

Appendix A11.4: Hydraulic Modelling Report

1 Introduction

Purpose of the Hydraulic Modelling

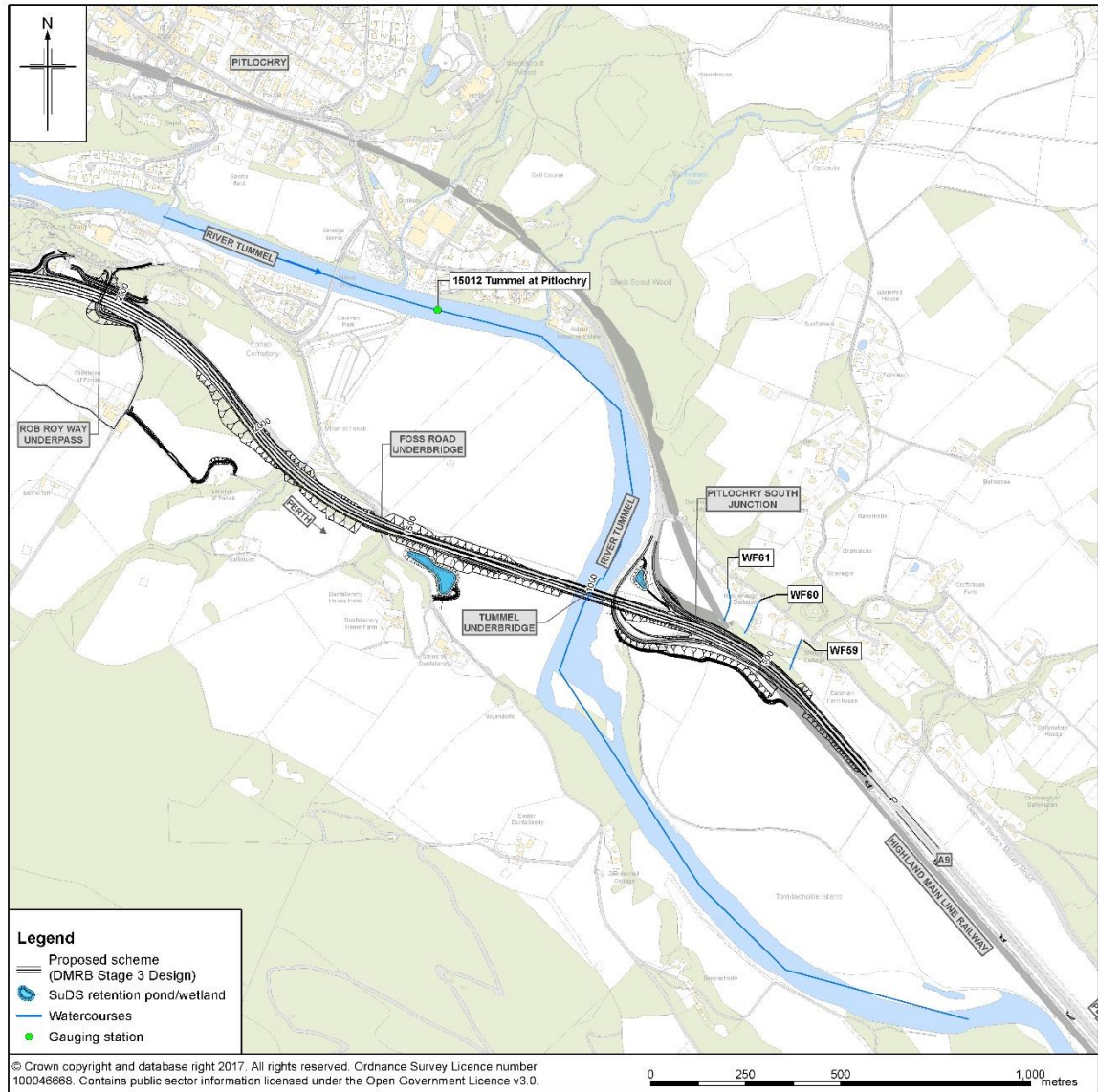
- 1.1.1 This Hydraulic Modelling Report provides detailed information on the hydraulic model build process undertaken to assess the risk of fluvial flooding from the River Tummel to the proposed scheme between Pitlochry and Killiecrankie (The hydraulic model is referred to as “A9 Model IV”).
- 1.1.2 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 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

- 1.1.4 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 4.2 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.
- 1.1.5 The hydraulic modelling aimed to predict the peak water level within the modelled river reach and the floodplain for the 3.33% AEP (30-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

Diagram 1: Illustration of the extent of the modelling work undertaken for the proposed scheme



- 1.1.6 A hydraulic model was constructed to understand the flood risk from the River Tummel to the existing A9. The model covers a 3500m long reach of the River Tummel around the Tummel Bridge near the Mains of Dunfallandy. The upstream end of the model is approximately 450m downstream of the Loch Faskally dam.
- 1.1.7 Three key lateral tributaries; WF59, WF60 and WF61, were also represented within the model arrangement, these are described further in Section 4.2 (Baseline Monitoring).
- 1.1.8 The model extents were chosen based on the key locations where the River Tummel 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.

2 Input Data

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

Table 1: Data used to build the hydraulic model.

Data	Description	Source
Digital Terrain Model (DTM)	1m horizontal resolution LiDAR DTM (Flown in 2011).	Emapsite
OS maps	Background maps and Master Map data	Ordnance Survey
BLOM topographic survey	Detailed topographic survey of an approximately 200m corridor along the A9.	BLOM
Channel survey	River Tummel in-channel cross sections and hydraulic structures, covering the model 1D domain.	Jacobs Site survey 2015
Watercourse photographs	Site visit photographs	Jacobs Site inspection 2015/2016
Hydrological analysis	Hydrological analysis carried out as discussed in Section 3	Jacobs 2015-2016
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

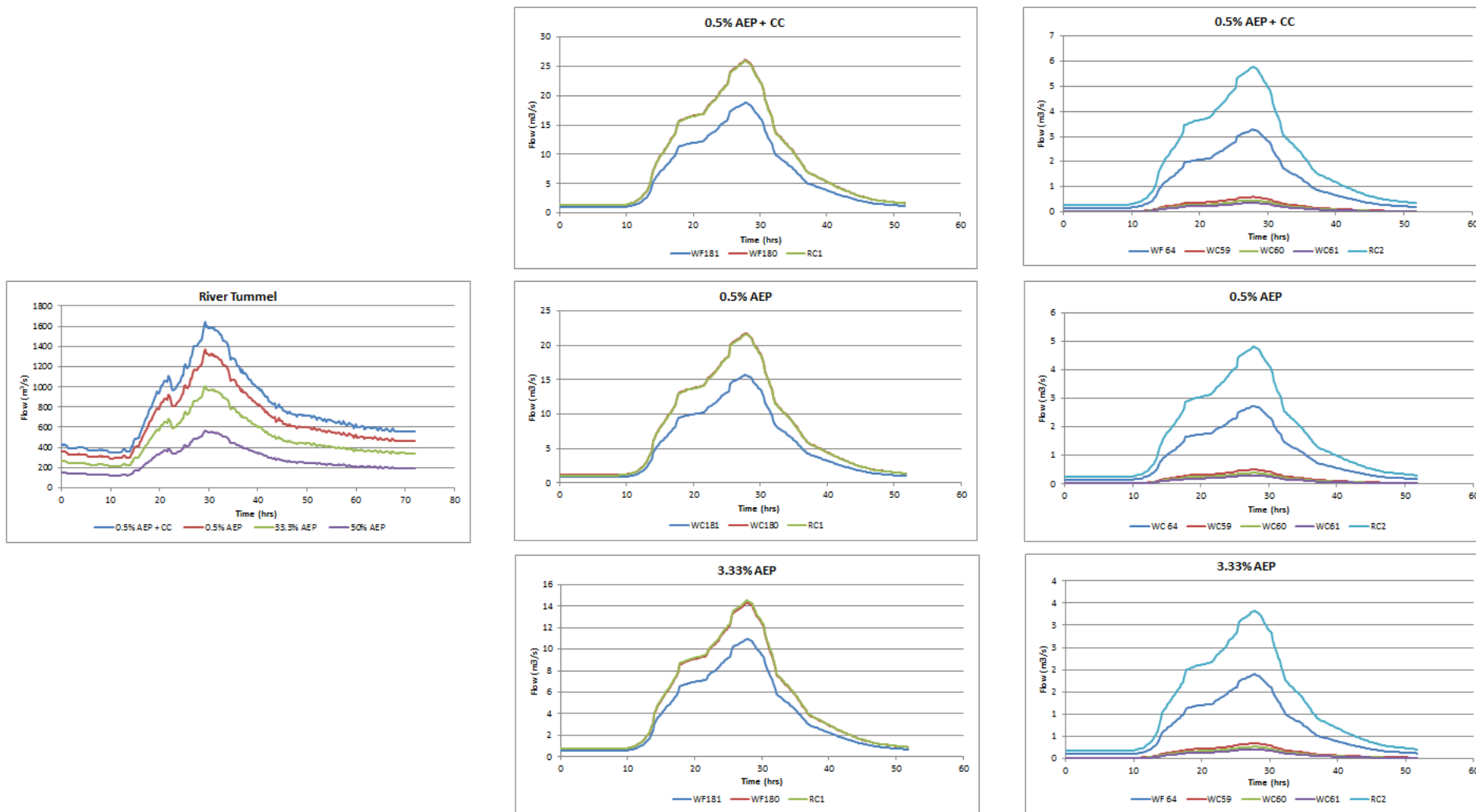
3 Hydrology

- 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 For the large watercourses (River Tummel, Kinnaird Burn and Edradour Burn): An initial estimate of the Index Flood (Qmed) was undertaken using FEH catchment descriptors, the Qmed was then adjusted using an adjustment factor from a nearby (donor) gauging station. The AEP peak flows for the target locations were estimated by applying the single site growth curve from the nearest gauging station to the adjusted Qmed flow. The hydrograph shape for the design inflows was selected from the five largest flood events on record.
- 3.1.3 For the minor watercourses, both the FEH statistical and rainfall-runoff methods were undertaken to calculate the peak flows, with the largest estimate carried forward into the assessment. The hydrograph shape used during the simulations is based upon an observed event on the River Tilt.
- 3.1.4 As discussed in Appendix A11.2 (Surface Water Hydrology), for Model IV 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 Tummel (18.25hrs) for all inflows in order to assess the flood risk from the main stem, whereas Run 2 uses the critical storm durations specific to each tributary, alongside QMED flow in the River Tummel. Run 1 was found to be the critical scenario for flood risk throughout the modelled extents; therefore these flows were used in the analysis.
- 3.1.5 The peak flows for the modelled catchments are shown in Table 2 along with the locations where they were estimated (as illustrated in Diagram 2). The flow hydrographs are shown in Diagram 2. As discussed above the hydrograph shapes used are based upon gauged data, as such the hydrographs do not have smooth rising and recession limbs.
- 3.1.6 It was seen that the modelled outflow for the three design events were between 2 and 4% above the hydrology targets for flow reconciliation. This minor conservative residual was deemed to be suitable and no further flow scaling was required.

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

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 Tummel U/S of A9 Crossing	Inflow estimated at the Clunie Bridge and applied in the model about 450m downstream of the Faskally Dam	571.26	1009.01	1371.22	1645.50
WF181	Inflow estimated for the Kinnaird Burn at its confluence with the River Tummel	5.134	10.982	15.699	18.839
WF180	Inflow estimated for the Edradour Burn at its confluence with the River Tummel	6.491	14.358	21.754	26.105
WF59	Inflow estimated for un-named watercourse 59	0.155	0.344	0.500	0.600
WF60	Inflow estimated for un-named watercourse 60	0.120	0.265	0.385	0.462
WF61	Inflow estimated for un-named watercourse 61	0.095	0.209	0.304	0.365
WF64	Inflow estimated for Littleton of Fonab	0.876	1.896	2.739	3.287
Residual catchment 1	Flow distributed laterally along the River Tummel between upstream extent of the model and Tummel Bridge	6.505	14.535	21.625	25.950
Residual catchment 2	Flow distributed laterally along the River Tummel between Tummel Bridge and downstream extent of model	1.545	3.337	4.818	5.872
Sum inflows		592.181	1054.936	1439.044	1726.98
Model outflow at downstream extent of Mode IV	Peak flow at the downstream end of the model, used for reconciliation of routed flows through the model.	N/A	932	1307	1569
River Tummel at downstream extent of Mode IV		N/A	990	1346	1615
Percentage error: Model outflow Vs hydrology target		N/A	6%	3%	3%

Diagram 2: Inflow hydrographs for Model IV



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 6 along with the model node labels.
- 4.1.2 Diagram 3 shows an example of the good correlation between the channel survey and the 1m LiDAR DTM, at the channel bank top. To aid model performance interpolated cross sections were added between the surveyed cross sections where needed.

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 in-channel coefficient used is shown in Table 3. Roughness values adopted 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.

Table 3: In-channel Manning's 'n' coefficients

Watercourse	Manning's 'n'	Bed Material
River Tummel	0.04	Large river with straight reaches. River bed with gravels, cobbles, and few boulders.

In-Channel Hydraulic Structures

- 4.1.5 The in-channel hydraulic structures included in the 1D model extent are specified in Table 4, and locations are shown in Diagram 3. Cross sections for the two bridge units (Aldour Bridge and Tummel underbridge) are shown in D4 and D5.
- 4.1.6 The Tummel Underbridge has been included in the 1D model, except for the span on the left bank (east) which extends across the A924. This span has been included in the 2D model to allow a better representation of the flow connectivity at this location.

Table 4: In-channel hydraulic structures (represented in Flood Modeller)

Watercourse	Existing Structure	Flood Modeller Node	Specification
River Tummel	Aldour bridge	Tum01_3098bu	Type: USBPR Spans: 3 Total Width: 71.7m Bed Level: 73.119mAOD Maximum soffit Height: 7.2m
River Tummel	A9 Tummel Underbridge	Tum01_1744bu	Type: USBPR Spans: 2 Total Width: 114.2m Bed Level: 70.035mAOD Maximum soffit Height: 12.3m

Diagram 3: Comparison of cross-section survey data with 1m LiDAR DTM

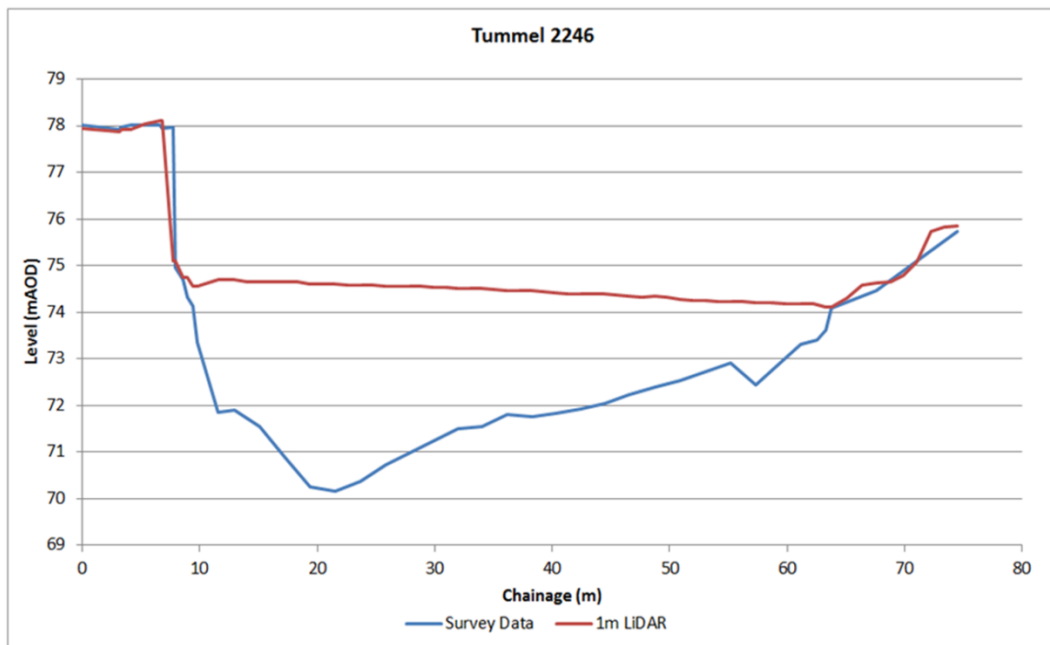


Diagram 4: Aldour Bridge 1D schematisation in Flood Modeller

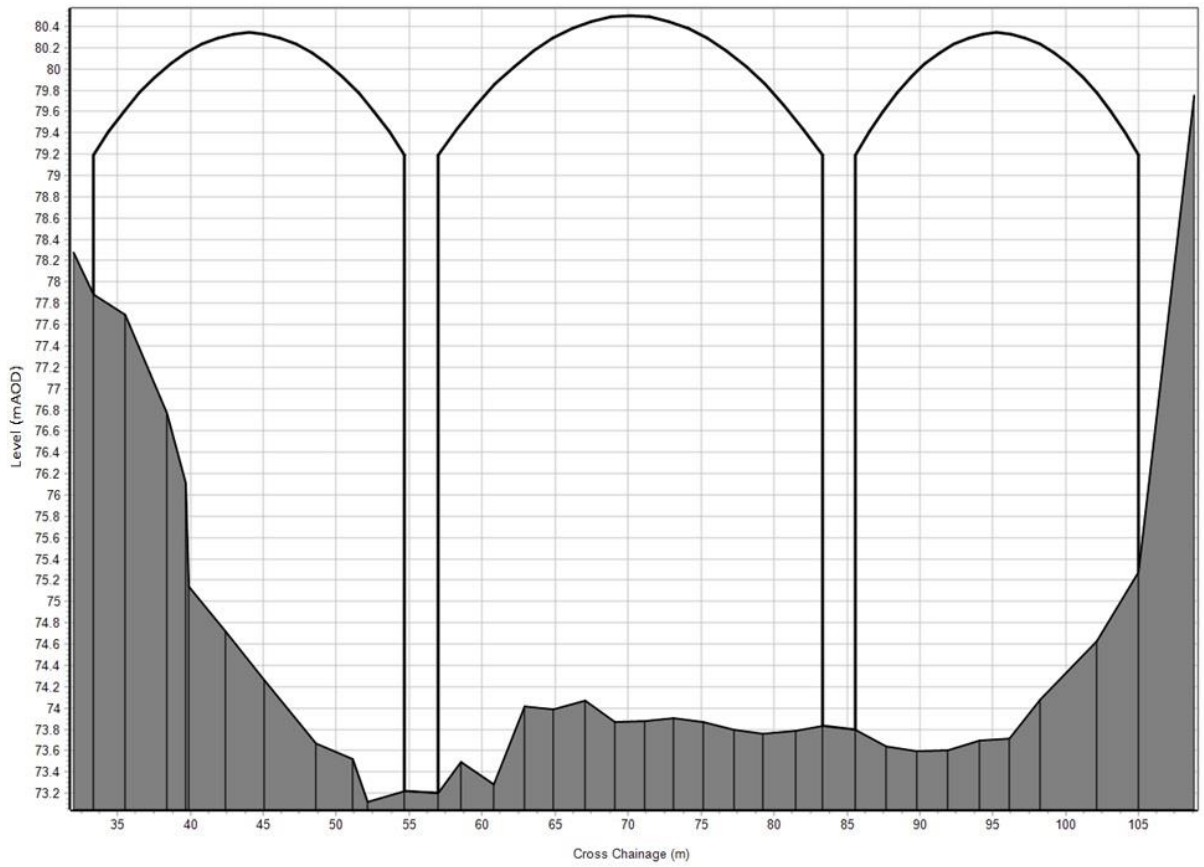
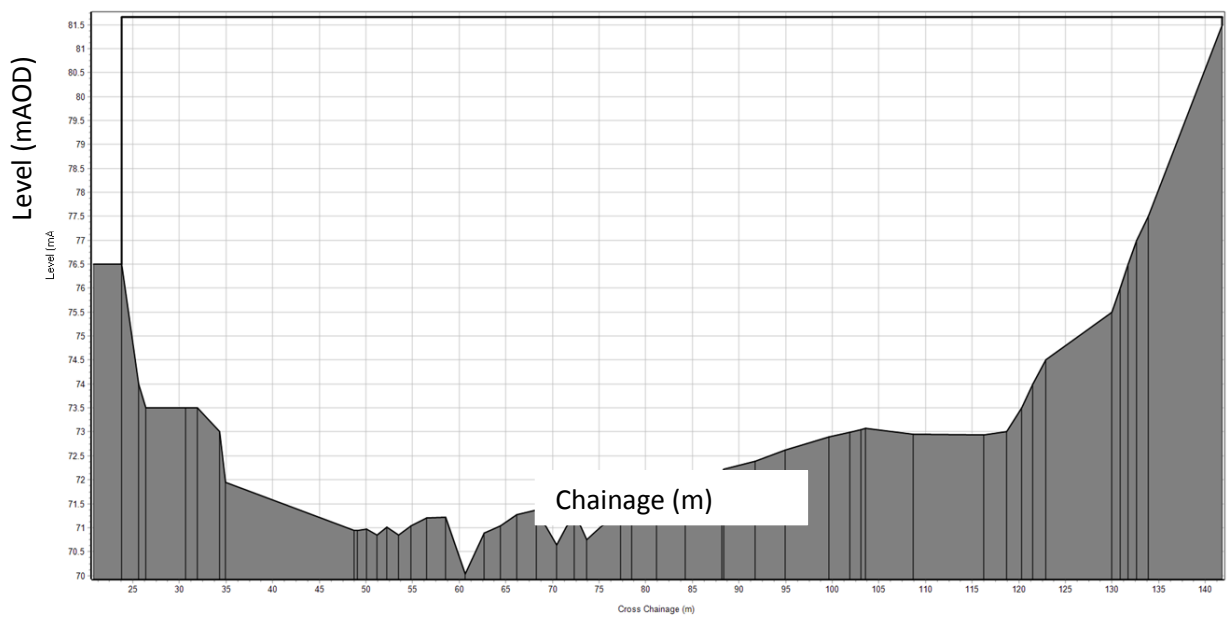


Diagram 5: Tummerl Underbridge 1D schematisation in Flood Modeller (NB: bridge piers are specified in the USBPR unit and are not displayed in the bridge cross section data)



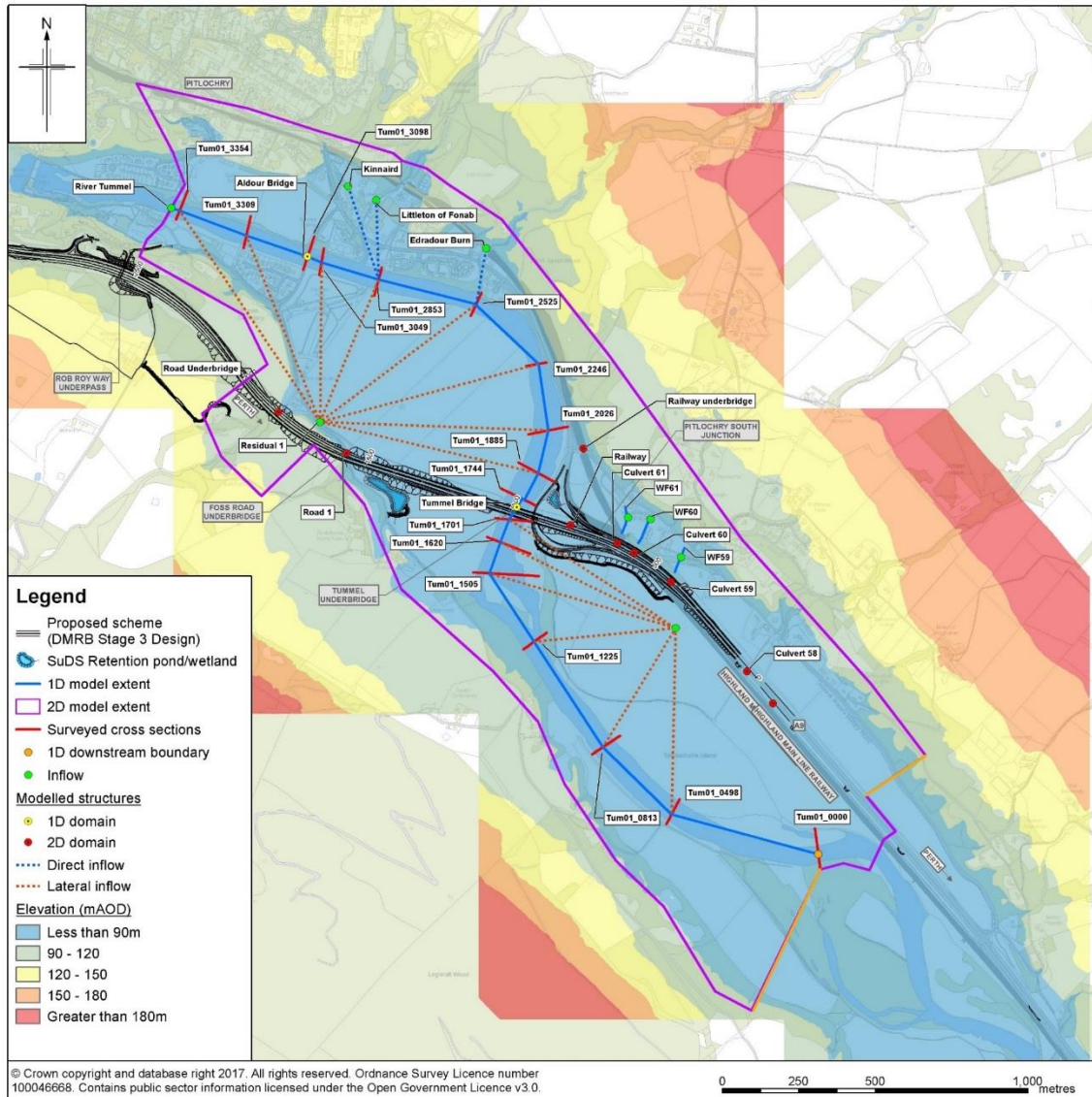
Boundary Conditions – 1D Domain

- 4.1.7 The upstream and downstream boundary conditions applied to the 1D domain are described in Table 5. Locations are shown in Diagram 6.

Table 5: 1D boundary conditions

Type of Boundary	Flood Modeller Node	Description
Flow-Time Boundary	Tummel_us	Hydrological inflow applied at the upstream end of the model.
Flow-Time Boundary	Residual1	Hydrological inflow distributed laterally between nodes Tum01_3572 and Tum01_1885.
Flow-Time Boundary	Residual2	Hydrological inflow distributed laterally between nodes Tum01_1701 and Tum01_0498.
Flow-Time Boundary	Litt_Fonab	Hydrological inflow applied at the confluence of Littleton of Fonab and the River Tummel.
Flow-Time Boundary	KinnairdBurn	Hydrological inflow applied at the confluence of the Kinnaird Burn and the River Tummel.
Flow-Time Boundary	EdradourBurn	Hydrological inflow applied at the confluence of the Edradour Burn and the River Tummel.
Normal Depth Boundary	Tum01_0000	Normal depth boundary condition applied at the downstream end of the model on River Tummel.

Diagram 6: Model IV baseline schematisation



Floodplain Schematisation – 2D Domain

Floodplain Topography

- 4.1.8 The 2D domain covers an area of 2.92km². The topography is represented using a 5m resolution square grid. The levels for the grid cells are based on a 1m resolution Digital Terrain Model (DTM) derived from LiDAR (Light Detection and Ranging) survey.
- 4.1.9 Appropriate use has been made of 2D breaklines and elevation polygons (z-shapes) to accurately represent topographic features (such as roads, drains and ridges) where they have a significant impact on flow across the floodplain. Elevations for these topographic features were informed by the BLOM topographic survey where available; outside of this survey the available 1 Lidar DTM was used.
- 4.1.10 The 2D domain includes z-shapes to model a section of slip road located on the left bank of the River Tummel at Mains of Dunfallandy, railway elevations at Westhaugh of Dalshian, and also a number of watercourses (Littleton of Fonab, Kinnaird Burn and Edradour Burn).
- 4.1.11 Three minor watercourses at the Westhaugh of Dalshian were modelled discretely in order to more accurately quantify flood risk at this location. Minor watercourse 59 and 60 were represented with 2D point inflows, 2d gully lines and 1d (Estry) elements for the culverts below the A9 and the railway line. Minor Watercourse 61 was modelled discretely with the channel upstream of the A9 represented with 1D Estry cross sections linked to the 2D domain (see Diagram 6). It is noted that these channels discharge into the field (Easthaugh of Dalshian) without any continuation channel connecting to the River Tummel. This is a cause of existing flood risk.

Floodplain Hydraulic Friction

- 4.1.12 Hydraulic roughness coefficients are applied across each cell of the 2D domain as shown in Table 6, depending on land use taken from OS Mastermap data. Roughness values adopted were taken from standard guidance (Chow 1959).

Table 6: 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

Key hydraulic structures in the floodplain were embedded in the 2D domain and modelled using 1D Estry software. Invert levels were taken from the DTM. Details are provided in

- 4.1.13 Table 7 and locations are shown in Diagram 6.
- 4.1.14 Four culverts were also embedded in the 2D domain as 1D (Estry) Elements. These structures run under the existing A9 and the Highland Main Line railway embankment. Survey information was available for the majority of these structures, however, in instances where survey was not available dimensions were assumed with the help of OS Mastermap data and photos taken during site visits where available.
- 4.1.15 Similarly five culverts (57 – 61) located in the vicinity of Westhaugh of Dalshian were represented as 1d_nwk components within the 2D domain. Dimensions were obtained from the minor watercourse channel survey.

Table 7: Floodplain hydraulic structures

Structure	Type	Dimensions (m)	Length (m)	Upstream Invert Level (mAOD)	Downstream Invert Level (mAOD)	Source
Culvert 57	Rectangular	1 x 1	90.90	73.69	73.04	Site Visit measurements
Culvert 58	Rectangular	4 x 4	89.04	73.35	72.92	Estimated
Culvert 59	Circular	0.59	56.30	74.31	73.48	Jacobs Survey
Culvert 60	Circular	0.44	63.00	73.88	73.31	Jacobs Survey
Culvert 61	Circular	0.67	67.00	74.42	73.70	Jacobs Survey
Railway Tunnel	Rectangular	12 x 4	144.40	77.70	76.43	Estimated
Culvert 64	Rectangular	3.5 x 3	61.50	95.20	89.15	Jacobs Survey
A9 Underbridge Underpass	Rectangular	5 x 4	61.60	85.57	84.64	Estimated
Railway Underbridge	Rectangular	7 x 4	14.65	78.98	77.73	Estimated

Boundary Conditions – 2D Domain

- 4.1.16 In order to more accurately represent flood risk to the residential properties at Dalshian of Westhaugh, point inflows have been applied directly to the 2D domain at watercourses 59 and 60. All other flows across the 2D domain are a result of the 1D channel being overtopped.
- 4.1.17 Free discharge (HQ) boundaries have been applied at the downstream end of the model aligned to the edge of 2D domains. This controls the rate at which floodplain flows leave the model, using a normal depth assumption and the local hillslope. The locations of these boundaries are shown on Diagram 6.

1D/2D Linking

- 4.1.18 The link between the 1D and the 2D domains was defined along the banks of the River Tummel using bank crest levels informed by the DTM data. Minor watercourse 61 which channel was represented in 1D (using Estry) was also linked to the 2D domain using bank crest levels informed by the surveyed cross sections.

5 Proposed Scheme Modelling

Initial Scheme Model Testing

- 5.1.1 Model simulations were tested initially with the proposed highway layout. This required the extension of Culverts 59, 60 and 61 (see Diagram 6) to cross the widened highway embankment. These simulations showed significant water level increase upstream of Culverts 59, 60 and 61, affecting a small number of residential properties in the Dalshian of Westhaugh area, along with other less significant water level changes in the River Tummel floodplain, which did not affect any residential locations. A range of mitigation options were then tested to determine the final, proposed scheme arrangement.

Proposed Scheme Arrangement

- 5.1.2 Diagram 7 shows the layout of the proposed scheme in the vicinity of the model.

1D Model Updates

- 5.1.3 The proposed scheme in Model IV includes an update to Tummel Underbridge (refer to: drawing number: A9P04-JAC-SBR-A_ML009_ST-DR-ST-0003).
- 5.1.4 The proposed scheme retains the existing bridge structure and includes an additional large single span arch bridge on the downstream side. This additional bridge has not been included in the model schematisation as there are no elements of the new structure which will be wetted in any of the design events. The model cross section for the proposed scheme bridge representation is shown in Diagram 8.

Diagram 7: Model IV proposed scheme layout

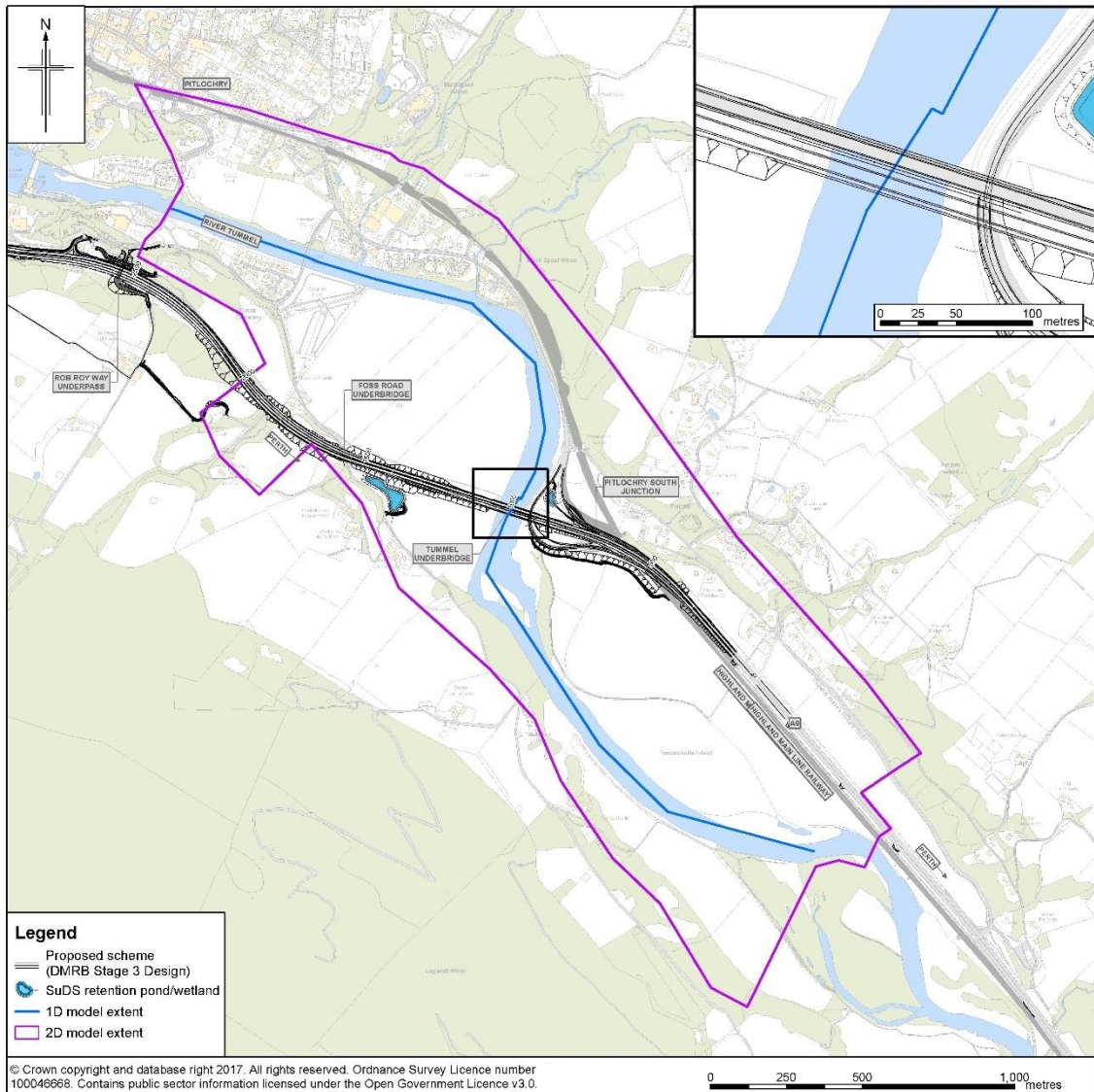
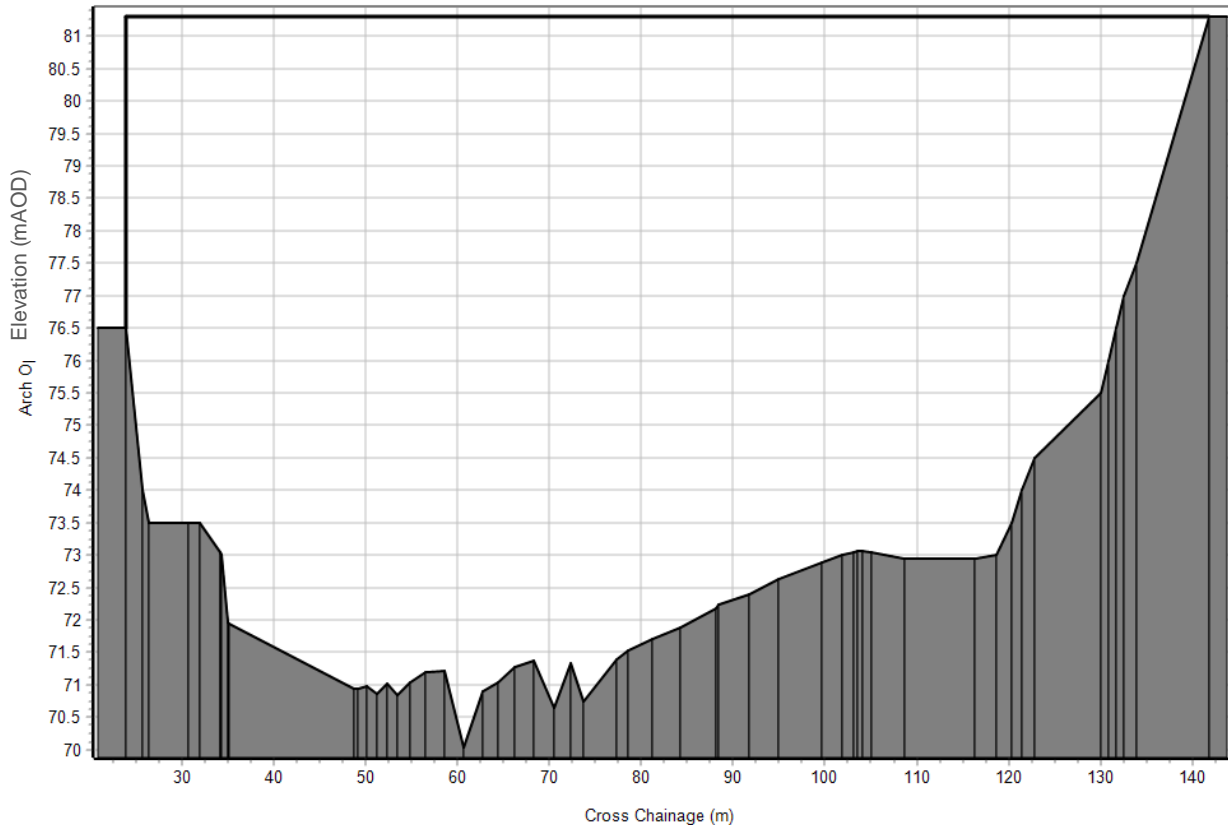


Diagram 8: River Tummel Underbridge, proposed opening dimensions



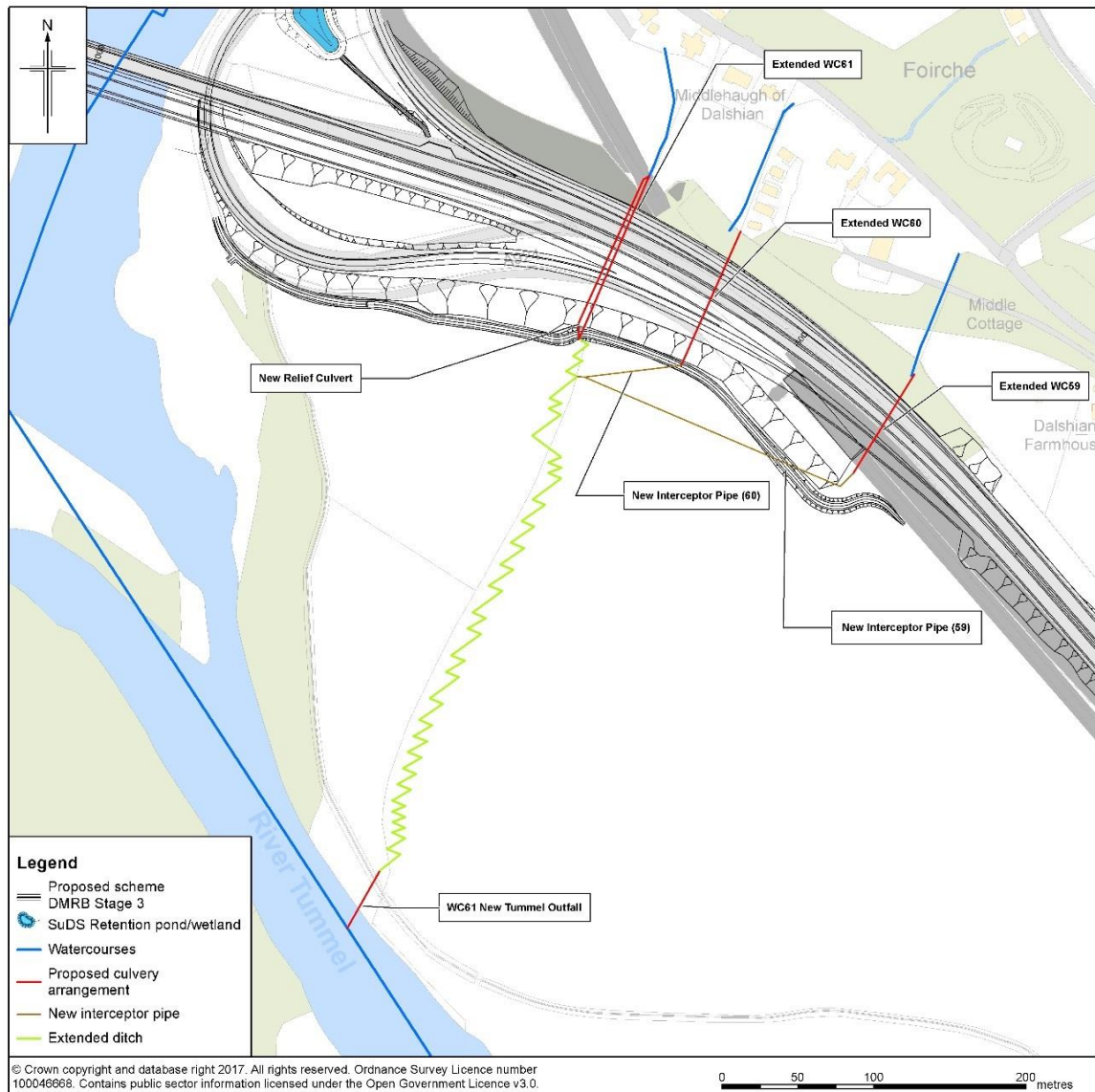
2D Model Updates

- 5.1.5 The proposed scheme elevations were exported from the 3D design drawings (MXROAD software) as raster grids (GeoTIFF), for inclusion in the hydraulic model. Within the footprint of the proposed scheme these raster grids were stamped onto the existing ground elevations.
- 5.1.6 Two SuDS ponds are included in the proposed scheme. These have been included in the model by updating the ground elevations using the raster grids exported from the 3D design drawings (MXROAD software).
- 5.1.7 The with scheme model includes modifications to the floodplain structures for the minor watercourse culverts (specifically WF59 – 61) under the A9. Currently Culverts 59 and 60 discharge directly into the field at Easthaugh of Dalshian with no continuation channel connecting to the River Tummel. WF60 particularly stops immediately downstream of the culvert, with just a very small, unsurveyed pipe collecting the culvert discharge. It is assumed that the continuation pipe is insufficient to pass the design flows. The minor watercourse culverts 59, 60 and 61 surcharge resulting in flooding to the properties upstream. Extension of the existing culverts, for the proposed highway widening exacerbated this flood mechanism.
- 5.1.8 As part of the proposed scheme additional structures will be constructed to help mitigate the existing flooding in the Westhaugh of Dalshian area (see Diagram 9). Downstream of culverts 59 and 60 a new interceptor pipe system will be constructed to convey culvert discharges to WF61, whilst a 1.2m relief culvert located to the north of Watercourse 61 will also be constructed. WF61 (downstream of the A9) will be excavated and extended down to the River Tummel. At the terminal end of the channel a 10m long 1.2m diameter pipe outfall (with flap valve) into the River Tummel will be implemented. Table 8 summarises these changes.

Table 8: Floodplain hydraulic structure modifications

Structure	Type	Dimensions (m)	Length (m)	Upstream Invert Level (mAOD)	Downstream Invert Level (mAOD)
Extended WF59	Circular Culvert	0.59	78	74.28	73.42
Extended WF60	Circular Culvert	0.44	96	73.88	73.08
Extended WF61	Circular Culvert	0.67	112	74.35	73.27
New Relief Culvert	Circular Culvert	1.2	112	74.35	73.07
New Interceptor pipe (59)	Circular Culvert	0.75	199.5	72.40	71.40
New Interceptor pipe (60)	Circular Culvert	0.75	81.1	72.87	71.40
WF61 New Tummel outfall	Circular Culvert	1.20	10	71.00	71.00

Diagram 9: Easthaugh of Dalshian, proposed culvert arrangement



6 Modelled Events

6.1.1 Table 9 shows the AEP flood events and model scenarios that were simulated with the hydraulic model.

Table 9: Modelled events

Model	Scenario	AEP Event		
		3.33% (30-year)	0.5% (200-year)	0.5% (200-year) + CC
Model IV	Baseline	✓	✓	✓
Model IV	Roughness Sensitivity			✓
Model IV	Hydrological Inflow Sensitivity			✓
Model IV	sensitivity to downstream conditions			✓
Model IV	Initial Scheme Simulation	✓	✓	✓
Model IV	Proposed Scheme with flood mitigation	✓	✓	✓

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 is calculated for each modelled time step, and shows the consistency of the modelled water level and flow within the iterations that are computed for each model time step.
- 7.1.2 As shown in Diagram 10, 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 diagnostics output from the TUFLOW 2D model have been checked. The accepted tolerance range recommended by the software manual is +/- 1% mass balance error. Diagram 11 shows that for the 0.5% AEP (200-year) plus CC flood event the cumulative mass error tolerance is exceeded somewhat at the onset of the floodplain wetting, but stabilises to less than the 1% error very early in the simulation, before there is any significant volume in the floodplain. This mass error diagnostic is typical for all events simulated.
- 7.1.4 The change in volume has also been checked and is noted to oscillate through the model simulation, it is understood that the observed oscillation is a genuine hydraulic effect, due to the oscillation in the inflow hydrographs which are based on gauged data. The coincidental timing of the two oscillations is shown in Diagram 12.

Diagram 10: Model convergence plot

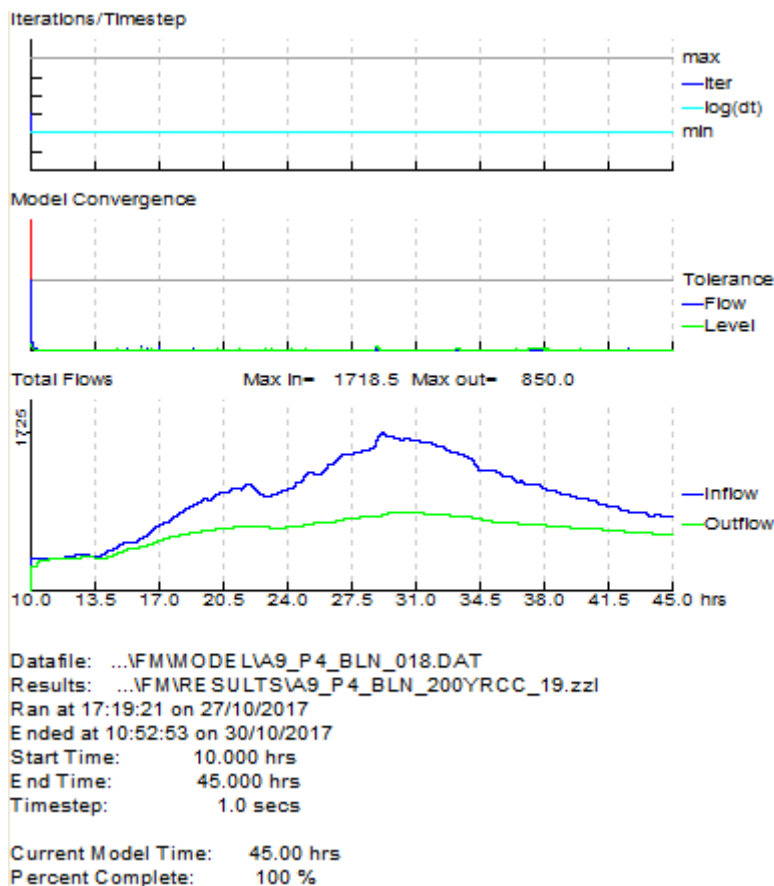


Diagram 11: 2D Cumulative mass error and change in volume - 0.5% AEP plus CC event

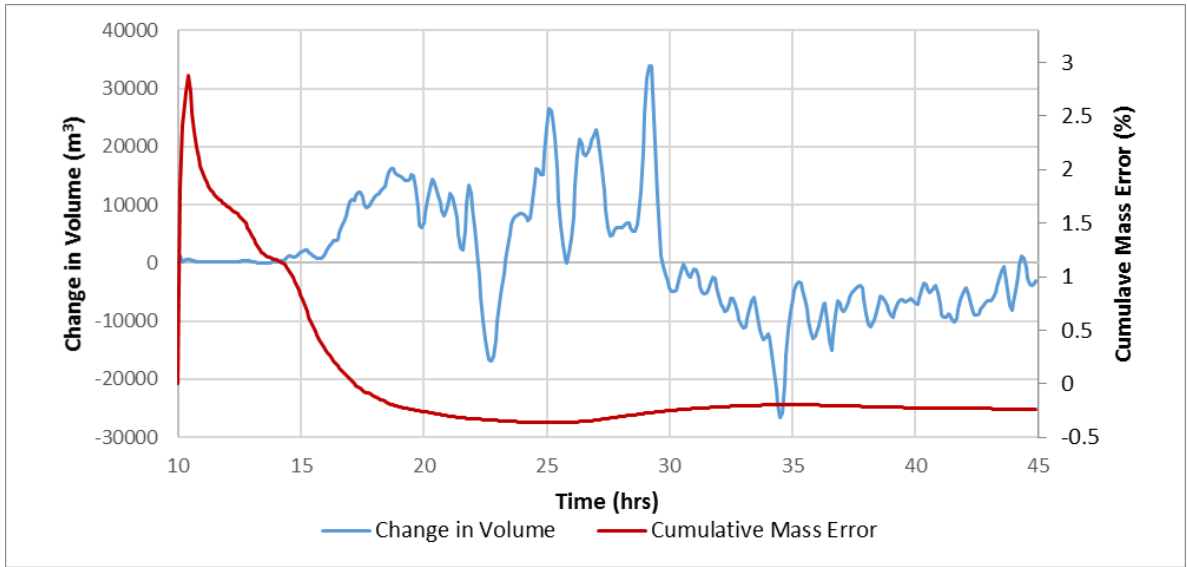
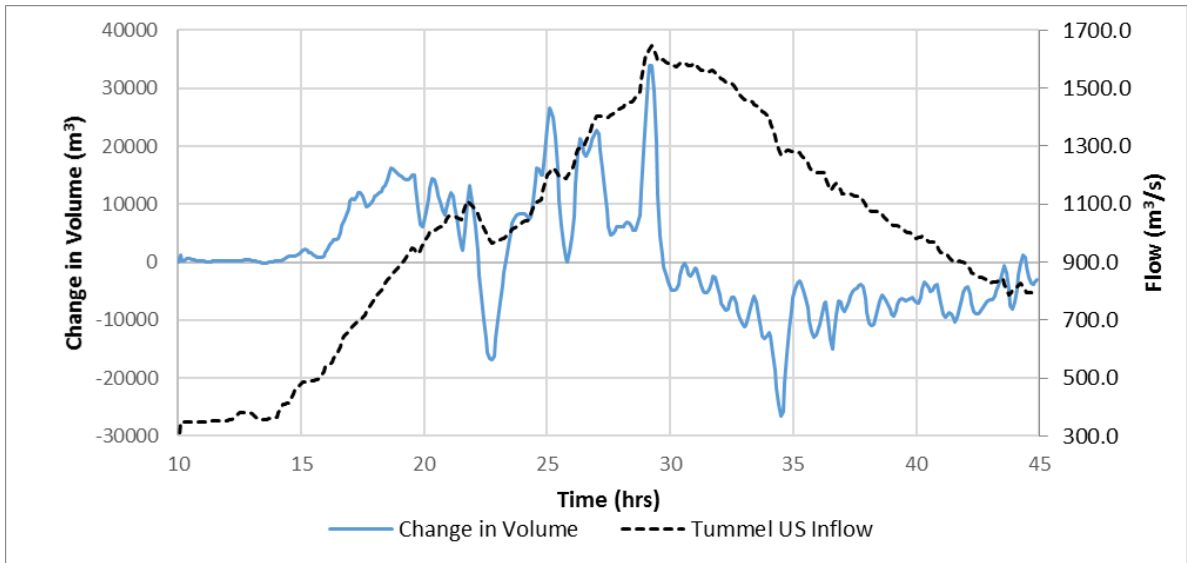


Diagram 12: Inflow hydrograph profile and 2D change in volume - 0.5% AEP plus CC event

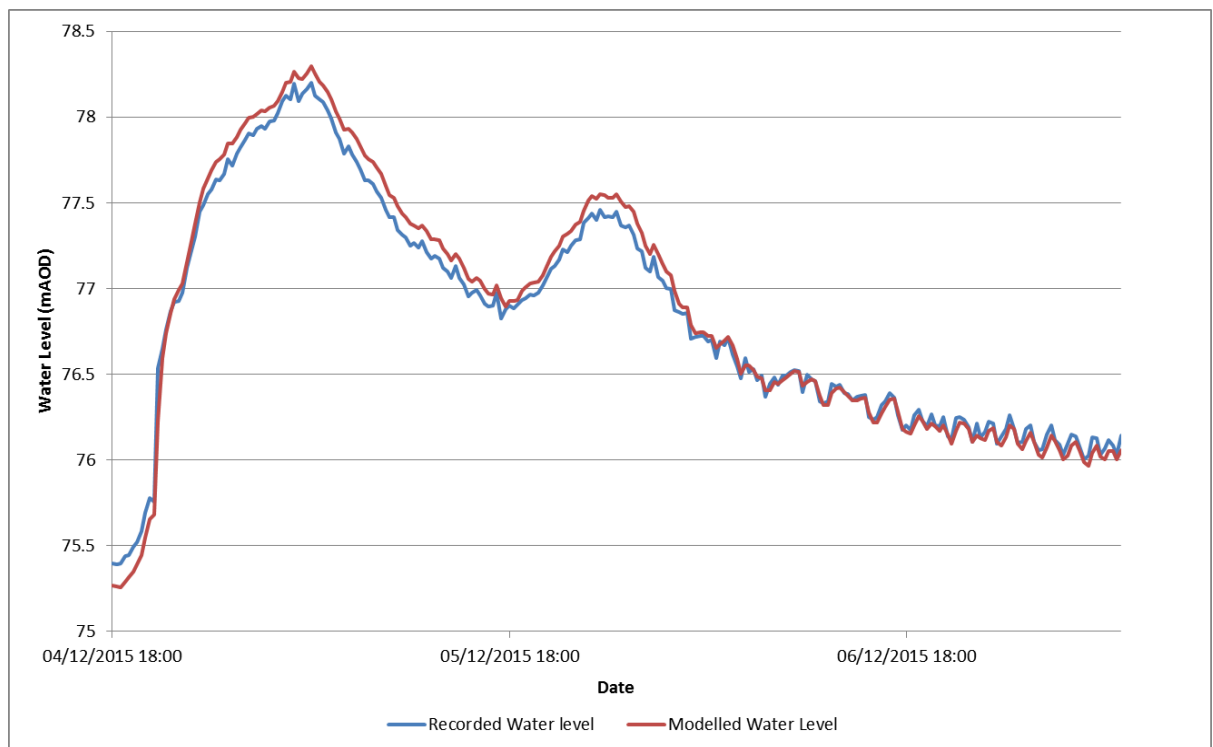


Calibration and Verification

Calibration

- 7.1.5 A limited calibration was undertaken, verifying that routed observed flows through the upper reach of the model gave the expected response at the gauge location (See Diagram 13).
- 7.1.6 A gauge is located on the River Tummel at Pitlochry, near the upstream extent of the model (see Diagram 1) for which the available 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, 26 January 2008 and 13 December 2006. For the December 2015 event, the full time series for both stage and 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.
- 7.1.7 The water level time series from the gauge are shown in Diagram 13, alongside the model results. As the gauge is located in between nodes TUM01_2853 and TUM01_2744 in the model, the average of the results from these two nodes was used for comparison. This shows that there is good agreement between the water levels throughout the simulated event. The modelled peak levels are slightly higher than those recorded at the gauging station and as such the model provides a conservative picture.

Diagram 13: 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 10, showing that peak water levels within 100mm of the gauge records were achieved for all three events.

Table 10: Model V calibration results

Flood Event	Maximum Recorded Water Level (mAOD)	Maximum Modelled Water Level (mAOD)	Difference (m)
December 2015	78.295	78.199	0.096
January 2008	78.012	77.939	0.073
December 2006	78.130	78.051	0.079

Verification

- 7.1.9 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 14 shows the comparison between the two flood extents. The modelled flood extent is broadly similar to that of the SEPA flood map which provides confidence to the present model analysis. These differences can be attributed to the more detailed representation of the modelled area.

Sensitivity Analysis

- 7.1.10 In order to test the model sensitivity to key hydraulic parameters, simulations were undertaken using the baseline 0.5% AEP plus CC event. The assessed hydraulic parameters were: Manning’s ‘n’ roughness coefficients and hydrological inflows.

Roughness Sensitivity

- 7.1.11 In-channel and floodplain roughness coefficients (Manning’s ‘n’) were changed by +20% and -20%. Table 11 shows the impact of changing the model roughness on the 1D in-channel water levels. The impact on the 2D maximum flood extents is illustrated in Diagram 15. The results show that the in-channel water levels are relatively sensitive to changes in roughness coefficients, but there is limited response for the 2D modelled flood extents.

Table 11: Model IV roughness sensitivity results

Sensitivity	Water Level Difference (m)			Water Level Difference at the Scheme (m)
	Max	Min	Average	Tum01_1744bu
+20% Roughness	0.382	0.203	0.281	0.350
-20% Roughness	-0.156	-0.887	-0.351	-0.179

Hydrological Inflow Sensitivity

- 7.1.12 The flows into the model were adjusted by +20% and -20%. Table 12 shows the impact of changing model inflows on the 1D in-channel water levels, the 2D maximum flood extents are shown in Diagram 16. The model responses are found to be relatively sensitive to changes in flow, and again there is limited response in the modelled 2D flood extents.

Table 12: Model IV flow sensitivity results

Sensitivity	Water Level Difference (m)			Water Level Difference at the Scheme (m)
	Max	Min	Average	Tum01_1744bu
+20% Flow	0.748	0.191	0.0.359	0.328
-20% Flow	-0.180	-1.207	-0.409	-0.270

Downstream Boundary Sensitivity

- 7.1.13 The Downstream boundary Condition of the model was adjusted with the gradient for normal depth slackened, to increase the modelled water level at the boundary, as follows:

Baseline – 1d Normal depth boundary = 1:1000, 2d Normal depth boundary = 1:100
 Uplift 1 – 1d Normal depth boundary = 1:2000, 2d Normal depth boundary = 1:200
 Uplift 2 – 1d Normal depth boundary = 1:5000, 2d Normal depth boundary = 1:500

Table 13 shows the boundary on the 1D in-channel water levels, the 2D maximum flood extents are shown in Diagram 17. The model responses are found to be relatively insensitive to changes in flow, and again there is limited response in the modelled 2D flood extents.

Table 13: Downstream Boundary sensitivity results

Sensitivity	Water Level Difference (m)			Water Level Difference at the Scheme (m)
	Max	Tum01_1744bu	Average	Tum01_1744bu
DS Boundary Uplift 1	0.374	NA	NA	0.000
DS Boundary Uplift 2	0.853	NA	NA	0.000

Diagram 14: Modelled 0.5% AEP (200-year) flood event extent vs. SEPA medium likelihood fluvial extent

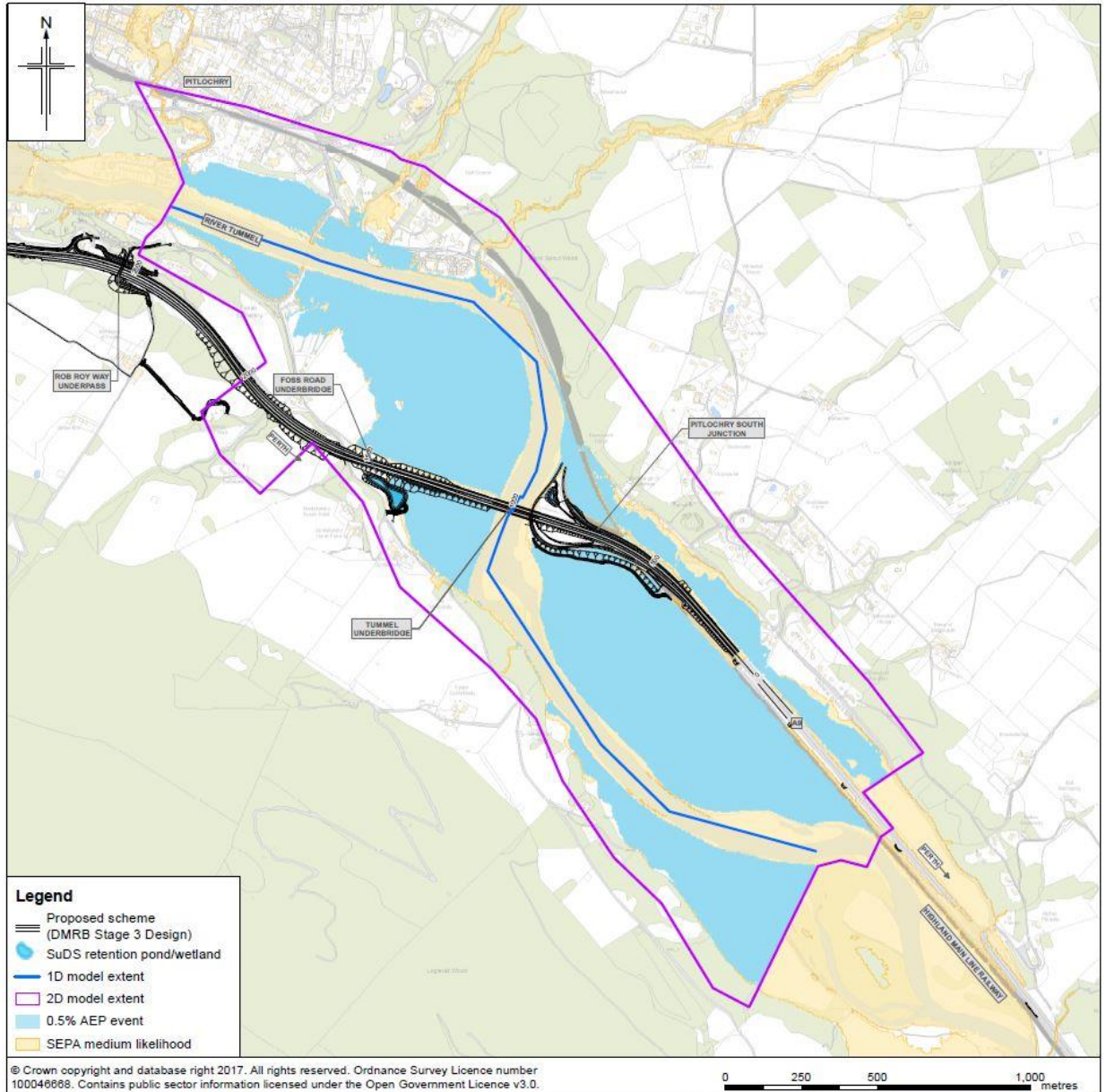


Diagram 15: Roughness sensitivity 2D flood modelled flood extents

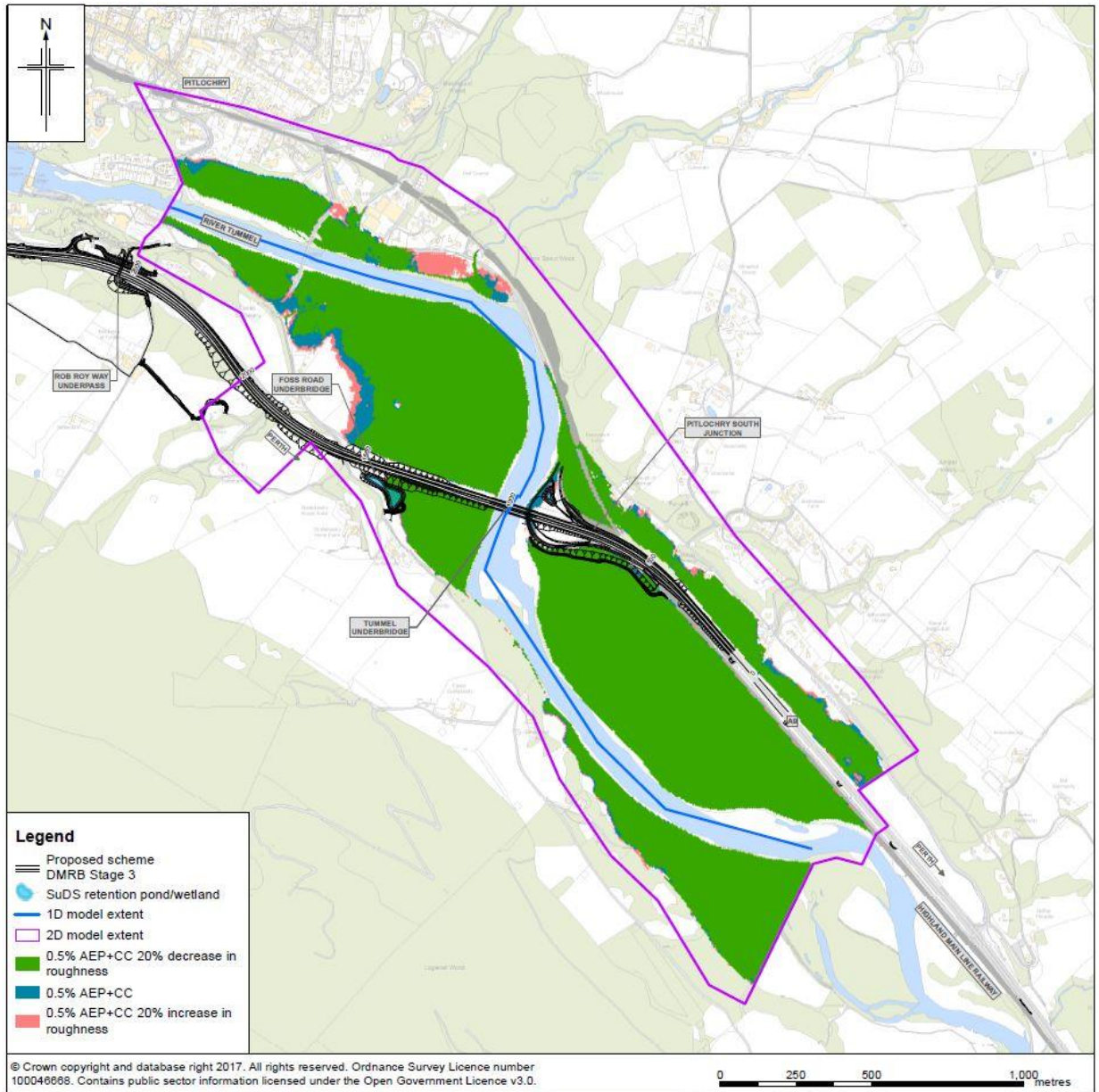


Diagram 16: Inflow sensitivity 2D flood modelled flood extents

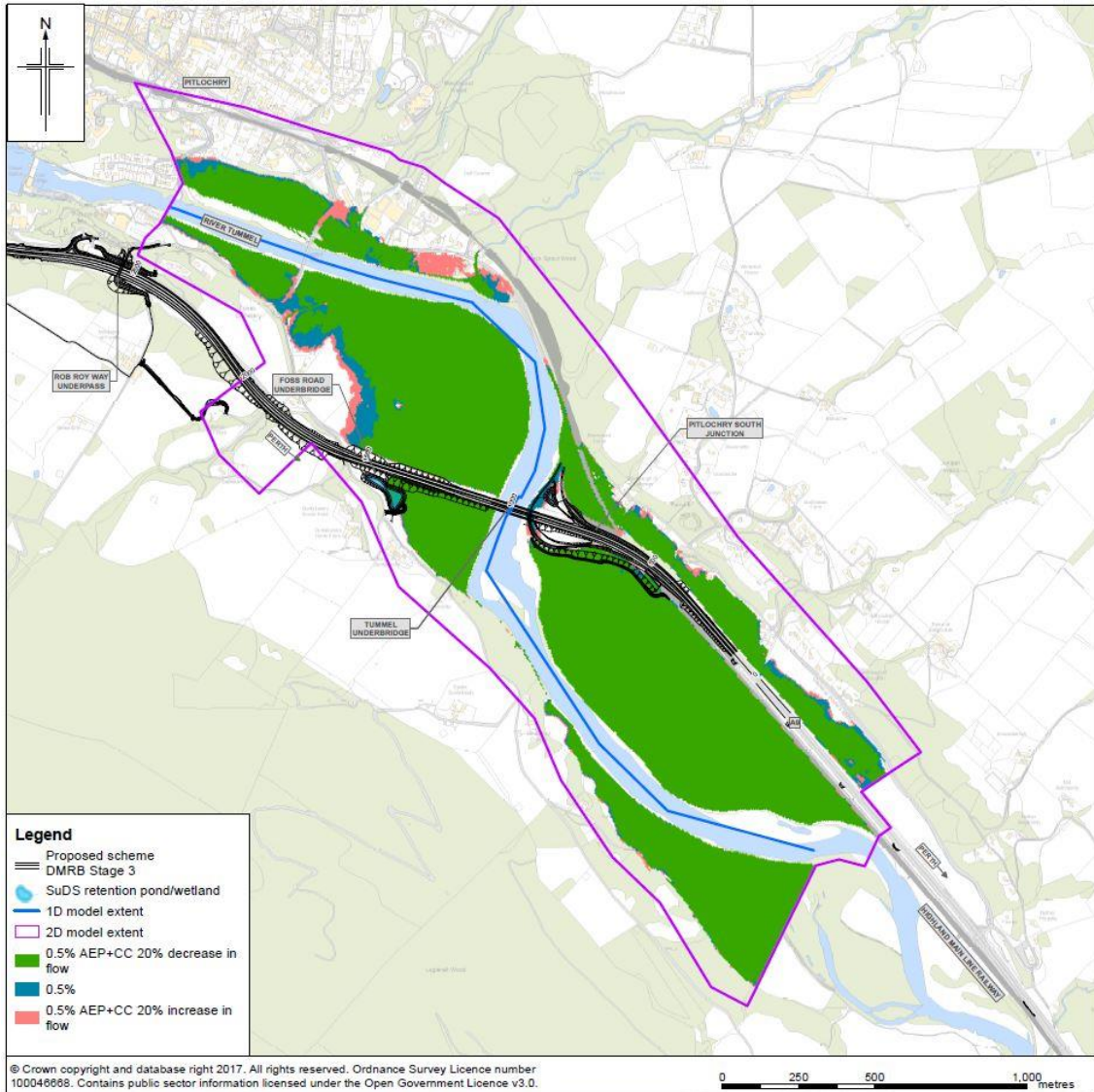
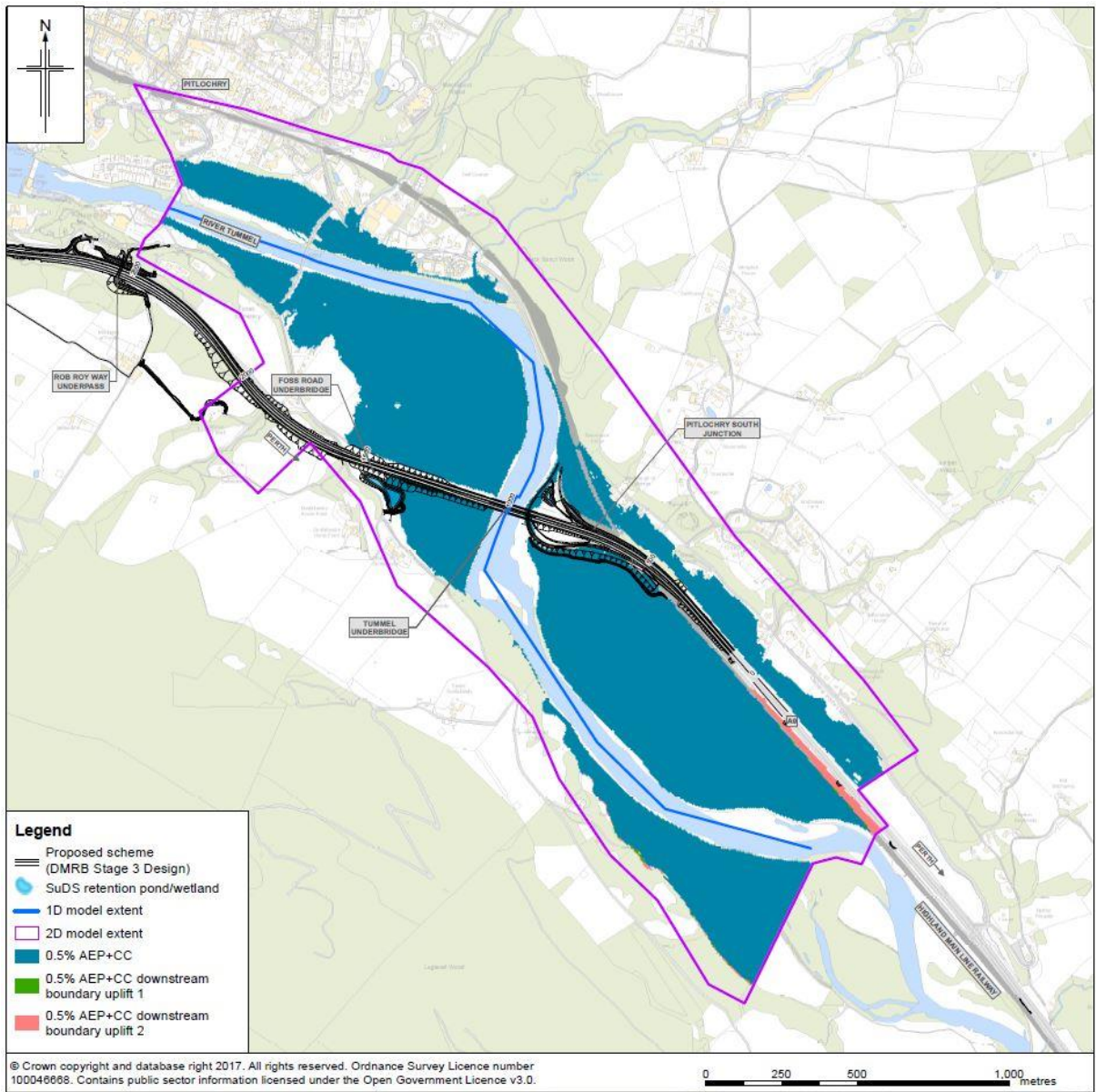


Diagram 17: Downstream Boundary 2D flood modelled flood extents



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 necessarily various uncertainties and limitations associated with the model.
- 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 Project 4.

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 standard industry 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

- 8.1.6 The 1D downstream boundary assumes a normal depth condition based on the local channel bed gradient of 1:1000. Sensitivity testing has shown that the boundary is suitably removed from the area of interest and that adjustment of the boundary assumption has limited impact upon the flood risk at the scheme location.

2D Domain

Floodplain Topography

- 8.1.7 The floodplain topography has been represented using 1m resolution LiDAR 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 Tummel is based on detailed topographical survey.
- 8.1.9 The 2D downstream boundary assumes a normal depth condition based on the local hillslope gradient of 1:100. Sensitivity testing has shown that the boundary is suitably removed from the area of interest that adjustment of the boundary assumption has limited impact upon the flood risk at the scheme location.

Floodplain Structures

Floodplain structures have only been included where they were considered to have an impact on flow mechanism. Levels and dimensions local to the scheme have been taken from the detailed topographic survey. Other structure dimensions, more remote from the scheme, have been estimated from DTM and OS Mastermap data as detailed in

8.1.10 Table 7.

Grid Size

8.1.11 A 5m grid has been used. This is suitable to represent most of the floodplain features across the model to an appropriate level of detail. Finer features have been incorporated into the grid using breaklines.

DTM Modifications

8.1.12 Breaklines and elevation polygons have been used as required to better represent topographic features. Elevations for these features have been informed by the detailed topographic survey as well as the 1m Lidar DTM data.

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

Blockage Scenario

8.1.14 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.

9 Conclusion

9.1.1 This report has detailed the modelling carried out to assess the baseline flood risk along the River Tummel for a 3500m reach of the river in the vicinity of the Tummel Underbridge. The 3.33% and 0.5% AEP+CC flood events were simulated.

9.1.2 Particular attention has been given to the modelling of three key watercourses which cause flood risk to properties adjacent to the scheme in Westhaugh of Dalshian.

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

9.1.4 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.