectivity and flood risk. Details are provided in Table 9 and locations are shown on Diagram 8 and Diagram 9.

4.1.14 Three culverts were included in Model V in the Essangal area, under tracks and the Highland Main Line railway embankment. No survey information was available, therefore dimensions were assumed with the help of OS Mastermap data and photos taken during site visits where available.

4.1.15 Similarly, six culverts were included in the floodplain under the existing A9 in Model V/VI. Dimensions were obtained from survey. Three of the six culverts are connected directly to the River Garry 1D model (Flood Modeller).

Table 9: Floodplain hydraulic structures

Model	Structure	Type	Dimensions (m)	Length (m)	Upstream Invert Level (mAOD)	Downstream Invert Level (mAOD)
Model V	c1	Circular Culvert	0.9	45	120.310	120.300
Model V	c2	Circular Culvert	0.9	10	120.250	120.240
Model V	c3	Rectangular Culvert	1m x 1m	15	120.140	120.130
Model V/VI	WC116	Circular Culvert	0.6	25.6	137.600	136.980
Model V/VI	WC121	Circular Culvert	1	24.5	147.403	144.463
Model V/VI	WC122	Circular Culvert	0.38	35	143.140	142.663
Model V/VI	WC117	Circular Culvert	0.6	23.8	139.640	139.320
Model V/VI	WC118	Circular Culvert	1	21.6	140.785	140.460
Model V/VI	WC119	Circular Culvert	1	25.8	144.405	141.620

Boundary Conditions – 2D Domain

4.1.16 No inflow has been applied directly to the 2D domain. Any flow across the 2D domain is a result of the 1D channel being overtopped.

4.1.17 Stage-Discharge (HQ) boundaries have been applied at the downstream end of both models at the edge of 2D domains. This controls the rate at which floodplain flows leave the model according to the local topography. The locations of these boundaries are shown on Diagram 8 and Diagram 9.

1D/2D Linking

4.1.18 The link between the 1D and the 2D domains was defined along the banks of the River Garry and River Bruar using bank crest levels informed by the DTM data. In the case of Allt Bhaic, the DTM data did not capture the channel shape therefore the channel alignment and bank levels were informed by the surveyed cross sections.

5 Proposed Scheme Modelling

Proposed Scheme Arrangement

5.1.1 Diagram 12 and Diagram 13 show the layout of the proposed scheme in the vicinity of the two models.

1D Model Updates

5.1.2 The proposed scheme in Model V includes an update to Essangal Underbridge. The proposed scheme retains the existing three span bridge structure and includes an additional three span bridge on the downstream side, mirroring the existing. Therefore, the existing bridge structure within the model has been modified to be modelled as a dual bridge.

5.1.3 In Model V/VI the existing Pitaldonich Underbridge structure remains unchanged in the proposed design. A new bridge has been added to the model 70m upstream of the existing bridge for the north-bound carriageway. The modelled bridge cross section is shown in Diagram 14, which includes access track culverts on both banks.

5.1.4 The Allt Bhaic Underbridge has been modified in the proposed scheme model. The existing culvert has been replaced with an arch bridge unit (flat soffit), located 47m upstream of the existing culvert inlet, with an access track included on the left bank within the cross section, as shown in Diagram 15.

Diagram 12: Model V proposed scheme layout

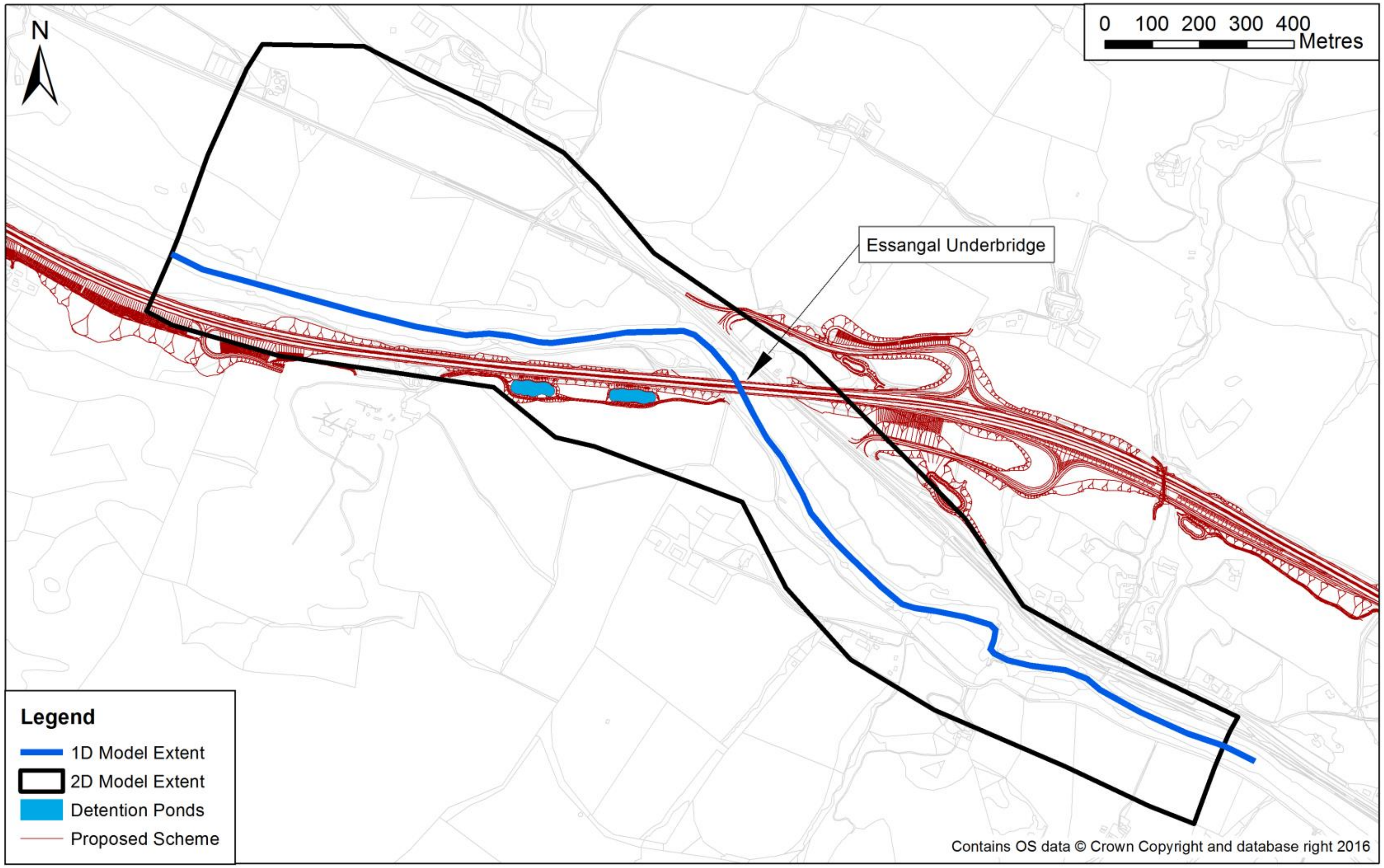


Diagram 13: Model V/VI proposed scheme layout

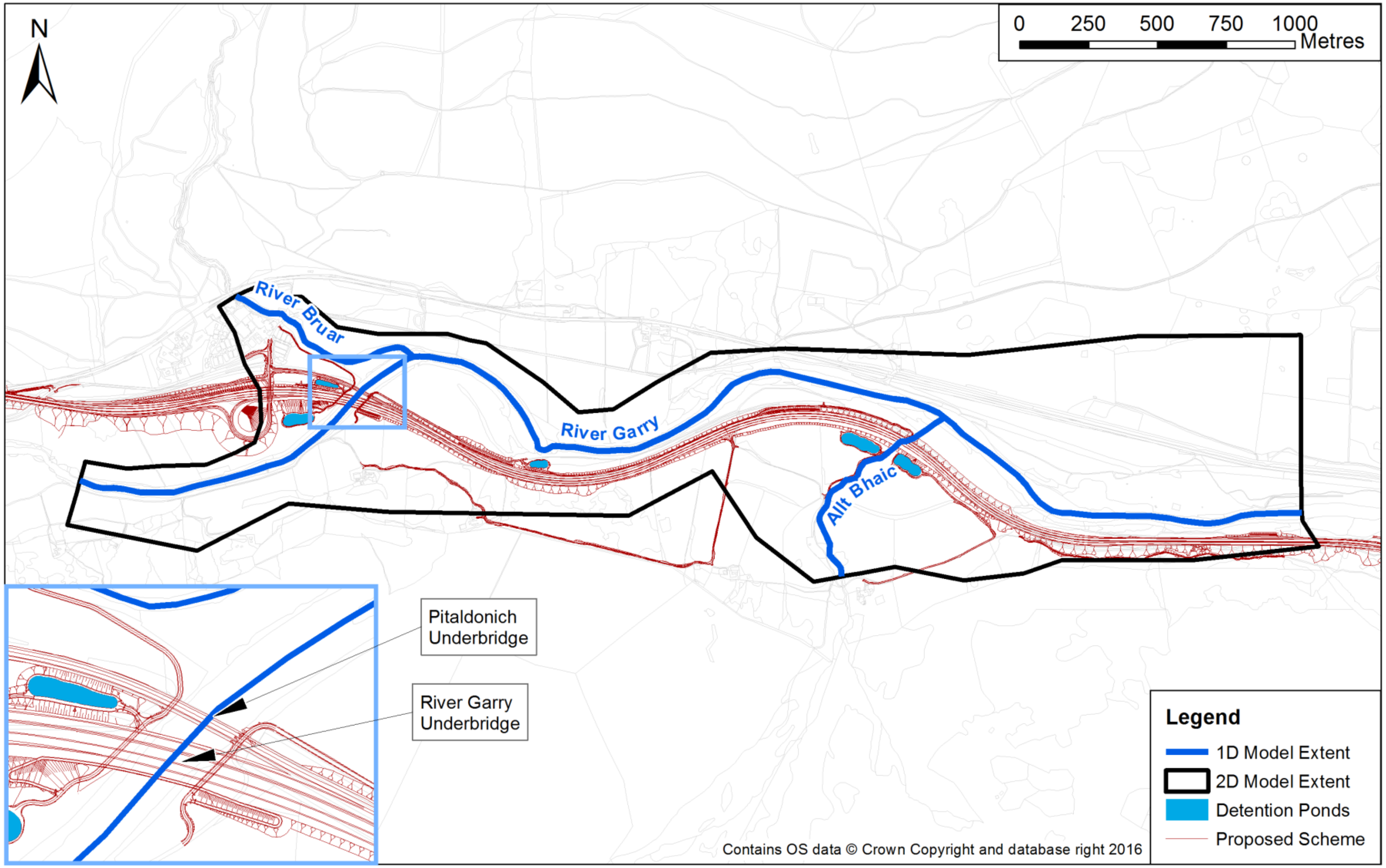


Diagram 14: River Garry Underbridge proposed scheme design schematisation

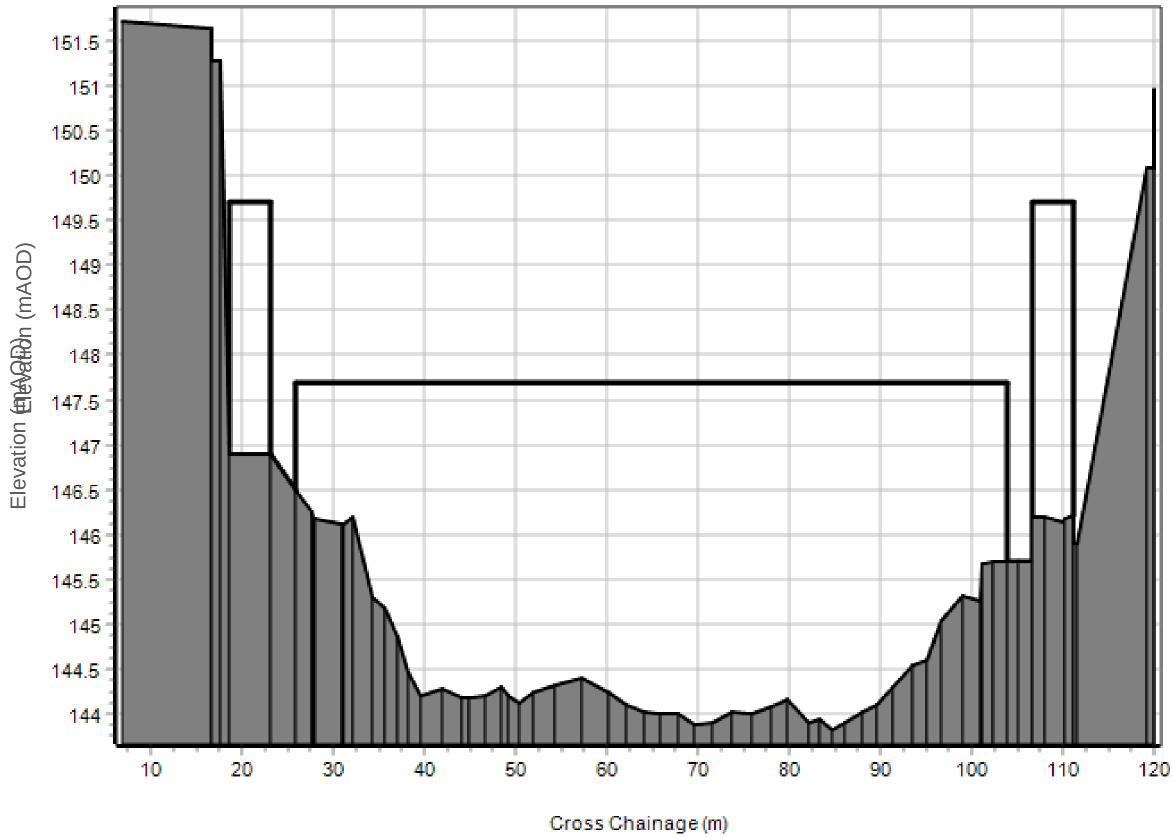
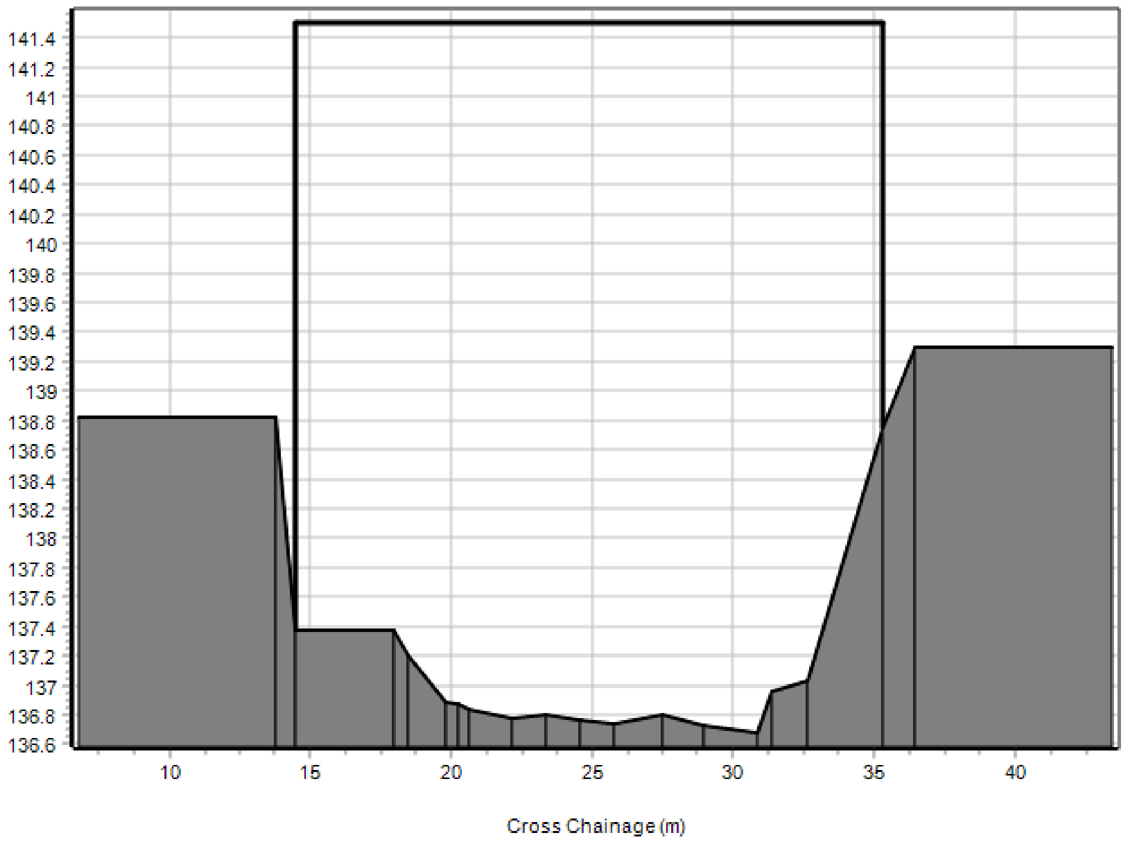


Diagram 15: Allt Bhaic Underbridge proposed scheme design schematisation



2D Model Updates

5.1.5 The proposed scheme elevations were exported from the MXROAD software as raster grids (GeoTIFF), for inclusion in the hydraulic model. Within the footprint of the proposed scheme these raster grids replaced the ground elevation with the elevations for the road embankments (as ASCII raster). The surface roughness values within the proposed scheme footprint were also updated.

5.1.6 A number of SuDS features are included in the proposed scheme. These have been included in the model with an initial water level set such that the retention ponds and detention basins are already full with water at the start of the simulation.

5.1.7 Model V/VI includes modifications to the floodplain structures for the minor watercourse culverts under the A9. Table 10 summarises these changes.

Table 10: Floodplain hydraulic structure modifications

Model	Structure	Type	Dimensions (m)	Length (m)	Upstream Invert Level (mAOD)	Downstream Invert Level (mAOD)
Model V/VI	WC116	Circular Culvert	1.2	83.8	138.838	138.176
Model V/VI	WC121	Circular Culvert	1.5	71.2	153.325	142.090
Model V/VI	WC122	Circular Culvert	0.9	78.3	144.284	143.377
Model V/VI	WC117	Circular Culvert	0.6	58.0	141.750	139.160
Model V/VI	WC118	Rectangular Culvert	1.5x1.2	49.3	145.788	140.180
Model V/VI	WC119	Circular Culvert	1	70.7	148.954	140.740

6 Modelled Events

6.1.1 Table 11 shows the AEP flood events and model scenarios that were simulated with the two hydraulic models.

Table 11: Modelled events

Model	Scenario	AEP Event			
		50% (2-year)	3.33% (30-year)	0.5% (200-year)	0.5% (200-year) + CC
Model V	Baseline	✓	✓	✓	✓
Model V	Roughness Sensitivity				✓
Model V	Hydrological Inflow Sensitivity				✓
Model V	Downstream Boundary Sensitivity				✓
Model V	Proposed Scheme	✓	✓	✓	✓
Model V/VI	Baseline	✓	✓	✓	✓
Model V/VI	Roughness Sensitivity				✓
Model V/VI	Hydrological Inflow Sensitivity				✓
Model V/VI	Downstream Boundary Sensitivity				✓
Model V/VI	Proposed Scheme	✓	✓	✓	✓

7 Model Proving

Model Performance

7.1.1 Run performance has been monitored throughout the model build process and then during each simulation carried out, to ensure a suitable model convergence was achieved. Convergence refers to the ability of the modelling software to arrive at a solution that is close to the exact solution within a pre-specified error tolerance.

7.1.2 As shown in Diagram 16 and Diagram 17, the only 1D non-convergence issues occurred at the very start of the model run and did not affect the model results. These convergence plots are typical for all the modelled events.

7.1.3 The cumulative mass error reports output from the TUFLOW 2D model have been checked. The accepted tolerance range recommended by the software manual is +/- 1% mass balance error. Diagram 18 and Diagram 19 show that for the 0.5% AEP (200-year) plus CC flood event for both models the cumulative mass error is well within this tolerance range for the majority of the run. Both models have an initial spike in the cumulative mass error which is outside the tolerance range. However, this spike occurs before there is significant volume of water in the model and is therefore deemed acceptable. This mass error diagnostic is typical for all events simulated.

7.1.4 The change in volume through the model simulation has also been checked and has been found to vary relatively smoothly which is another indicator of good convergence of the 2D model.

Diagram 16: Model convergence plot - Model V

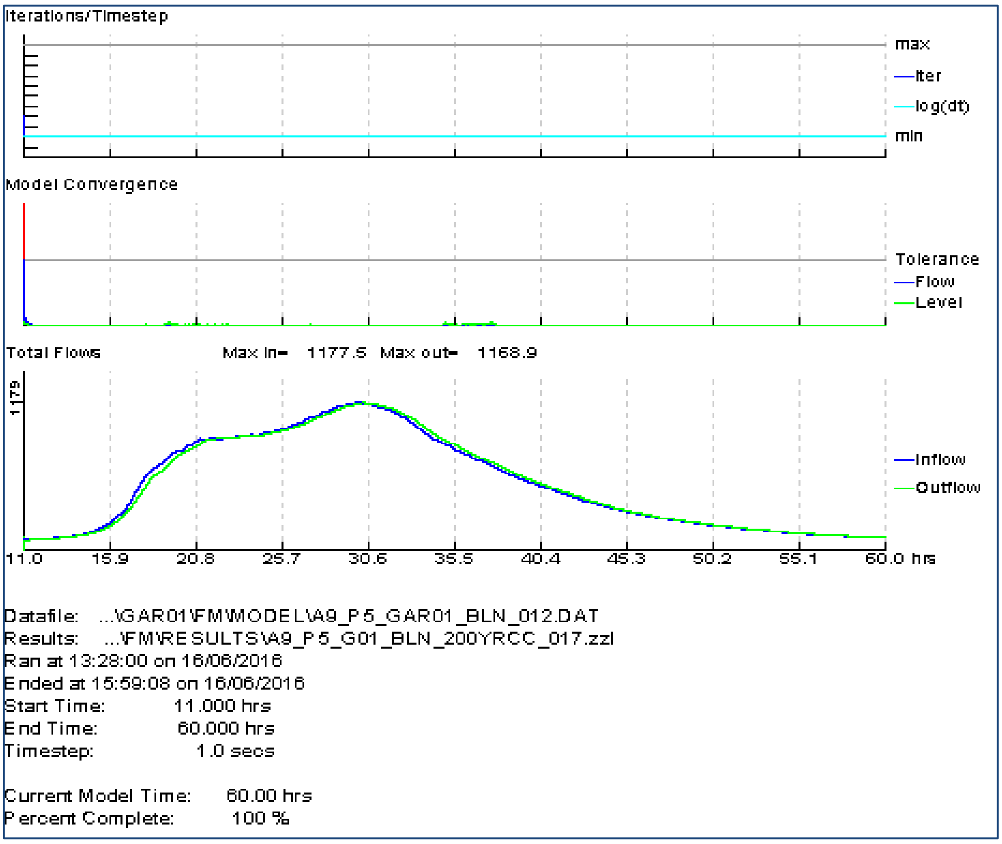


Diagram 17: Model convergence plot - Model VI

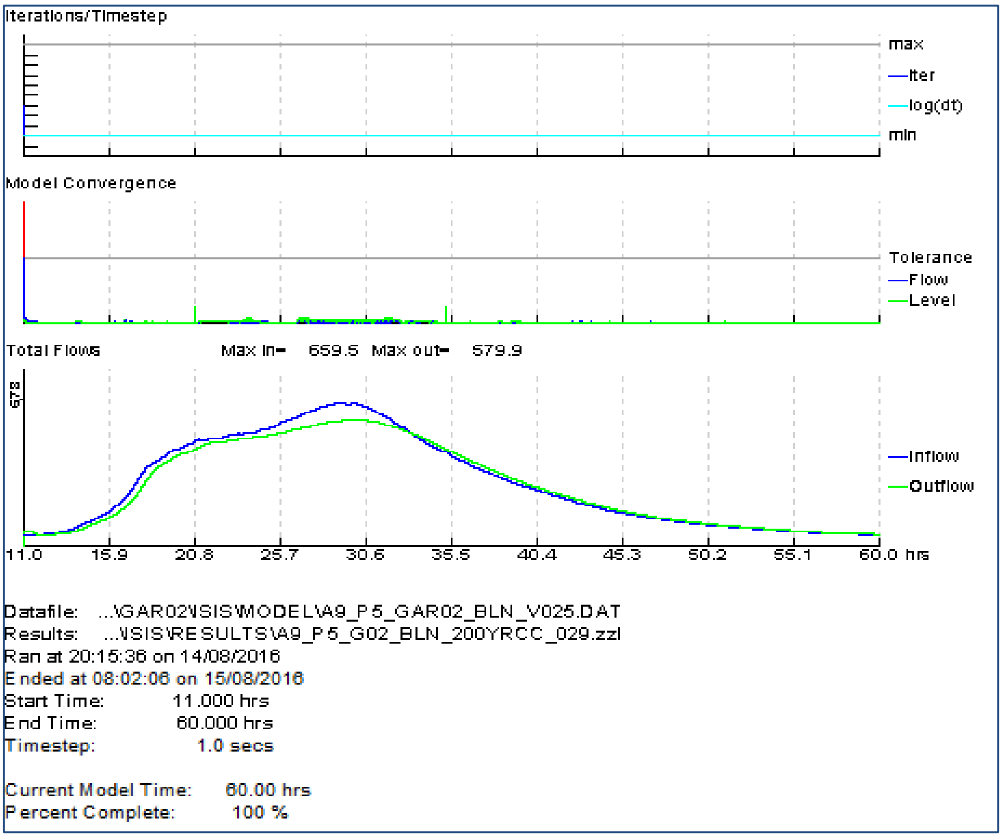


Diagram 18: Cumulative mass error and change in volume Model V 0.5% AEP plus CC event

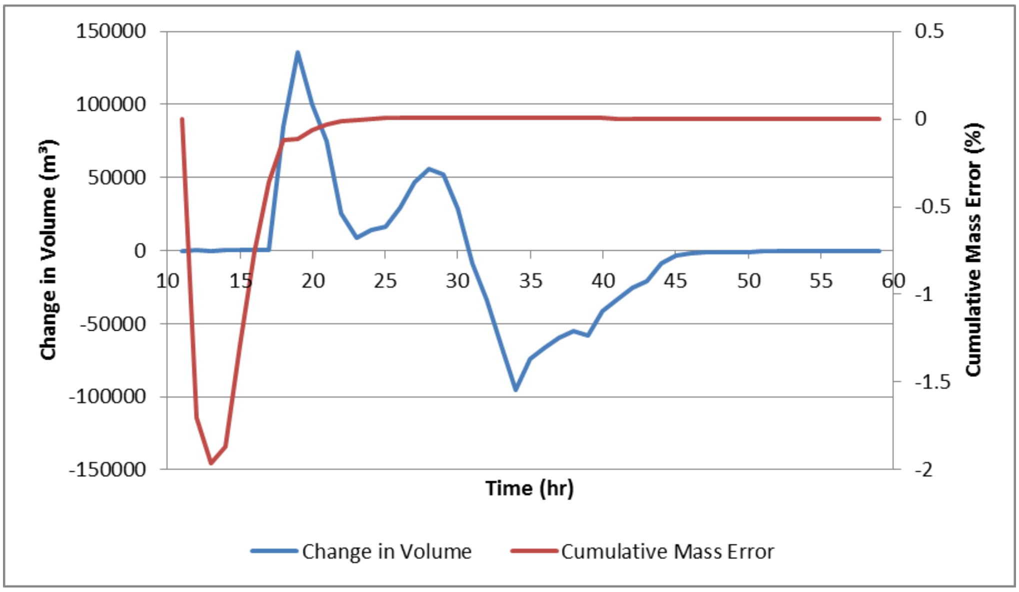
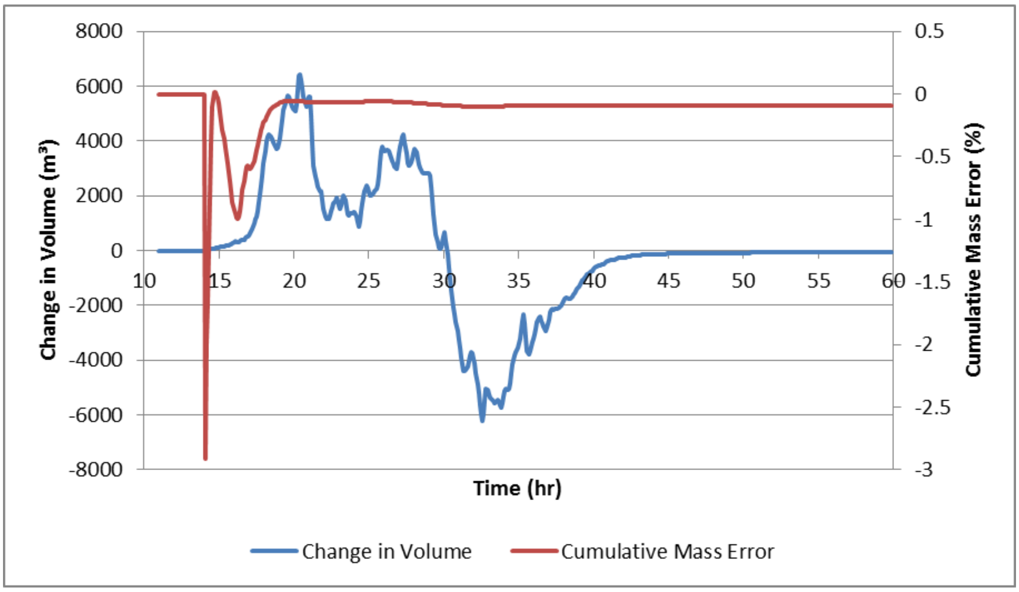


Diagram 19: Cumulative mass error and change in volume Model VI 0.5% AEP plus CC Event



Calibration and Verification

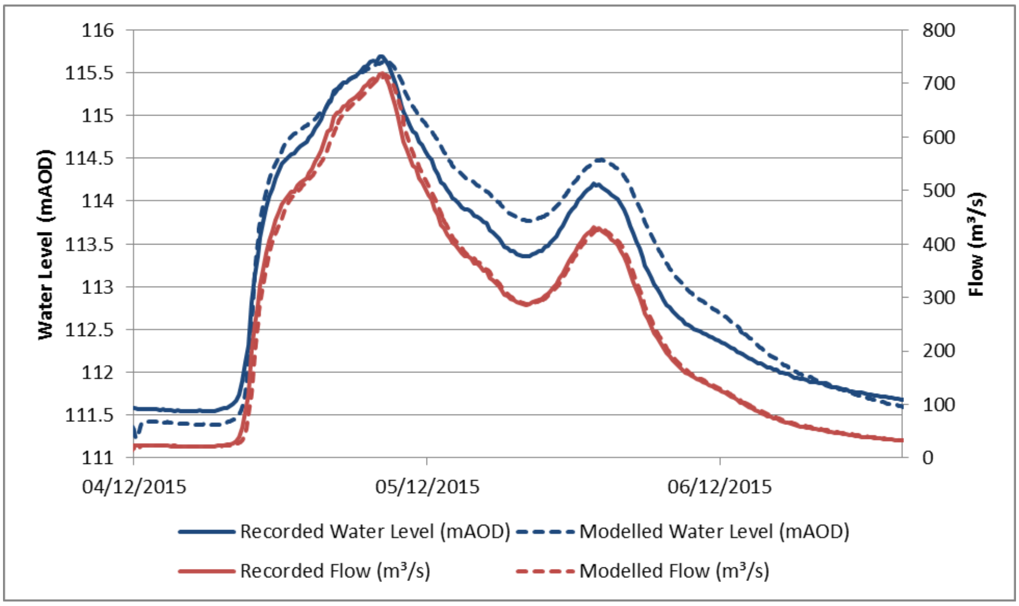
Calibration

7.1.5 A gauge is located on the River Garry at Killiecrankie, near the downstream extent of Model V for which 15-minute time series data for stage and flow has been provided by SEPA. From this data three historic events were extracted and used for model calibration: 5 December 2015, 13 December 2006 and 17 January 1993. For the December 2015 event the full time series for both the stage and the flow were available, however for the other two events the full time series was available for the flow but only the peak stage at the gauge was available. The observed flows were input at the upstream end of the model and the modelled water level results were compared against the recorded stage at the gauge location.

7.1.6 Initially the modelled water level results were different to the observed levels and it quickly became apparent that the roughness parameter was not the right parameter to use for calibration if roughness values were to be kept within a reasonable range. Instead, a good match was achieved by modifying the slope of the downstream boundary. The final value used is in agreement with the average slope at the downstream end of the model.

7.1.7 The flow and water level time series from the gauge are shown in Diagram 20, alongside the model results. As the gauge is located in between nodes GAR01_0150 and GAR01_0225 in the model, the average of the results from these two nodes was used for comparison. Diagram 20 shows that there is good agreement between the water levels on the rising limb as well as at the peak. The match between the model results and the recorded results is not so good on the receding limb. A possible cause for this could be changes in the channel geometry caused by the flood event which cannot be reflected in our fixed geometry model. The model results provide a conservative picture.

Diagram 20: Model V calibration results for December 2015 event



7.1.8 A summary of the maximum water level results for all three events is provided in Table 12, showing that peak water levels within 100mm of the gauge records were achieved for all three events.

Table 12: Model V calibration results

Flood Event	Maximum Recorded Water Level (mAOD)	Maximum Modelled Water Level (mAOD)	Difference (m)
December 2015	115.684	115.632	-0.052
December 2006	115.406	115.456	0.050
January 1993	114.979	115.011	0.032

7.1.9 By changing the downstream boundary slope successful calibration of the model was achieved. It should be noted that the results of the sensitivity analysis, discussed in the following sections show that changes to the downstream boundary do not affect model results at the scheme.

7.1.10 No data was available to calibrate Model V/VI.

Verification

7.1.11 As no calibration data was available for Model V/VI, a high level verification of the model was undertaken by comparing the 0.5% AEP (200-year) flood event extent predicted by the model with the corresponding medium likelihood flood extent (0.5% AEP (200-year) event) on the SEPA Flood Map. Diagram 21 and Diagram 22 show the comparison between the two flood extents for both models. The model results generally show larger flood extents than SEPA Flood Maps. This difference can be attributed to the better and more detailed representation of the modelled area. Although no hydrometric station and hence SEPA predicted flow is available within the Model V/VI modelling extent, the hydrological inflows applied to the model are in line with the inflows predicted by SEPA at Killiecrankie on the River Garry located further downstream of this model.

Sensitivity Analysis

7.1.13 In order to test the model sensitivity to key hydraulic parameters a series of simulations were undertaken for the baseline 0.5% AEP plus CC event. The assessed hydraulic parameters were: Manning's 'n' roughness coefficients, hydrological inflows and downstream boundary slope.

Roughness Sensitivity

7.1.14 In-channel and floodplain roughness coefficients (Manning's 'n') were changed by +20% and -20%. Table 13 and Table 14 show the impact of changing the model roughness on the 1D in-channel water levels for the two models. Diagram 23 and Diagram 24 show the impact on the 2D maximum flood extents. The results show that the in-channel water levels are highly sensitive to changes in roughness coefficients, and there is some variability in the 2D extents in the location of the proposed scheme.

7.1.15 One of the implications of the increased roughness on the A9 structures would be that part of the freeboard applied in the design of structures (which is generally 600mm), would be reduced if the water levels are higher as predicted by the model. However, the increase of 319mm and 205mm at the A9 bridge for Model V and Model V/VI respectively, is well within the overall freeboard tolerance applied in the structure design.

7.1.16 Comparison of the flood extents between the baseline and increased roughness results shows that no additional receptors are likely to be affected as a result of the increased roughness in Model V or Model V/VI.

7.1.17 As discussed in section 4.1.3 roughness values have been chosen based on site observations and photographs and by consulting the relevant literature and are considered to be appropriate.

Table 13: Model V roughness sensitivity results

Sensitivity	Water Level Difference (m)			Water Level Difference at the Scheme (m)
	Max	Min	Average	GAR01_1452bu
+20% Roughness	0.616	0.000	0.166	0.319
-20% Roughness	0.000	-0.716	-0.169	-0.310

Table 14: Model V/VI roughness sensitivity results

Sensitivity	Water Level Difference (m)			Water Level Difference at the Scheme (m)	
	Max	Min	Average	GAR02_3857bu	ALB01_0110i
+20% Roughness	0.442	0.000	0.226	0.205	0.341
-20% Roughness	0.000	-0.541	-0.261	-0.251	-0.283

Hydrological Inflow Sensitivity

7.1.18 The flows into the model were adjusted by +20% and -20%. Table 15 and Table 16 show the impact of changing model inflows on the 1D in-channel water levels for the two models and the 2D maximum flood extents are shown in Diagram 25 and Diagram 26. The model responses are found to be highly sensitive to changes in flow, and again there is some variability in the 2D extents in the location of the scheme.

7.1.19 Comparison of the baseline 0.5% AEP plus CC event with the 20% increased flow results show that flood extents are similar across most of the model with only one additional receptor (House of Bruar) potentially being affected in Model V/VI.

7.1.20 The details about the generation of model inflows can be found in Appendix A11.2 (Surface Water Hydrology).

Table 15: Model V flow sensitivity results

Sensitivity	Water Level Difference (m)			Water Level Difference at the Scheme (m)
	Max	Min	Average	GAR01_1452bu
+20% Flow	0.777	0.000	0.195	0.432
-20% Flow	0.000	-0.773	-0.216	-0.460

Table 16: Model V/VI flow sensitivity results

Sensitivity	Water Level Difference (m)			Water Level Difference at the Scheme (m)	
	Max	Min	Average	GAR02_3857bu	ALB01_0110i
+20% Flow	0.870	-0.018	0.254	0.208	0.756
-20% Flow	0.000	-0.755	-0.289	-0.187	-0.425

Downstream Boundary Condition Sensitivity

7.1.21 The slope of the downstream boundaries in the 1D models were adjusted by +20% and -20%. The results show that the changes to the downstream boundary only affect the downstream ends of the models.

7.1.22 Table 17 and Table 18 show the response at the downstream boundary of Model V and Model V/VI respectively. The locations at which there is no change in water level as a result of changing the boundary have been identified. Distances from these locations, in relation to the downstream end of the models (tailwater distance) and in relation to the proposed scheme, are included in the tables. The results indicate that the proposed scheme is outside of the influence of the downstream boundary for both models.

Table 17: Model V downstream boundary sensitivity results

Sensitivity	Water Level Difference (m) at the Downstream Boundary (GAR01_0000)	Tailwater Distance (m)
+20% Downstream Boundary Slope	-0.324	1020 (This is approximately 420m downstream of Essangal Underbridge)
-20% Downstream Boundary Slope	0.280	1020

Table 18: Model V/VI downstream boundary sensitivity results

Sensitivity	Water Level Difference (m) at the Downstream Boundary (GAR02_0000)	Tailwater Distance (m)
+20% Downstream Boundary Slope	-0.189	570 (This is approximately 860m downstream of the Allt Bhaic confluence with the River Garry)
-20% Downstream Boundary Slope	0.146	570

Diagram 21: Model V modelled 0.5% AEP (200-year) flood event extent vs. SEPA medium likelihood fluvial extent

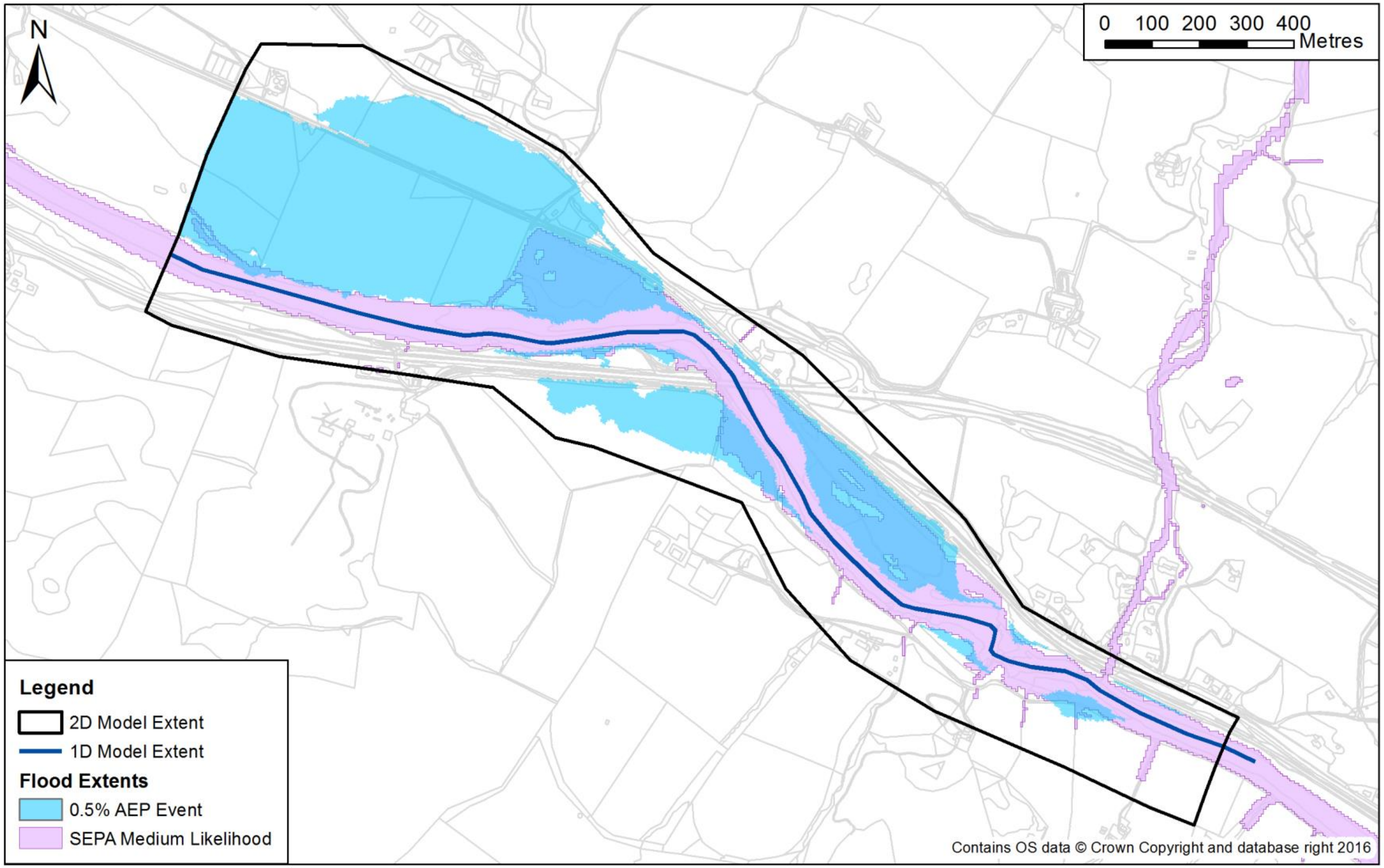


Diagram 22: Model V/VI modelled 0.5% AEP (200-year) flood event extent vs. SEPA medium likelihood fluvial extent

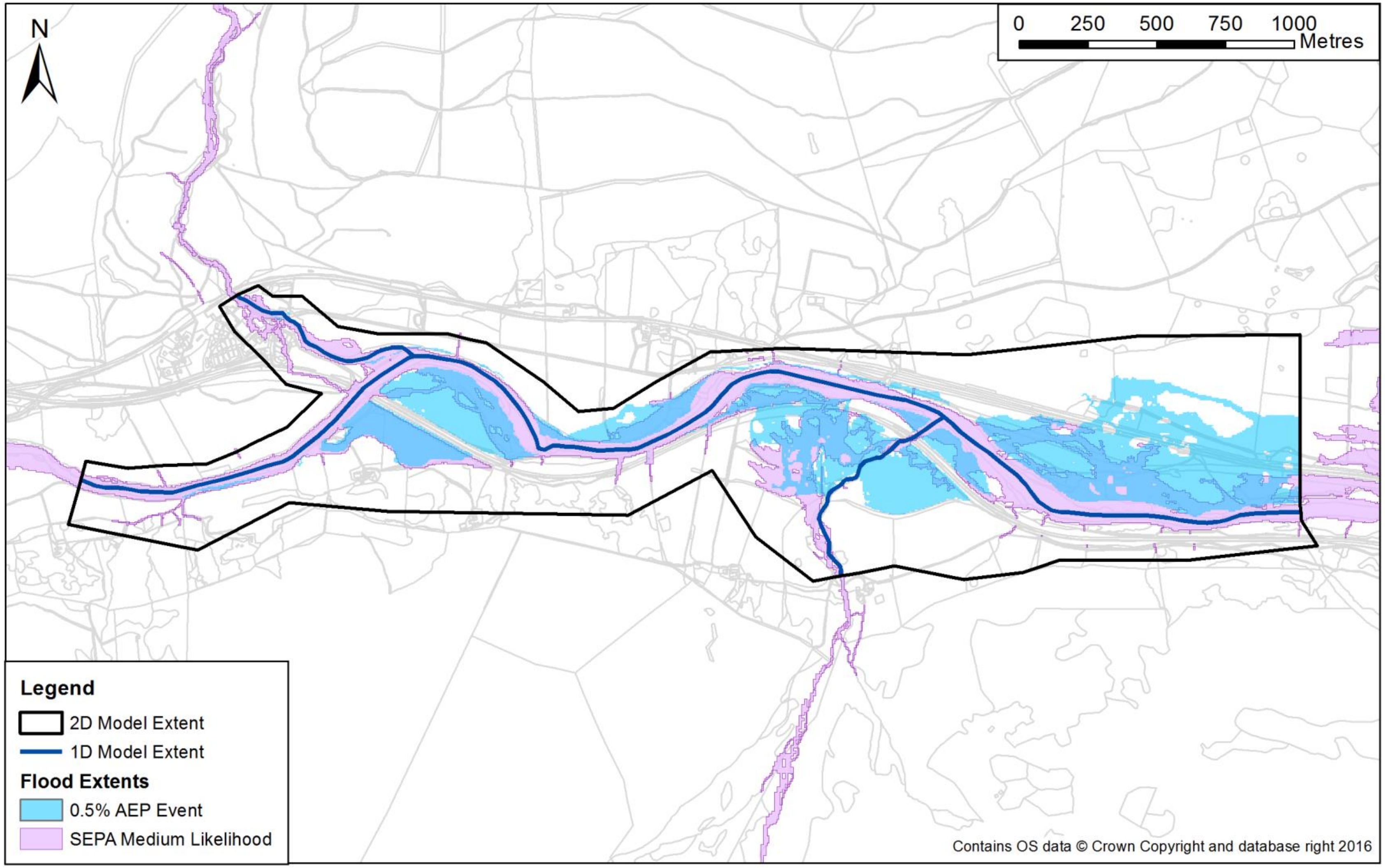


Diagram 23: Model V roughness sensitivity results

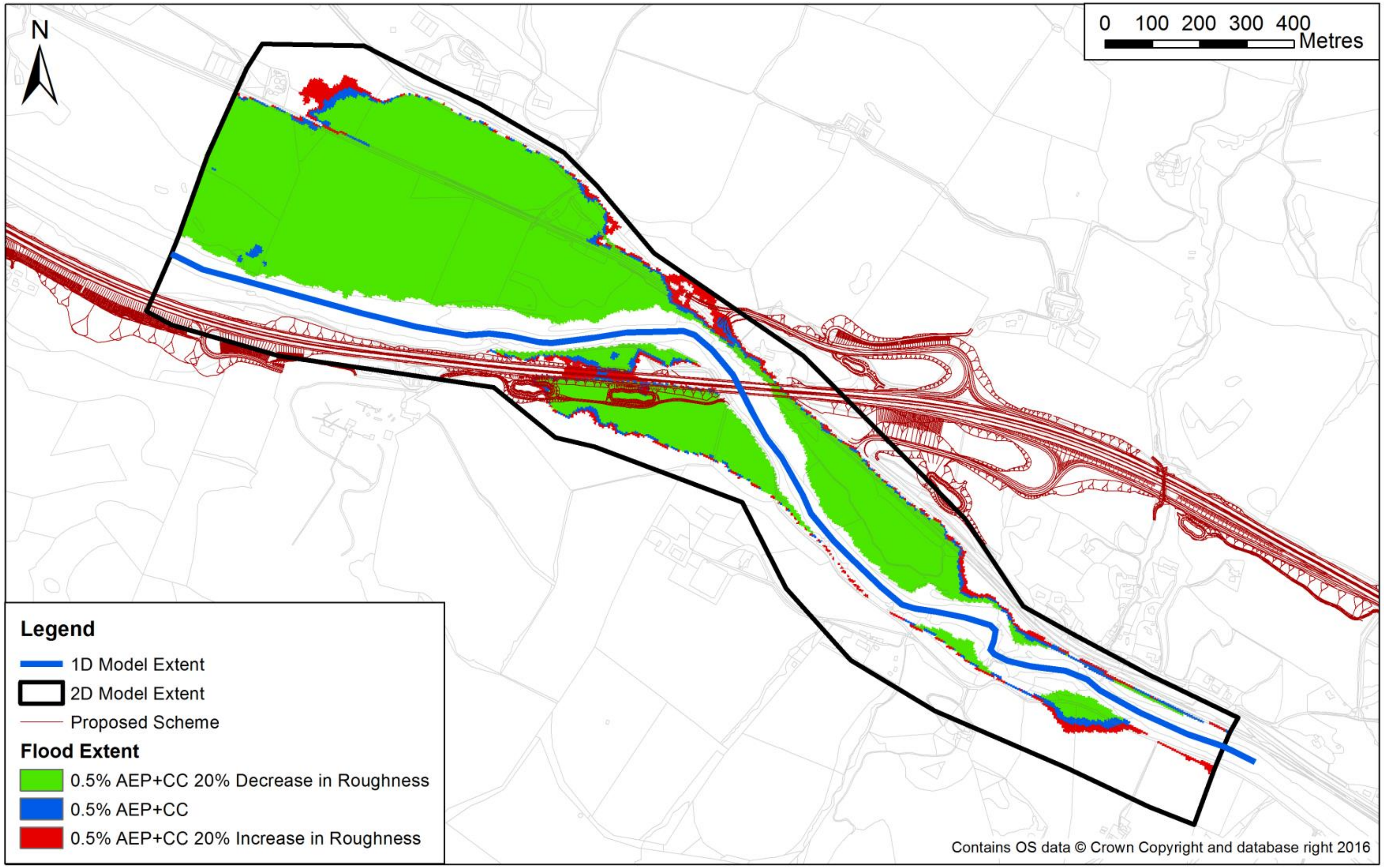


Diagram 24: Model V/VI roughness sensitivity results

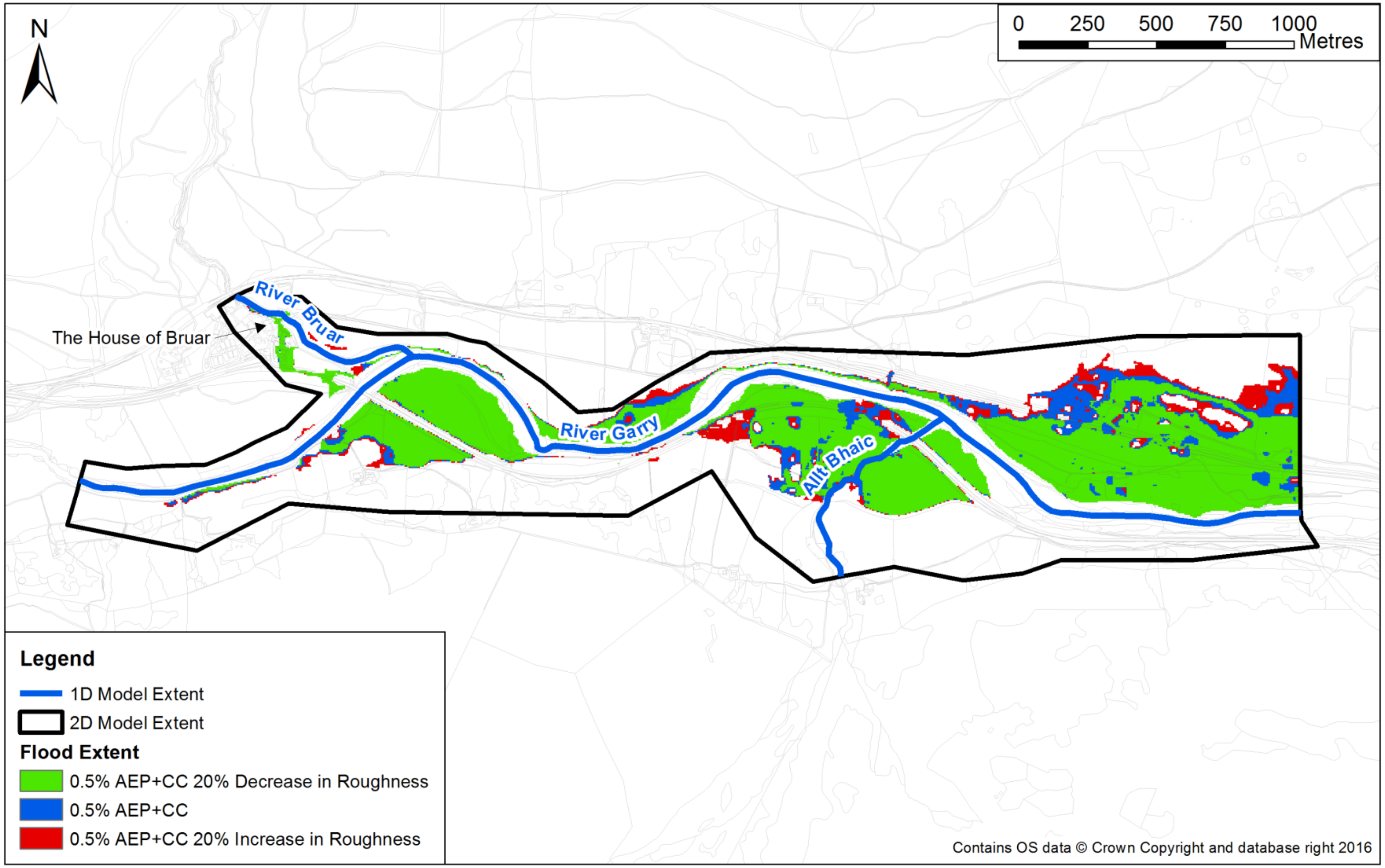


Diagram 25: Model V inflow sensitivity results

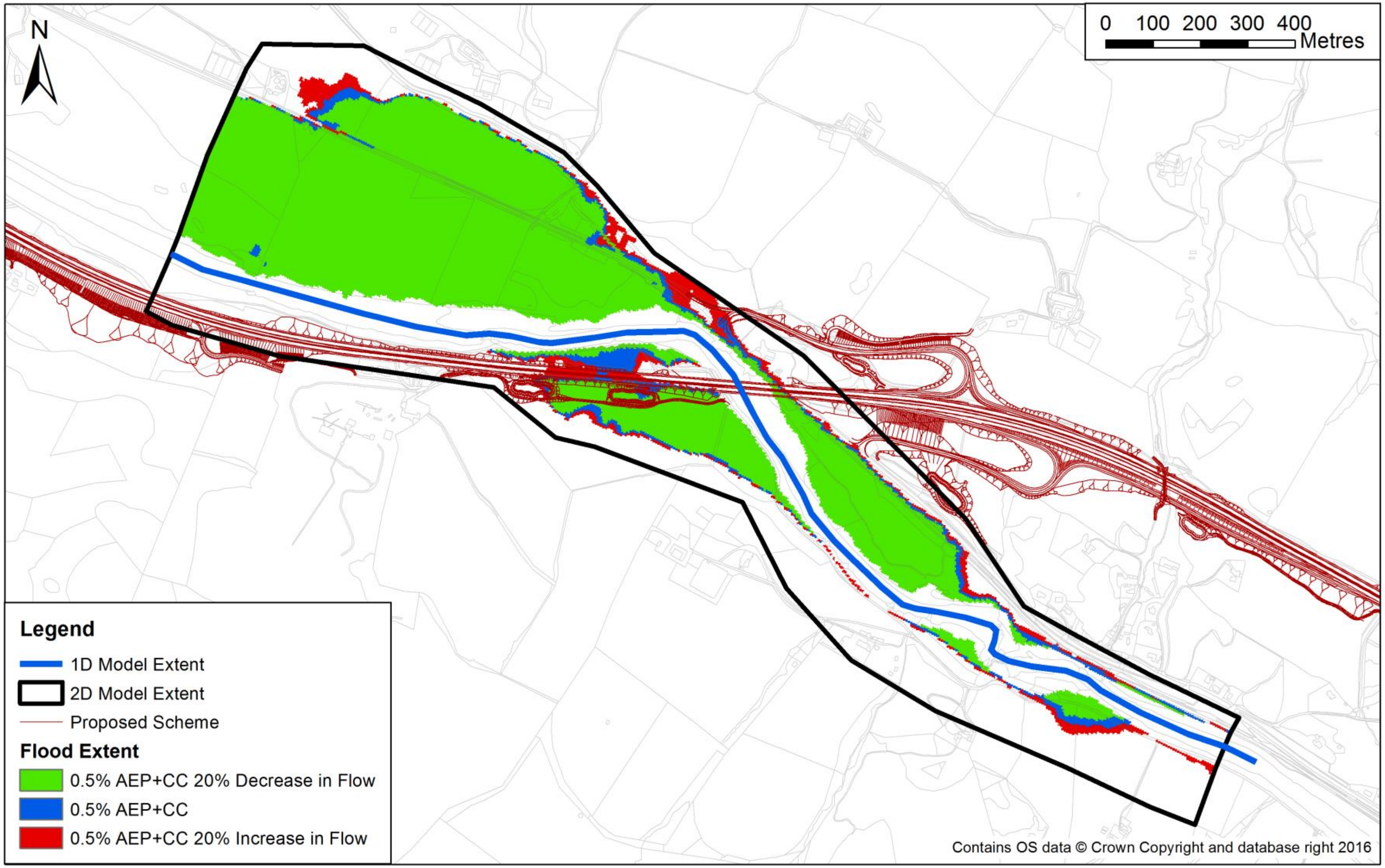
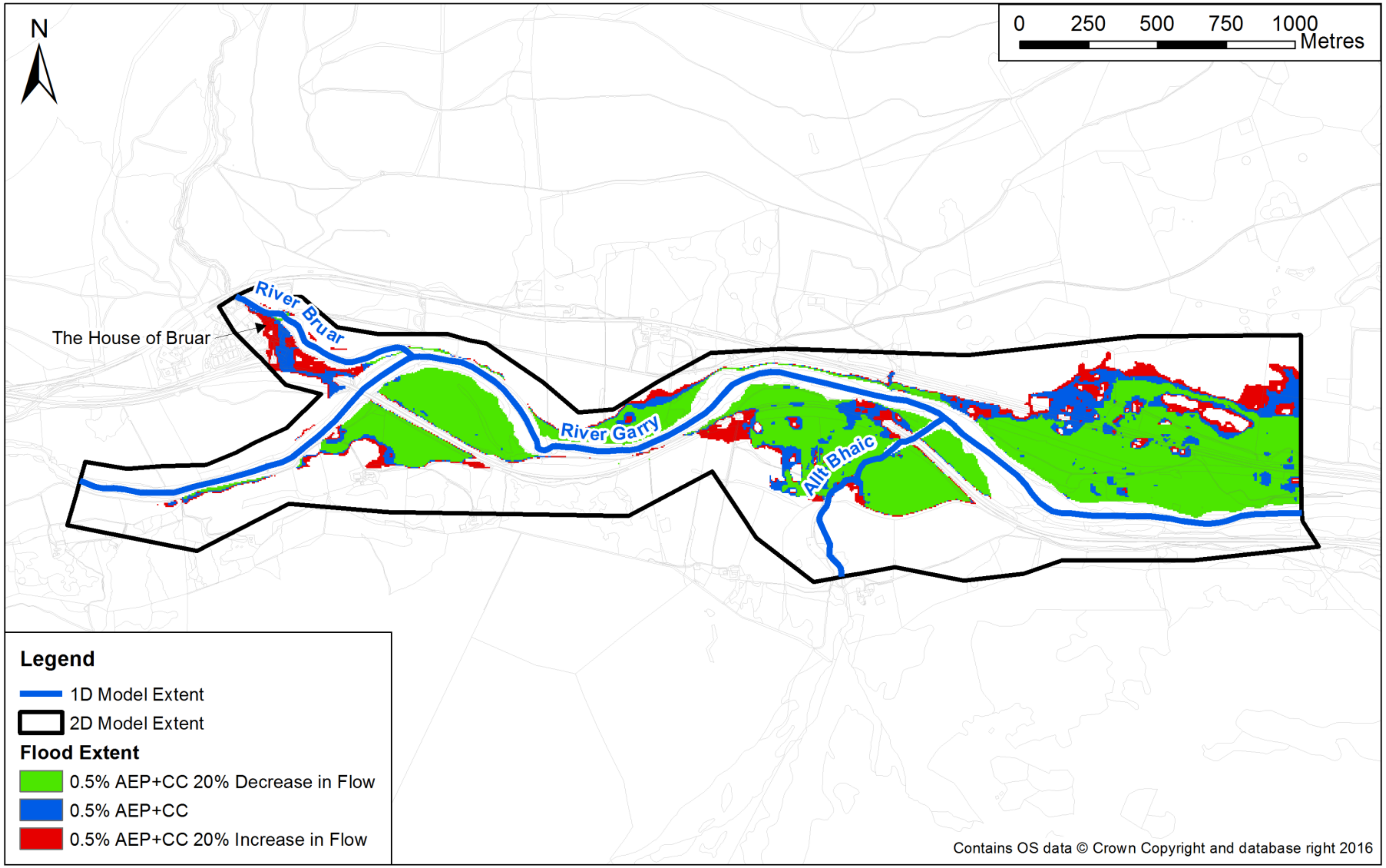


Diagram 26: Model V/VI inflow sensitivity results



8 Model Assumptions and Limitations

Introduction

8.1.1 The accuracy and validity of the hydraulic model results is heavily dependent on the accuracy of the hydrological and topographic data included in the model. While the most appropriate available information has been used to construct the model to represent fluvial flooding mechanisms, there are uncertainties and limitations associated with the model. These include assumptions made as part of the model build process.

8.1.2 Efforts have been made to assess and reduce levels of uncertainty in each aspect of the modelling process. The assumptions made are considered to be generally conservative for modelled water levels at the proposed scheme location and are therefore appropriate for the flood risk assessment. Additionally, the sensitivity analysis has quantified the magnitude of potential uncertainty, and the calibration and verification process indicates that the modelling outputs are sensible.

8.1.3 The following sections summarise the key sources of uncertainty in addition to the limitations associated with the modelling undertaken for Models V and VI.

1D Domain

Channel Roughness

8.1.4 Channel roughness has been assigned using the best available information (site visit, survey data and aerial photographs). The roughness values are based on available guidance (Chow 1959). The channel roughness values may vary over the year and the sensitivity tests have been carried out to quantify the impact.

Representation of Structures

8.1.5 Hydraulic coefficients for structures have been applied using available guidance within the Flood Modeller software. The dimensions for structures have been based on detailed survey measurements for baseline scenario and using the detailed structural drawing for the proposed scheme.

Downstream Boundary Conditions

8.1.6 The downstream boundary condition is free discharge type without any downstream control. This is deemed appropriate as the boundary is sufficiently downstream of the proposed scheme location. In addition, the sensitivity analysis has shown that changes to the downstream boundary do not affect water levels in the location of the scheme.

2D Domain

Floodplain Topography

8.1.7 The floodplain topography has been represented using 5m resolution photogrammetry data, which is acceptable for the DMRB Stage 3 assessment.

8.1.8 The connectivity of the river channel and the floodplain at the banks for River Garry and River Bruar is based on the DTM. The DTM data did not capture the channel shape for Allt Bhaic and the channel alignment and the bank levels are informed by the surveyed cross sections.

Floodplain Structures

8.1.9 Floodplain structures have only been included where they were considered to have an impact on flow mechanism. Levels and dimensions have been taken from DTM and OS Mastermap data as these were not surveyed.

Grid Size

8.1.10 A 5m grid has been used. This is suitable to represent most of the floodplain features across the Model V and Model V/VI extents to an appropriate level of detail. Finer features have been incorporated into the grid using breaklines.

DTM Modifications

8.1.11 Breaklines and elevation polygons have been used as required to better represent topographic features. Elevations for these features have been informed by the DTM data.

8.1.12 For the proposed scheme, the existing ground levels were modified within the proposed scheme footprint from the MXROAD software.

Blockage Scenario

8.1.13 Considering the large size of the bridge openings, it is considered unrealistic that these structures would experience blockage during flood event conditions. As such no blockage sensitivity scenarios were considered.

Model Calibration

8.1.14 Model V/VI was unable to be calibrated due to lack of observed data in the modelled area.

9 Conclusion

9.1.1 This report has detailed the modelling carried out to assess the baseline flood risk for two areas along the River Garry with reference to the location of the proposed scheme. A 2730m reach of the River Garry around Essangal Underbridge was represented in Model V and a 5000m reach of the River Garry around the proposed River Garry Underbridge at Pitaldonich along with parts of the tributaries River Bruar and Allt Bhaic were represented in Model V/VI. A range of flood events from 50% to 0.5% AEP plus CC events were simulated.

9.1.2 The proposed scheme was then incorporated into the models for the design scenarios in order to assess its impact on the baseline flood risk.

9.1.3 Model results have been used to inform the Flood Risk Assessment and are presented in Appendix A11.3 (Flood Risk Assessment) of the Environmental Statement.

10 References

Chow, Ven Te (1959). Open-Channel Hydraulics. McGraw-Hill.

Annex A: Minor Watercourse Modelling

Introduction

Hydraulic modelling has been undertaken for nine minor watercourses where it was identified during preliminary assessments that there could potentially be adverse flood impacts as a result of the proposed scheme. These minor watercourses were explicitly modelled in order to better define the baseline flood risks and the impacts to and from the proposed scheme.

Methodology

The nine minor watercourses have been modelled using a combination of 1D and 2D approaches in Flood Modeller Pro, TUFLOW and InfoWorks ICM as shown in Table 19.

All models have been run for both the baseline and proposed scheme scenarios with the exception of WF164. The purpose of modelling WF164 was to ensure that there was no risk of flooding to a SuDS feature alongside the watercourse. As the baseline model results showed that flow remained within the channel in the 0.5% AEP (200-year) plus CC flood event and the SuDS feature was not at risk there was no need to model the design scenario.

Hydrological inflows were derived based on the appropriate critical storm durations for each watercourse. The peak flows for the hydrographs routed through the hydraulic models are included in Table 19 These inflows have been applied at the upstream boundary of each of the 1D models, with the exception of WF92 which is discussed in more detail below.

Table 19: Minor watercourse model summary

Watercourse	Approach	Software	Modelled Events	Peak Hydrological Inflow
WF87	1D only	Flood Modeller Pro	0.5% AEP + CC	4.42m³/s
WF92	1D/2D	TUFLOW	3.33% AEP 1% AEP 0.5% AEP + CC	1.86m³/s 2.37m³/s 3.26m³/s
WF117	1D/2D	Flood Modeller Pro TUFLOW	0.5% AEP + CC	2.52m³/s
WF132	1D/2D	InfoWorks ICM	3.33% AEP 0.5% AEP + CC	0.83m³/s 1.79m³/s
WF134	1D/2D	InfoWorks ICM	3.33% AEP 0.5% AEP + CC	0.83m³/s 1.79m³/s
WF136	1D/2D	InfoWorks ICM	3.33% AEP 0.5% AEP + CC	0.76m³/s 1.65m³/s
WF145	1D/2D	InfoWorks ICM	0.5% AEP + CC	2.98 m³/s
WF156	1D/2D	Flood Modeller Pro TUFLOW	0.5% AEP + CC	2.89m³/s
WF164	1D only	Flood Modeller Pro	3.33% AEP 0.5% AEP + CC	24.98m³/s 47.46m³/s

In-channel geometry has been informed by surveyed cross sections for all of the modelled watercourses and hydraulic roughness (Manning's 'n' coefficient) values have been defined based on in–channel photographs. All hydraulic structures included within the minor watercourse models are shown in Table 20.

Ground levels for the 2D domains have been obtained from the topographic survey data provided by BLOM and the 5m photogrammetry DTM. Proposed road levels have been included in the design scenarios where required. Hydraulic roughness coefficients have been applied across each cell of the 2D domain based on land use categories.

With the exception of WF92 no inflow has been applied directly to the 2D domain; instead all 2D flows come from overtopping of the 1D model. The link between the 1D and the 2D domains has been defined along the top of the banks.

Table 20: Minor watercourse modelled hydraulic structures

Watercourse	Structure	Baseline Model Schematisation	Proposed Design Schematisation
WF87	A9 Culvert	2.5m x 2.5m rectangular conduit	Dimensions unchanged Culvert extended downstream
WF92	A9 Culvert	0.89m diameter circular conduit	2.1m x 2.4m rectangular conduit Culvert extended upstream and downstream
	B8079 Culvert	0.6m diameter circular conduit (assumed from site observations)	No changes
WF117	A9 Culvert	0.6m diameter circular conduit	Dimensions unchanged Culvert moved upstream to new road location
	Downstream Culvert	0.6m diameter circular conduit	No changes
WF132	A9 Culvert	1m diameter circular conduit	1.4m diameter
	B847 Culvert	0.6m diameter circular conduit	No changes
	Railway Culvert	1m diameter circular conduit	No changes
WF134	A9 Culvert	1m diameter circular conduit	1.4m diameter Culvert inlet moved upstream
	Access Crossing 1	0.55m diameter circular conduit	No changes
	Access Crossing 2	0.6m diameter circular conduit	No changes
	B847 Culvert	0.9m diameter circular conduit	No changes
	Railway Culvert	0.5m x 0.47m rectangular conduit	No changes
	A9 Underpass	1.9m diameter circular conduit	No changes
WF136	A9 Culvert	0.67m diameter circular conduit	1.2m diameter Culvert inlet moved upstream and outlet lowered with channel regraded downstream
	B847 Culvert	0.6m diameter circular conduit	No changes
WF145	A9 Culvert	1.2m diameter circular conduit	1.5m diameter Culvert inlet moved upstream and outlet lowered with channel regraded downstream Additional inflow of 0.31m³/s included from WF146 which will be diverted into WF145 upstream of the A9.
	Clunes Lodge Access Road Culvert	0.75m diameter circular conduit	No changes
WF156	A9 Culvert	0.68m diameter circular conduit	1.8m x 2.4m rectangular conduit Culvert inlet moved upstream and outlet lowered with channel regraded downstream
	U521 Culvert	0.7m x 0.3m rectangular conduit (culvert inlet blocked by debris)	0.7m x 0.8m after removal of built up debris
WF164	A9 Bridge	Arch bridge unit	Design scenario not modelled
	Downstream Bridge	Arch bridge unit	Design scenario not modelled

In all cases run performance has been monitored to ensure a suitable model convergence was achieved and that mass balance errors were within the accepted tolerance range.

Results

Model results are presented in Appendix A11.3 (Flood Risk Assessment) of the Environmental Statement.

WF92 Modelling Methodology

WF92 does not include a 1D component for the open channel due to the small size and steep gradient of the channel and limitations on the available survey data. The model has been built in TUFLOW only with the A9 and B8079 culverts represented as 1D ESTRY components. The available survey data upstream and downstream of the A9 has been represented using a gully line for the bed level and breaklines for the top of bank. The hydrological inflow has been applied at the upstream end of the gully line.

Surveys were not able to be undertaken for much of the downstream area, therefore dimensions for the B8079 culvert have been assumed based on site visit observations and the channel depth has been extrapolated from the upstream survey. In order to test the sensitivity of the model results to these assumptions two test runs were undertaken. The first increased the depth and width of the channel by 50%, and the second also increased the diameter of the B8079 culvert from 0.6m to 1m diameter. The effects of these changes on the model results were not considered to be significant.

As discussed in Appendix A11.3 (Flood Risk Assessment) of the Environmental Statement, in the case of WF92 the additional flow being passed forward by the upsized culvert under the A9 leads to increased flood risk at some downstream properties. Therefore, for this watercourse mitigation options have been considered including upstream flood storage, floodplain earth embankments, additional culverts underneath the B8079 and the HML railway, and upstream flow diversions. These options have been considered within the hydraulic model and conceptually looking at ground levels and flood hydrographs.