JACOBS

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 Tay, and a number of its tributaries, to the proposed scheme between Tay Crossing and Ballinluig (also known as Project 03).

1.1.2 This 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 2016-03-AD software, with a number of minor watercourses included as 1D ESTRY components. The linked 1D/2D modelling approach means that the model dynamically transfers the water between the watercourses and the floodplain.

1.1.5 The hydraulic modelling aimed to predict the peak water levels within the modelled river reach and the floodplain for the 50% Annual Exceedance Probability (AEP), 3.33% AEP (30-year), 2% AEP (50-year), 0.5% AEP (200-year) and 0.5% AEP (200-year) plus an allowance for climate change[1] (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. Subsequently, the hydraulic model was used to test options to mitigate these impacts.

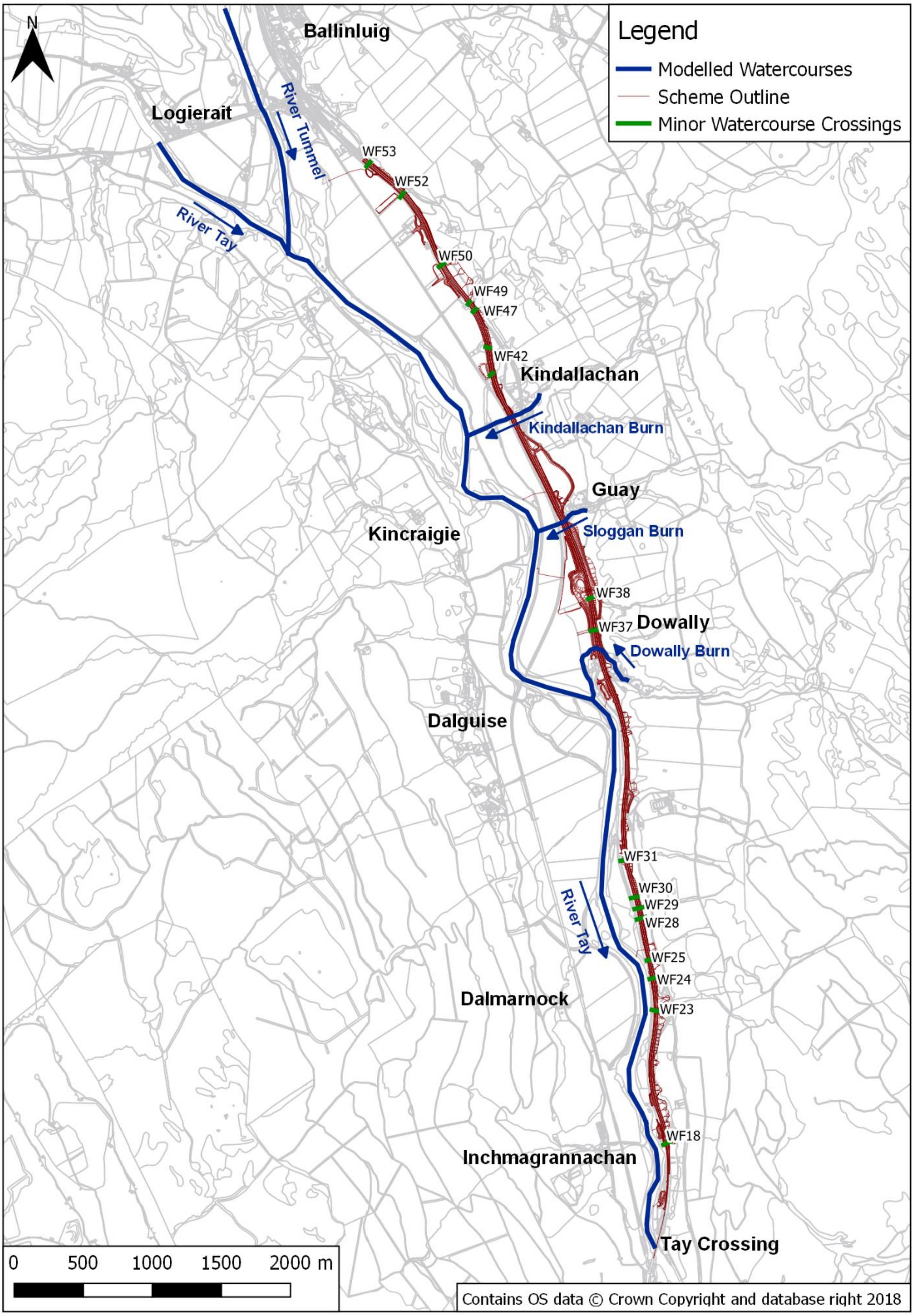
Modelled Area

1.1.6 Diagram 1 illustrates the extent of the modelling work undertaken between Tay Crossing and Ballinluig. The model covers a 9.9km long reach of the River Tay between Logierait and the Tay Crossing, as well as 1.7km of the River Tummel from Ballinluig to the confluence with the River Tay. The model also includes three key tributaries of the River Tay, namely, Kindallachan Burn, Sloggan Burn and Dowally Burn and also 16 minor watercourses crossing the proposed scheme.

1.1.7 The model extents were chosen based on the key locations where the River Tay 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.

[1] A 20% uplift has been applied to all hydrological inflows for the climate change allowance. See Appendix A11.2 (Surface Water Hydrology Report) for further details.

Diagram 1: Modelled area



2 Input Data

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

Table 1: Data used to build the hydraulic models

Data	Description	Source
Digital Terrain Model (DTM)	1m horizontal resolution DTM derived from LiDAR See Section 4.1.18	Emapsite, (received 2016)
Digital Terrain Model (DTM)	5m horizontal resolution DTM derived from photogrammetry (2013) See Section 4.1.18	Transport Scotland
OS maps	Background maps and Master Map data See Section 4.1.22	Ordnance Survey
BLOM topographic survey	Detailed topographic survey of an approximately 200m corridor along the existing A9. See Table 10	BLOM
Channel survey	In-channel cross sections and hydraulic structures See Section 4	Jacobs Site survey 2015-2017
SEPA channel survey	In-channel cross sections and hydraulic structures for the River Tummel and the River Tay upstream of the confluence with the Tummel (2016) See Section 4.1.3	SEPA
Watercourse photographs	Site visit in-channel watercourse photographs See Section 4.1.5	Jacobs Site survey 2015-2017 Site inspection 2015-2017
Hydrological analysis	Hydrological analysis carried out as discussed in Section 3	Jacobs
Scottish Environment Protection Agency (SEPA) Flood Maps	Flood maps showing the fluvial flood extent for medium likelihood of flooding See Section 8.1.27	SEPA
Proposed Scheme Topography – Road vertical and horizontal alignments	MXROAD ASCII grids of the road alignment that also include flood mitigation measures and drainage ponds across the floodplain See Section 5 and Section 6	Jacobs
Proposed Scheme Structure Details	Design drawings for proposed structure modifications: watercourse crossings, drainage ponds and side roads See Section 5	Jacobs

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), 2% (50-year), 0.5% AEP (200-year) and 0.5% AEP (200-year) plus CC flood events. For each of these events the estimated peak flow near the downstream end of the model has also been provided.

3.1.2 As discussed in Appendix A11.2 (Surface Water Hydrology), 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 Tay for all inflows in order to assess the flood risk from the main river, whereas Run 2 combined the individual critical storm durations for the tributaries and minor watercourses with the QMED flow in the River Tay and River Tummel. Run 2 scenarios were run for the 3.33% AEP (30-year), 0.5% AEP (200-year) and 0.5% AEP (200-year) plus CC flood events only.

3.1.3 Hydrograph shapes for the River Tay and River Tummel inflows and the Run 1 inflows on the tributaries and minor watercourse were derived from historic flood events. In order to reconcile flows routed through the hydraulic model to the design peak flows estimated near the downstream end of the model, the timing of the inflows on the River Tay and the River Tummel were adjusted so that the peak flows do not occur at the same time. A time lag of 11 hours was found to achieve a satisfactory reconciliation and was in line with the lag times observed in historic flood events.

3.1.4 The peak flows for the River Tay, River Tummel and the three key tributaries are shown in Table 2 and Table 3 for the Run 1 and Run 2 events, and the flow hydrographs are shown in Diagram 2 and Diagram 3. These flows have been used as inflows to the Flood Modeller Pro components of the model (See Section 4.1.7).

3.1.5 Additional inflows have been applied to the 2D domain for the minor watercourses. The peak flows for these watercourses are shown in Table 4 for both Run 1 and Run 2.

Table 2: Hydrological inflow peak values for Run 1

Inflow	Peak Flow (m³/s)				
	AEP 50% (2-year)	AEP 3.33% (30-year)	AEP 2% (50-year)	AEP 0.5% (200-year)	AEP 0.5% (200-year) + CC
River Tay	356	697	770	1064	1277
River Tummel	566	1000	1050	1359	1630
Kindallachan Burn	7.8	15.7	17.3	22.4	26.9
Sloggan Burn	0.8	1.8	2.1	2.6	3.2
Dowally Burn	3.3	5.7	6.6	8.2	9.8
Peak flow on River Tay near downstream end of the model for reconciliation	769	1445	1578	2136	2563

Table 3: Hydrological inflow peak values for Run 2

Inflow	Peak Flow (m³/s)		
	AEP 3.33% (30-year)	AEP 0.5% (200-year)	AEP 0.5% (200-year) + CC
River Tay	356 (QMED from Run 1)		
River Tummel	566 (QMED from Run 1)		
Kindallachan Burn	16.3	24.1	28.9
Sloggan Burn	2.3	3.6	4.3
Dowally Burn	6.3	8.7	10.5

Table 4: Hydrological inflow peak values for the minor watercourses

Inflow	Run 1 Peak Flow (m³/s)					Run 2 Peak Flow (m³/s)		
	AEP 50% (2-year)	AEP 3.33% (30-year)	AEP 2% (50-year)	AEP 0.5% (200-year)	AEP 0.5% (200-year) + CC	AEP 3.33% (30-year)	AEP 0.5% (200-year)	AEP 0.5% (200-year) + CC
WF18	0.07	0.16	0.18	0.23	0.27	0.30	0.44	0.53
WF23	0.25	0.54	0.60	0.78	0.93	0.84	1.29	1.55
WF24	0.07	0.15	0.16	0.21	0.25	0.28	0.42	0.50
WF25	0.06	0.13	0.15	0.19	0.23	0.26	0.39	0.46
WF28	0.03	0.06	0.07	0.09	0.10	0.13	0.19	0.23
WF29	0.07	0.16	0.18	0.23	0.28	0.30	0.45	0.54
WF30	0.06	0.13	0.15	0.19	0.23	0.26	0.39	0.47
WF31	0.15	0.34	0.38	0.49	0.58	0.57	0.86	1.03
WF37	0.11	0.26	0.29	0.38	0.45	0.41	0.63	0.76
WF38	0.25	0.57	0.64	0.83	1.00	0.81	1.26	1.51
WF42	0.14	0.33	0.37	0.49	0.58	0.56	0.84	1.01
WF47	0.06	0.14	0.16	0.20	0.24	0.27	0.39	0.47
WF49	0.08	0.19	0.21	0.28	0.34	0.35	0.51	0.62
WF50	0.13	0.31	0.35	0.45	0.54	0.59	0.87	1.04
WF52*	0.10	0.23	0.26	0.34	0.41	0.39	0.58	0.69
WF53	0.07	0.16	0.18	0.23	0.28	0.28	0.41	0.49

*Combined inflow for the three tributaries which feed into the existing A9 culvert

Diagram 2: Run 1 inflow hydrographs

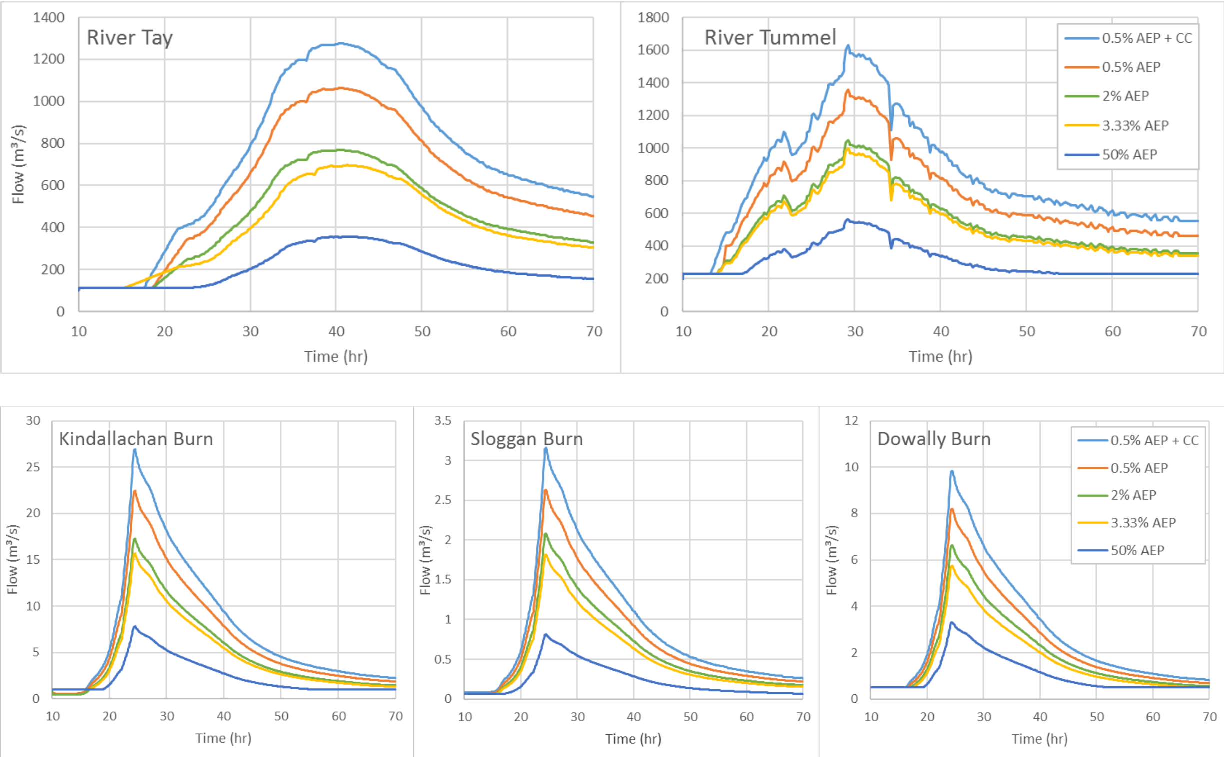
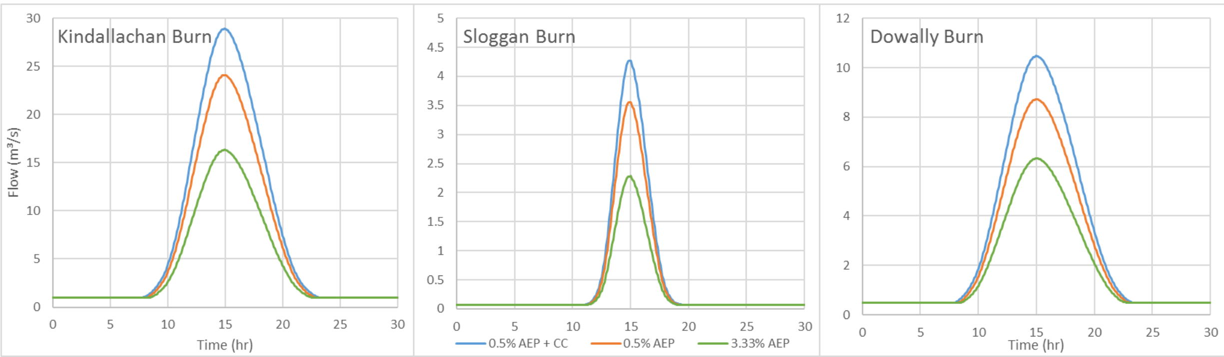


Diagram 3: Run 2 inflow hydrographs



4 Baseline Modelling

4.1.1 The baseline model comprises of channels and structures represented within Flood Modeller Pro, minor watercourses represented in TUFLOW using 1D ESTRY components and the 2D schematisation of the floodplain.

Watercourse Schematisation – Flood Modeller Pro (1D)

4.1.2 Five watercourses have been modelled in 1D using Flood Modeller Pro, as shown in Diagram 4. These include the full modelled lengths of the River Tay, River Tummel and Sloggan Burn, as well as the sections of Kindallachan Burn and Dowally Burn upstream of the existing A9.

In-Channel Geometry

4.1.3 Surveyed river cross section data has been used to inform the in-channel geometry of the watercourses modelled in Flood Modeller Pro. The locations of the surveyed river cross sections are shown in Diagram 4, along with the source of the surveyed information. To aid model performance interpolated cross sections were added between the surveyed cross sections where needed.

4.1.4 Table 5 shows the Flood Modeller nodes associated with the modelled watercourses. Node labels at key locations are provided on Diagram 4.

Table 5: Flood Modeller nodes

Watercourse	Upstream Node	Downstream Node	Downstream Node Location
River Tay	TAY02_1243	TAY00_0000	At the model downstream boundary
River Tummel	Tum00_1836	Tum00_0000	Confluence with the River Tay
Kindallachan Burn	TUL01_543	TUL01_250	Link to 2D domain downstream of the existing A9
Sloggan Burn	SLO01_366	SLO01_114	Upstream end of culvert connection to the River Tay
Dowally Burn	DOW01_736	DOW01_385	Link to 2D domain downstream of the existing A9

In-Channel Hydraulic Friction

4.1.5 Hydraulic roughness (Manning's 'n' coefficient) values were determined primarily using the photographs taken during the survey, typical photos for each watercourse are shown in Diagram 5 and Diagram 6. The in-channel coefficients used are shown in Table 6. Roughness values adopted were taken from standard guidance (Chow, 1959) and adjusted as part of the calibration process discussed in Section 8.

Table 6: In-channel Manning's 'n' coefficients

Watercourse	Manning's 'n'	Bed Material
River Tay	0.032 – 0.034	Large river with straight reaches. River bed with gravels, cobbles, and few boulders.
River Tummel	0.034	Large river with straight reaches. River bed with gravels, cobbles, and few boulders.
Kindallachan Burn	0.041	Mountain stream, no vegetation in channel. River bed with gravels, cobbles and few boulders.
Sloggan Burn	0.046	Mountain stream, no vegetation in channel. River bed with gravels, cobbles and few boulders.
Dowally Burn	0.046 upstream of the existing A9 0.041 downstream	Mountain stream, no vegetation in channel. River bed with gravels, cobbles and few boulders.

Diagram 4: Flood Modeller Pro baseline schematisation

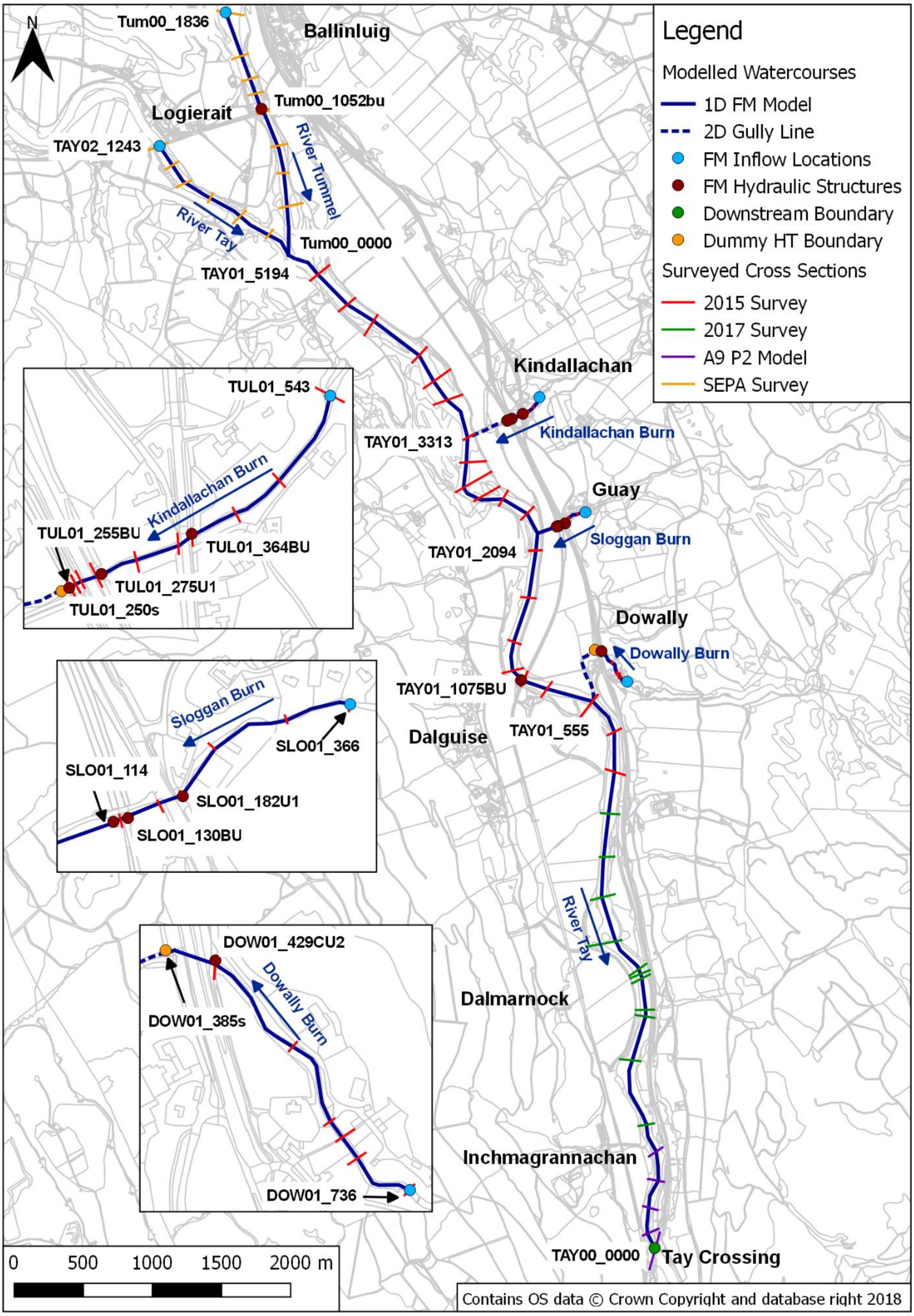


Diagram 5: Channel material for the River Tay (left) and River Tummel (right)

Diagram 6: Channel material for the Kindallachan Burn (left), Sloggan Burn (centre) and Dowally Burn (right)

In-Channel Hydraulic Structures

4.1.6 The in-channel hydraulic structures included in the 1D model extent are specified in Table 7 and locations are shown in Diagram 4.

In order to have a consistent approach between baseline and design scenarios, culvert dimensions have been represented using an embedment depth of between 0.15m and 0.3m depending on the size of the culvert. This assumes appropriate maintenance is undertaken, regardless of the degree of blockage observed in the survey data. In rectangular culverts, this embedment depth has been included by reducing the height of the culvert by the appropriate embedment depth. In circular culverts, an equivalent diameter has been calculated.

Table 7: In-channel hydraulic structures (represented in Flood Modeller)

Watercourse	Structure	Flood Modeller Node	Specification
River Tummel	A827 Bridge	Tum00_1052bu	Type: USBPR Spans: 3 Total Width: 84m Upstream Bed Level: 57.704mAOD Downstream Bed Level: 57.670mAOD Maximum Height: 6.4m
River Tay	Tay Viaduct	TAY01_1075BU	Type: USBPR Spans: 2 Total Width: 110m Upstream Bed Level: 47.21mAOD Maximum Height: 10m
Kindallachan Burn	Dowally to Kindallachan Side Road Bridge	TUL01_364BU	Type: Arch Bridge Spans: 1 Total Width: 11m Upstream Bed Level: 57.856mAOD Downstream Bed Level: 57.856mAOD Maximum Height: 2.5m A slot has been added to the base of the channel to improve model stability at low flows.
Kindallachan Burn	Existing A9 Bridge	TUL01_275U1	Type: Rectangular Conduit Inlet: Headwall with 20mm chamfers Length: 15m Width: 8.88m Height: 3.23m Upstream Invert Level: 56.970mAOD Downstream Invert Level: 56.900mAOD
Kindallachan Burn	Highland Main Line Railway Bridge	TUL01_255BU	Type: Arch Bridge Spans: 1 Total Width: 9m Upstream Bed Level: 56.645mAOD Downstream Bed Level: 56.684mAOD Maximum Height: 1.9m
Sloggan Burn	Existing A9 Culvert	SLO01_182U1	Type: Rectangular Conduit Inlet: Headwall with 20mm chamfers Length: 22m Width: 2.12m (width of the upstream cross section, which survey showed to be constricted) Height: 1.05m Upstream Invert Level: 56.890mAOD Downstream Invert Level: 56.680 mAOD
Sloggan Burn	Highland Main Line Railway Bridge	SLO01_130BU	Type: Arch Bridge Spans: 1 Total Width: 5.1m Upstream Bed Level: 55.970mAOD Downstream Bed Level: 55.832mAOD Maximum Height: 1.9m
Sloggan Burn	Culvert connection to River Tay	SLO01_114	Type: Orifice Bore Area: 0.785m Invert Level: 54.900mAOD Soffit Level: 55.870mAOD An orifice unit has been used to represent the culvert between the downstream end of Sloggan Burn and the River Tay as using a conduit unit caused instabilities in the model. This was considered to be a suitable representation as the culvert is submerged throughout most of the model run duration and levels are controlled by the water levels in the River Tay.

Watercourse	Structure	Flood Modeller Node	Specification
Dowally Burn	Existing A9 Culvert	DOW01_429CU2	Type: Rectangular Conduit Inlet: Headwall with 20mm chamfers Length: 39m Width: 5.3m Height: 1.4m Upstream Invert Level: 56.232 mAOD Downstream Invert Level: 55.750mAOD The twin culverts have been modelled as a single culvert with the combined width. A 0.9 reduction factor has been applied to the width due to constriction from an arch bridge at the upstream face. Spill units have been used at the bed level at the inlet and outlet to improve model stability.

Boundary Conditions – 1D Domain

4.1.7 The upstream and downstream boundary conditions applied to the 1D domain for each modelled reach are described in Table 8. Locations are shown in Diagram 4.

Table 8: 1D boundary conditions (represented in Flood Modeller)

Type of Boundary	Flood Modeller Node	Description
Flow-Time Boundary	Tum	Hydrological inflow applied at the upstream end of the model on the River Tummel.
Flow-Time Boundary	Tay	Hydrological inflow applied at the upstream end of the model on the River Tay.
Flow-Time Boundary	Kindallachan	Hydrological inflow applied at the upstream end of Kindallachan Burn.
Flow-Time Boundary	Guay	Hydrological inflow applied at the upstream end of Sloggan Burn.
Flow-Time Boundary	Dowally	Hydrological inflow applied at the upstream end of Dowally Burn.
Flow-Head Boundary	TAY00_0000	Flow against stage rating relationship for the downstream end of the model on the River Tay. Data for this boundary has been extracted from the hydraulic model for the A9 Dualling Programme: Pass of Birnam to Tay Crossing – Project 02 – DRMB Stage 2[2].
Head-Time Boundary	TUL01_250s	Downstream of the existing A9, Kindallachan Burn hydraulics are dominated by the flows across the River Tay floodplain and has therefore been included within the 2D domain. This is a dummy boundary used to link the 1D and 2D domains. An SX boundary in the 2D domain is being used to allow flows in/out of the 1D model.
Head-Time Boundary	DOW01_385s	Downstream of the existing A9 Dowally Burn hydraulics are dominated by the flows across the River Tay floodplain and has therefore been included within the 2D domain. This is a dummy boundary used to link the 1D and 2D domains. An SX boundary in the 2D domain is being used to allow flows in/out of the 1D model.

Watercourse Schematisation – TUFLOW

4.1.8 Sixteen minor watercourses which cross the proposed scheme have been represented within the TUFLOW model, where they were considered as potentially influencing flood risk. Their locations are shown in Diagram 7.

Channel Geometry

4.1.9 As the key constraint on these watercourses is the culvert crossing under the existing A9, a detailed representation of the watercourse channels was not considered to be necessary for the purposes of assessing flood risk. These watercourses have therefore been represented using a simple schematisation with an upstream inflow boundary, flowing into a 1D culvert under the existing A9, and

[2] At the time of writing this report, A9 Dualling Programme: Pass of Birnam to Tay Crossing – Project 02 is currently progressing to Stage 3 of the DMRB process. At Stage 2, a 1D/2D hydraulic model of the River Tay has been developed from Tay crossing to Birnam to support the DMRB Stage 2 - Flood Risk Assessment.

then linked back into the 2D domain at the downstream end of the culvert. The culverts have been represented using ESTRY 1D components and are informed by detailed survey data at each structure.

4.1.10 The inflows have been applied to the 2D domain and connected to the upstream end of the existing A9 culverts using gully lines and SX links. The gully lines have been used to adjust the levels of one or two 2D cells to match the surveyed invert levels of the culverts, directing the flow towards the culverts, but not forcing all the flow to pass through the culverts. The purpose of this approach was to allow the flow to spill out across the 2D domain upstream of the existing A9 once the culvert's capacity is exceeded.

4.1.11 The downstream ends of these culverts have been connected to the 2D domain, using SX links, at the surveyed outlet levels. In a few locations, the surveyed level was lower than the level in the 2D domain, either where the DTM had not picked up the channel bed levels, or where the 2D grid size was not picking up the detail from the DTM. Sections of gully line have been used in these locations to lower the 2D cell levels to better match the survey and the DTM, in order to create a smooth connection from the 1D culverts to the 2D domain.

4.1.12 There is one minor watercourse where this approach was not able to provide sufficient detail to inform the flood risk assessment. It was WF52 (see Diagram 7). Bed levels within this channel were not being picked up by the 2D grid cells. In addition, this watercourse is perched above the level of the surrounding floodplain which made matching channel levels to 2D cell levels difficult. Initial results showed that in the critical Run 2 events, the proposed scheme was causing an increase in flood risk which was not well-defined with the simple schematisation. A more detailed model was therefore constructed for this area. The details are provided in Annex A of this report.

Hydraulic Structures

4.1.13 Hydraulic structures (culverts) modelled on the minor watercourses are listed in Table 9 and shown in Diagram 7.

4.1.14 Dimensions and levels for all the minor watercourse culverts have been obtained from channel survey. Culvert dimensions provided below have been represented assuming the 0.15m to 0.3m embedment depth, as for the Flood Modeller Pro culverts discussed previously.

Table 9: Minor watercourse hydraulic structures

Watercourse ID	Model ID	Shape	Dimensions (m)	Length (m)	Upstream Invert Level (mAOD)	Downstream Invert Level (mAOD)
WF18	Culvert18	Circular	0.77	75.5	68.58	55.21
WF23	Culvert23	Circular	1.00	35.6	55.82	51.41
WF24	Culvert 24	Circular	0.87	40.4	52.71	50.63
WF25	Culvert 25	Circular	0.95	32.0	54.56	51.18
WF28	Culvert 28	Circular	1.00	60.3	54.88	51.49
WF29	Culvert 29	Circular	0.87	52.4	52.49	51.88
WF30	Culvert 30	Circular	1.00	43.7	52.97	51.69
WF31	Culvert 31	Circular	1.00	56.5	60.30	52.20
WF37	Culverta37-r	Circular	1.05	43.3	55.24	54.65
WF37	Culvert 37-a	Rectangular	0.51 wide x 0.65 high	7.6	55.32	55.15
WF38	Culvert 38	Circular	0.60	22.3	55.80	55.64
WF42	Culvert 45*	Circular	0.60	27.7	56.00	56.05
WF42	Culvert 42*	Circular	1.30	28.3	55.65	55.60
WF47	Culvert 47	Circular	0.90	26.2	61.44	58.50
WF49	Culvert 49-p	Circular	1.00	14.9	60.87	60.67
WF50	Culvert 50	Circular	0.34	37.9	61.74	60.52
WF52	Culvert 52	Circular	0.59	37.9	61.71	60.84
WF53	Culvert 53	Circular	1.02	42.1	59.71	59.68

*Culvert 45 and Culvert 42 are now known as WF42 and WF41 respectively throughout the rest of the project, however the model IDs have not been updated to reflect this change. Only one inflow is being applied upstream of these two culverts.

Boundary Conditions

4.1.15 Hydrological inflows for the minor watercourses have been applied as ST boundaries within the 2D domain. The flow hydrographs for these boundaries were applied based on the hydrological flows discussed in Section 3.

4.1.16 SX boundaries at the culvert inlets and outlets link the flow between the 1D and 2D domains.

4.1.17 For four of the minor watercourses, the culvert outlet was located within the extent of the Flood Modeller Pro 1D domain rather than the 2D domain. Therefore, instead of using a SX boundary, a connection was made between the downstream end of the culvert and the appropriate Flood Modeller Pro node on the River Tay using a FM/ESTRY link. This applies to WF18, WF23, WF24 and WF25.

Floodplain Schematisation – TUFLOW

Floodplain Topography

4.1.18 The 2D domain covers an area of 10.15km², as shown in Diagram 7. The topography is represented using a 6m resolution square grid. The levels for the grid cells are based on a 1m resolution Digital Terrain Model (DTM) derived from LiDAR, with the exception of a 0.1km² area of high ground in the north east, where the model was extended using the 5m resolution photogrammetry DTM. The area is indicated in Diagram 7.

4.1.19 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. Table 10 summarises all the model layers used to modify the floodplain topography.

4.1.20 Downstream of the existing A9, both Kindallachan Burn and Dowally Burn are completely inundated by the Tay floodplain flows in most of the Run 1 events (3.33% AEP, 2% AEP, 0.5% AEP and 0.5% AEP + CC). Because of this, both watercourses have been represented within the 2D domain in these areas and the channel is represented using a gully line as well as two breaklines for the left and right banks.

Table 10: Layers used to modify floodplain topography

Model Layer	Comment
2d_zln_bank_04.MIF	Breakline to define the bank levels along the 1D/2D link. Elevations were informed by the LiDAR data along the River Tay and the River Tummel, and from the surveyed cross sections along Sloggan Burn, Kindallachan Burn and Dowally Burn.
2d_zln_Tribbank_03.MIF	Breakline to define the bank levels along the sections of Kindallachan Burn and Dowally Burn represented within the 2D domain, based on the surveyed cross sections.
2d_zsh_ridge_094.MIF	Breakline to ensure the highest levels are picked up by the model cells along the Highland Main Line railway, a key section of embankment, and the bank line along the channel downstream of culverts 47 and 49. Elevations were informed by the LiDAR data.
2d_zsh_Road_Extension_02.MIF	Existing A9 Road levels obtained from the BLOM topographic survey data to improve the road representation in the northern extent of the model.
2d_zsh_gully_094.MIF	Gully lines used for three purposes: • to define the bed levels along the sections of Kindallachan Burn and Dowally Burn represented within the 2D domain. Levels are based on surveyed cross sections of the watercourses. • to connect the 2D inflows for the minor watercourses to the culvert inlets. Levels are matched to the culvert invert levels. • to ensure floodplain drain levels from the DTM are picked up by the model cells in a few key locations and to ensure a smooth connection between surveyed culvert outlet levels and the 2D domain in some areas.
2d_zsh_compensatory_storage_001.MIF	Adjusts the levels for the compensatory storage areas at a new development near Inch Farm which is not present in the DTM.
2d_zsh_buildings_001.MIF	Adjusts the levels for the buildings at a new development near Inch Farm which is not present in the DTM.
2d_zsh_bank_wide_093.MIF	A smoothing z-shape in two locations along the banks of the River Tay which widens the embankment slightly to decrease the slope, as the sudden drop from the top of the bank to the floodplain was causing model stability issues.

4.1.21 An initial water level has been applied to the 2D domain around Lamb Island as this area is lower than the initial water level used within the 1D channel.

Floodplain Hydraulic Friction

4.1.22 Hydraulic roughness coefficients are applied across each cell of the 2D domain depending on land use taken from OS Mastermap data, as shown in Table 11. Roughness values adopted were taken from standard guidance (Chow, 1959) and adjusted as part of the calibration process discussed in Section 8.

4.1.23 In a few locations along the river banks the roughness has been increased from that specified based on the OS Mastermap land use to improve the model stability. Sensitivity tests indicated that this would not have a significant impact on the model results.

Table 11: Manning's 'n' coefficients - 2D domain

Land Use	Manning's 'n'
Water bodies	0.018
Roads, tracks and paths	0.023
Short grass	0.032
Gardens	0.046
Railway	0.046
Embankments	0.046
General green areas	0.051
Trees	0.092
Buildings and glasshouses	1

Floodplain Hydraulic Structures

4.1.24 Hydraulic structures in the floodplain (2D) were included where they were considered important for flow connectivity and flood risk, either using 1D ESTRY culverts or as 2D structures using flow constriction shapes. Details are provided in Table 12 and locations are shown on Diagram 7. Dimensions and levels for most of these structures have been informed by either survey data or site visit notes. In some cases, assumptions have been made based on LiDAR data.

4.1.25 Due to model stability issues four culverts (ref 24-27 in Table 12) were represented as 2D structures using flow constriction shapes (2d_lfcsh). Invert levels were applied based on the surveyed upstream invert levels, the surveyed width was represented by applying a blockage factor to the 2D cells, and the surveyed heights were used to determine the obvert levels.

4.1.26 The culvert with model ID 'UnsurPotato' has not been observed on site and culvert dimensions have been assumed. This culvert was added to the model during the calibration process in order to provide connectivity between the River Tay floodplain and the field between the existing A9 and Dowally to Kindallachan Side Road north of Guay. See Section 8 for further details.

Table 12: Floodplain hydraulic structures represented in ESTRY

Figure ID	Model ID	Type	Dimensions (m)	Length (m)	Upstream Invert Level (mAOD)	Downstream Invert Level (mAOD)
1	cul8	Circular Culvert	2	34.1	57.800	57.700
2	RLWC_008	Rectangular Culvert	2.5 wide x 1 high	25.0	65.794	62.822
3	A9C_001	Circular Culvert	1.05	53.1	60.870	60.630
4	MINC_007	Rectangular Culvert	2 wide x 1 high	14.1	59.693	59.761
5	A9C_003	Rectangular Culvert	2.5 wide x 1 high	7.9	63.500	62.190
6	A9C_004	Rectangular Culvert	2.5 wide x 1 high	10.6	64.874	64.682
7	cul1	Rectangular Culvert	1.76 wide x 1.5 high	21.2	58.183	57.878
8	Cul2	Rectangular Culvert	1.83 wide x 2.1 high	9.1	55.670	55.660

Figure ID	Model ID	Type	Dimensions (m)	Length (m)	Upstream Invert Level (mAOD)	Downstream Invert Level (mAOD)
9	cul3	Rectangular Culvert	3.1 wide x 2.3 high	4.8	57.080	57.070
10	CulV8_c1	Rectangular Culvert	3 wide x 2.75 high	3.9	54.550	54.540
11	culv5	Circular Culvert	0.3	7.2	59.870	59.850
12	Culvert6	Circular Culvert	0.3	9.4	59.300	59.250
13	Culv7	Rectangular Culvert	1.8 wide x 1.5 high	4.6	59.670	59.650
14	Culv_8	Rectangular Culvert	1.84 wide x 1.7 high	4.6	59.630	59.620
15	Culv10	Circular Culvert	1.34	7.9	62.190	62.150
16	Culv111	Circular Culvert	1.2	24.1	60.460	60.460
17	UnsurPotato	Circular Culvert	0.5	41.8	55.900	56.000
18	Culvert1a	Circular Culvert	2no. 0.4m diameter	22.0	51.400	51.670
19	Culvert3	Rectangular Culvert	1.64 wide x 2.48 high	14.5	50.370	50.300
20	Culvert7	Rectangular Culvert	2.75 wide x 2.95 high	17.0	52.270	52.190
21	Culvert1b	Circular Culvert	2no. 0.4m diameter	22.0	51.400	51.620
22	Stank	Circular Culvert	2	46.8	51.750	51.700
23	Culvert3_ds	Rectangular Culvert	1.63 wide x 2.48 high	26.7	50.470	50.410
24	Culvert6w	2d_lfcsh	4.28 wide x 1.7 high	8.4	52.860	52.860
25	Culvert 2	2d_lfcsh	3.55 wide x 2.8 high	9.6	52.180	52.180
26	Culvert 5	2d_lfcsh	3.57 wide x 2.55 high	8.7	51.780	51.780
27	Culvert 4	2d_lfcsh	3 openings: 5.5 wide x 3.4 high 3.6 wide x 3.4 high 5.6 wide x 3.4 high	9.9	51.060	51.060

<u>Boundary Conditions – 2D Domain</u>

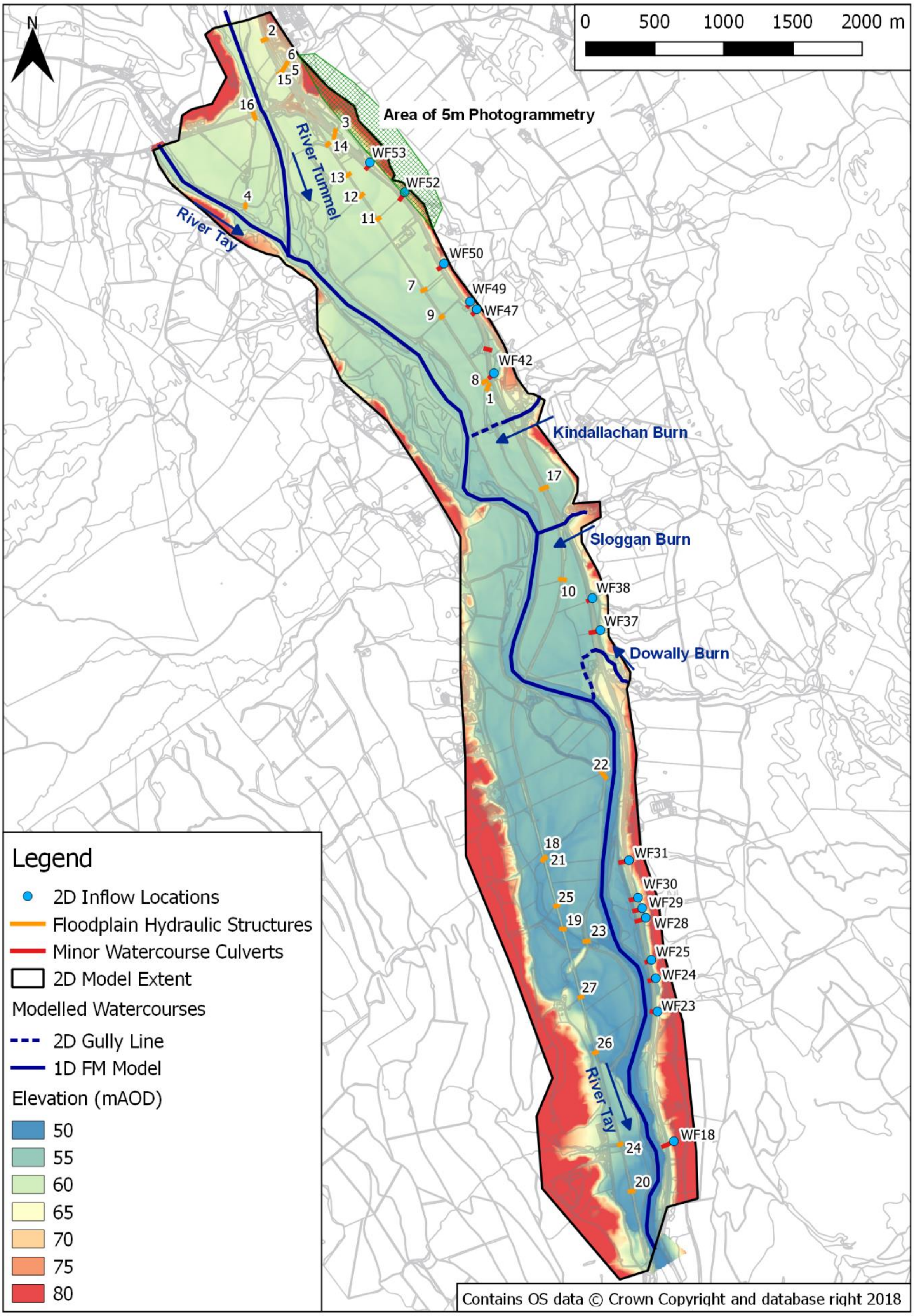
4.1.27 Inflows to the 2D domain have been applied for the minor watercourses, as discussed within the watercourse schematisation section above. No 2D boundaries have been applied at the downstream end of the model as all flow returns to the 1D domain.

<u>1D/2D Linking</u>

4.1.28 The link between the 1D and the 2D domains was defined along the banks of the watercourses represented in Flood Modeller Pro using HX connections. As discussed in Table 8, Kindallachan Burn and Dowally Burn were also linked to the 2D domain by an SX link downstream of the existing A9.

4.1.29 SX links were also used to connect the 1D ESTRY components for the minor watercourses and floodplain structures to the 2D domain.

Diagram 7: TUFLOW baseline schematisation



5 Proposed Scheme Modelling

Proposed Scheme Arrangement

5.1.1 Diagram 8 shows the layout of the proposed scheme as per Design Fix 8a of the DRMB Stage 3 process. The modifications to the baseline model for the inclusion of the proposed scheme include the updates to the road elevations and roughness values along the scheme footprint, inclusion of Sustainable Drainage System (SuDS) features within the floodplain, updates to the dimensions, lengths and invert levels for the existing A9 culverts within Flood Modeller Pro and ESTRY, and the merging of three minor watercourse inflows where watercourses are being diverted.

Flood Modeller Pro Model Updates

5.1.2 The proposed scheme crosses each of the three tributaries, Kindallachan Burn, Sloggan Burn and Dowally Burn. At each of these crossings, the existing hydraulic structures have been extended to fit the widened road footprint. An additional culvert has also been added for a new side road crossing on Sloggan Burn downstream of the proposed scheme. The modifications at these structures are summarised in Table 13.

Table 13: Flood Modeller Pro hydraulic structure updates

Watercourse	Structure	Flood Modeller Node	Modifications
Kindallachan Burn	A9 Bridge	TUL01_275U1	Extended upstream by 21m. Width and height unchanged from baseline model. Upstream invert level and cross section interpolated from existing bed levels. Details taken from drawing: A9P03-JAC-SBR-A_ML061_ST-DR-ST-0001 Rev P1 - Kindallachan Underbridge.pdf
Sloggan Burn	A9 Culvert	SLO01_203c	Extended upstream by 29m at approximately 40° angle to existing culvert. Included a FM bend unit with loss coefficient of 0.35. Extended downstream by 6m. Width increased to 2.4m due to removal of constriction at inlet. Invert levels extrapolated using existing culvert gradient. Details taken from drawing: A9P03-JAC-SBR-A_ML052_ST-DR-ST-0001 Rev P1 - Guay Culvert.pdf
Sloggan Burn	New culvert for downstream side road	SLO01_154d	The design includes a 1.8m section of open channel separating the main road culvert from a downstream side road culvert with the same dimensions. As this section of open channel is significantly smaller than the 6m 2D grid size it was not considered appropriate to explicitly model this section of open channel. Instead the new culvert has been modelled as a continuation of the existing A9 culvert, connected by a junction, and with a change in gradient. A spill and HT boundary at this junction represent the open channel section by allowing connectivity to the 2D domain via an SX link. Downstream invert level has been interpolated from the existing bed levels. Details taken from drawing: A9P03-JAC-SBR-A_ML052_ST-DR-ST-0001 Rev P1 - Guay Culvert.pdf
Dowally Burn	A9 Culvert	DOW01_458c	Extended upstream by 29m at approximately 30° angle to existing culvert. Included a FM bend unit with loss coefficient of 0.3. Extended downstream by 17m. Width increased to 5.9m due to removal of arch bridge constriction at the inlet. Invert levels extrapolated using existing culvert gradient. Details taken from drawing: AP0903_JAC_SBR-A_ML042_ST-DR-DT-001 AS PER DF6 13.12.2017.pdf

TUFLOW Model Updates

5.1.3 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.

5.1.4 Five SuDS ponds and one ecological mitigation pond are included in the proposed scheme. These have been included in the model with an initial water level set such that the ponds are already full with water at the start of the simulation.

5.1.5 Table 14 summarises the modifications which have been made to the minor watercourse crossings as part of the proposed scheme, which are based on drawings and details provided by the design team. See Table 9 for the corresponding details in the baseline.

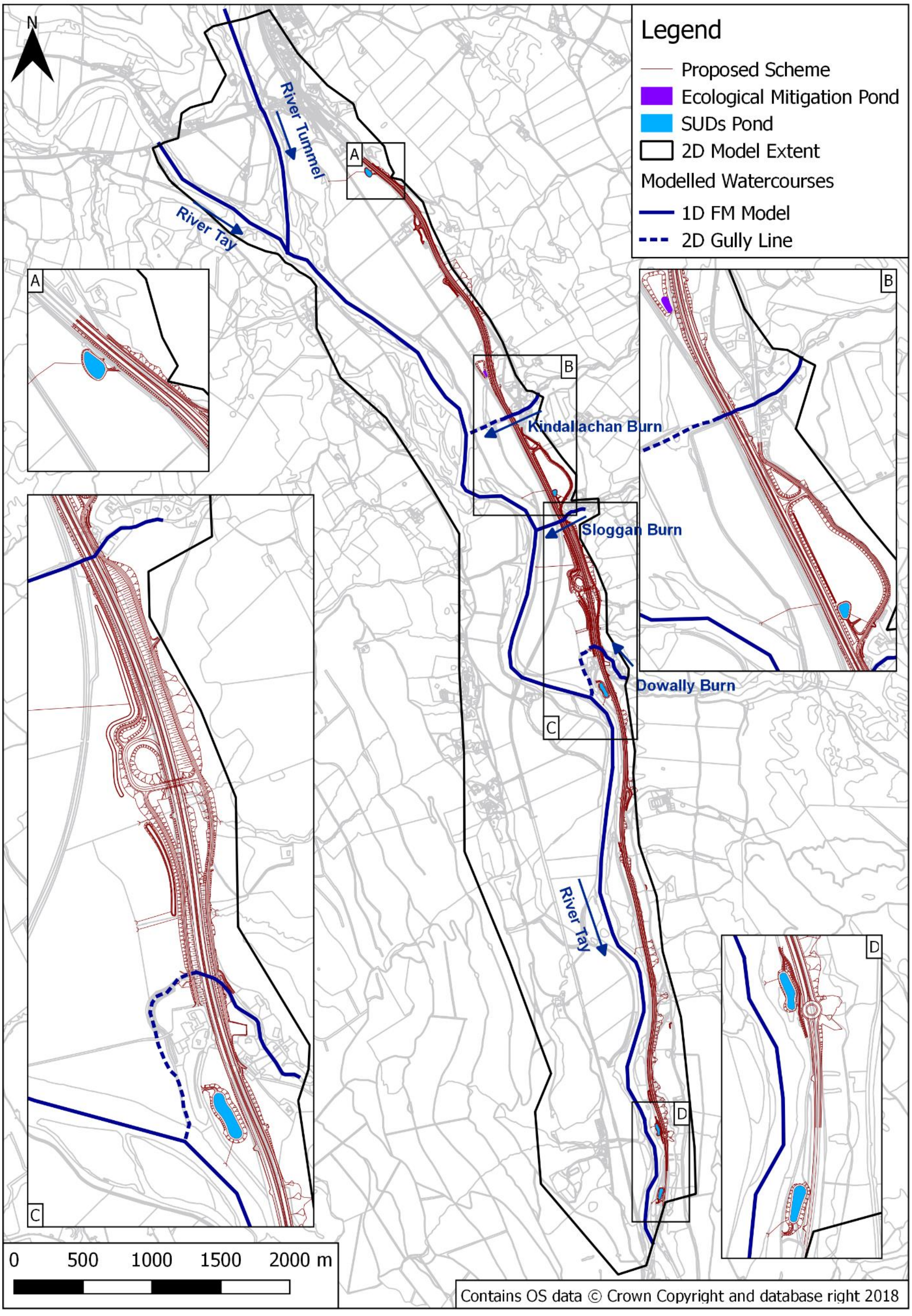
5.1.6 The assumed culvert which connects the River Tay floodplain with the field between the existing A9 and Dowally to Kindallachan Side Road north of Guay has been removed from the proposed scheme model. This is because the nature of the connectivity between the River Tay and this field is uncertain and it was considered conservative to assume that it may not be retained in the proposed scheme.

Table 14: Minor watercourse modifications

WF ID	Model ID	Modification	Shape	Dimensions (m)	Length (m)	Upstream Invert Level (mAOD)	Downstream Invert Level (mAOD)
WF18	Culvert18	Upsized Additional inflow from WF17	Rectangular	1.8 wide x 1.2 high	46.3	56.05	55.03
WF23	Culvert23	Upsized Additional inflow from WF21 and WF22	Rectangular	2 wide x 1.7 high	46.3	57.95	52.47
WF24	Culvert 24	Upsized	Rectangular	1.8 wide x 1.3 high	43.4	53.79	50.23
WF25	Culvert 25	Extended upstream	Circular	0.95	33.8	54.76	51.18
WF28	Culvert 28	No change	Circular	1.00	60.3	54.88	51.49
WF29	Culvert 29	No change	Circular	0.87	52.4	52.49	51.88
WF30	Culvert 30	Upsized	Rectangular	1.5 wide x 1.35 high	53.4	57.86	51.84
WF31	Culvert 31	Extended upstream	Circular	1.00	63.5	61.28	52.20
WF37	Culvert 37	Extended upstream and downstream	Circular	1.00	85.7	55.64	54.00
WF38	Culvert 38	Upsized	Rectangular	2 wide x 1.3 high	41.5	56.08	55.59
	Culvert 38a	New culvert under downstream side road	Rectangular	2 wide x 1.3 high	34.8	55.43	55.18
WF42	Culvert 45	Culverts extended	Circular	0.60	49.0	56.00	55.83
	Culvert 42	Channel excavated between Culvert 45 and Culvert 42.	Circular	1.30	53.1	55.68	55.59
WF47	Culvert 47	Upsized Downstream channel realigned along the bottom of the embankment. Additional inflow from WF49	Rectangular	1.8 wide x 1.2 high	38.3	61.43	59.24
WF50	Culvert 50	Upsized Realigned further north	Circular	1.34	33.8	59.11	58.98
	Culvert 50a	New pipe upstream with manhole at connection	Circular	1.34	15.8	65.55	59.11

WF ID	Model ID	Modification	Shape	Dimensions (m)	Length (m)	Upstream Invert Level (mAOD)	Downstream Invert Level (mAOD)
WF52	Culvert 52	Upsized	Circular	1.00	50.6	61.74	60.43
	Culvert 52a	Inflow has been split between three new upstream pipes with manhole connections to existing A9 culvert	Circular	0.70	7.1	62.86	61.74
	Culvert 52b		Circular	1.00	49.5	62.21	61.74
	Culvert 52c		Circular	0.70	14.8	64.25	62.21
	Culvert 52d	Extended downstream, replacing track culvert These updates have also been included in the detailed WF52 model, see Annex A	Circular	1.00	30.7	62.50	62.21
WF53	Culvert 53	Upsized	Circular	1.08	42.1	59.71	59.68

Diagram 8: Proposed scheme layout



6 With Mitigation Modelling

6.1.1 The proposed scheme was found to increase flood risk in a number of locations, as presented in Appendix A11.3 (Flood Risk Assessment). A large number of mitigation options have been tested to try and reduce flood risk in these areas back to baseline flood levels. The following section discusses the final options which have been incorporated into the proposed scheme. A full list of the tested options can be found in Annex B.

Mitigation Measures

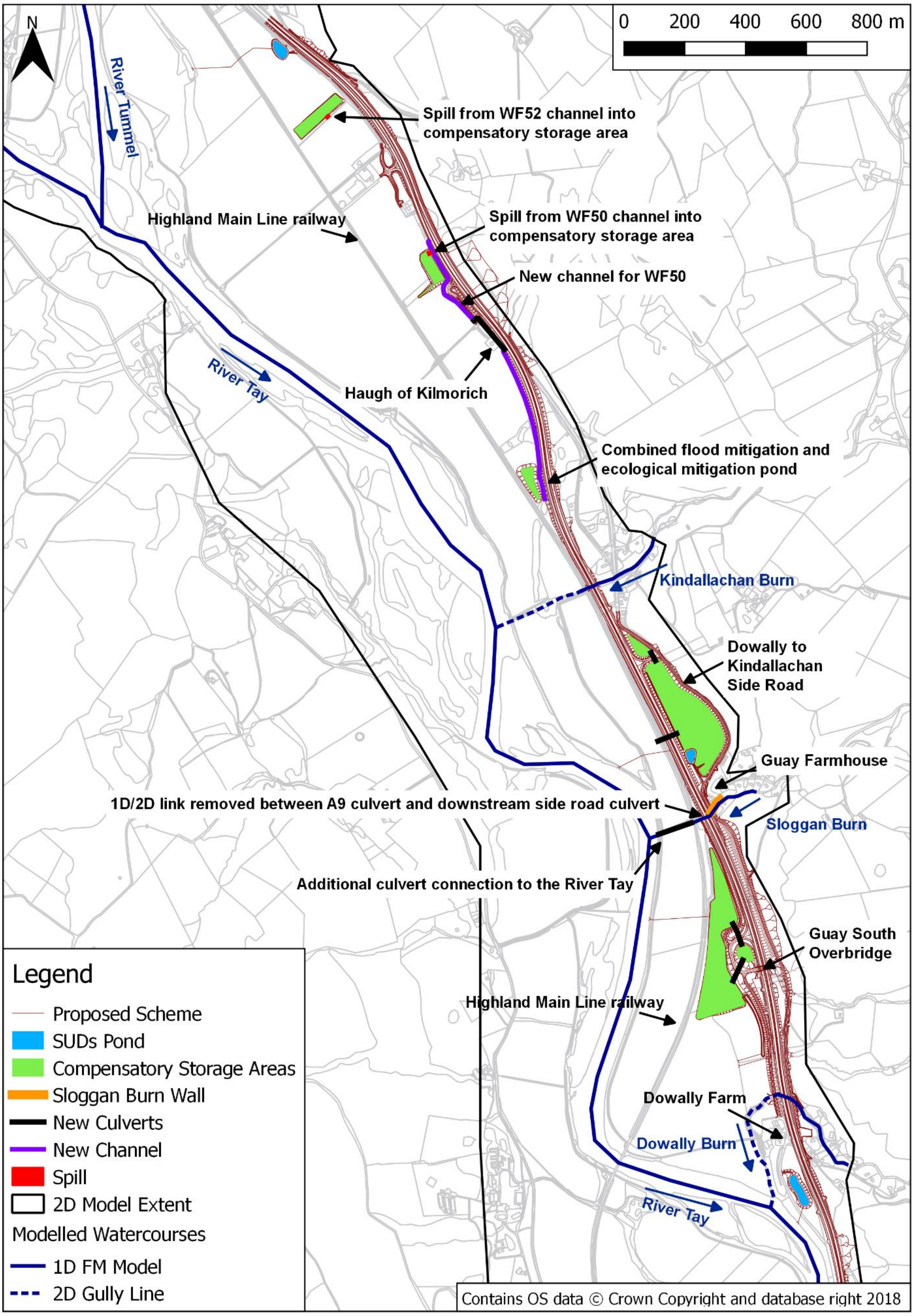
6.1.2 Table 15 lists the locations where increased flood risk has been identified and the consequent mitigation measures which have been incorporated into the proposed scheme model in order to resolve these issues. The locations are shown in Diagram 9.

Table 15: Locations with increased flood risk and the proposed mitigation measures

Location	Event	Change in Flood Risk	Proposed Mitigation Measure
Guay Farmhouse	Run 2 -0.5% AEP and 0.5% AEP + CC	Increased road footprint encroaches on floodplain for water spilling out of Sloggan Burn, leading to increased water levels around Guay Farmhouse.	Wall along the right bank of Sloggan Burn to keep all water within the channel in the Run 2 0.5% AEP + CC event. This has been modelled with an artificial glass wall(z-shape) along the bank.
Highland Main Line railway embankment on the right bank of Sloggan Burn	Run 1 and Run 2 - 0.5% AEP + CC	Increased road footprint prevents flow from spilling out of left bank between the proposed scheme and the Highland Main Line railway, instead flow is forced to spill out of the right bank, through the link between the main road culvert and the downstream side road culvert, leading to increased water levels along the railway embankment.	Culvert the small section of open channel between the main road culvert and downstream side road culvert. Within the model the spill and SX link have been removed.
Left bank of Sloggan Burn downstream of the Highland Main Line railway	Run 2 - 0.5% AEP + CC event	By preventing the flow from spilling out of Sloggan Burn upstream of the proposed scheme and the Highland Main Line railway, increased flows are reaching the culvert to the River Tay and it is surcharging, leading to new flooding across the neighbouring fields.	Additional 0.5m diameter culvert parallel to the existing culvert between Sloggan Burn and the River Tay. This has been represented in the model using an orifice unit, using the same approach as for the existing culvert.
Highland Main Line railway embankment west of Dowally overbridge	Run 1 - 3.33% AEP to 0.5% AEP + CC	Loss of floodplain due to the Guay South Overbridge footprint leads to increased water levels across the field and along the Highland Main Line railway embankment.	Compensatory storage area around Guay South Overbridge. The excavated area has been included within the MXROAD export (see Table 1) for inclusion in the model. Three culverts have been added to connect the storage areas beneath the road. Two 1m diameter culverts in the north, allow water beneath the two roads into the inner storage area. The levels for one of these culverts have been raised to allow water into the area during the peak of the 0.5% AEP +CC event. This culvert is not utilised during the 2% AEP or more frequent events. A 0.5m unidirectional culvert in the south with invert levels matched to the ground levels, allows water to drain out of the inner storage area.
Fields north of Dowally Farm	Run 1 - 50% AEP Run 2 - 3.33% AEP to 0.5% AEP + CC	Increased capacity of the proposed scheme culverts on WF37 and WF38 lead to increased flows and increased flooding across the fields between these culverts and the River Tay.	
Fields between the proposed scheme and Dowally to Kindallachan Side Road north of Guay	Run 1 - 3.33% AEP to 0.5% AEP + CC	This area has no local increase in flood risk but is instead providing general mitigation for the loss of floodplain storage across the whole model extent due to the proposed scheme.	Compensatory storage areas within the fields between the proposed scheme and Dowally to Kindallachan Side Road north of Guay. Two excavated areas have been included within the MXROAD export for inclusion in the model. The bottom of the storage areas is represented using a polygon (z-shape) that set the level at 55.8mAOD. The culvert (model ID 'UnsurPotato') has been added back into the model and lowered to match

Location	Event	Change in Flood Risk	Proposed Mitigation Measure
			the new ground levels. An additional culvert connects the two lowered areas beneath the road.
Along the WF52 channel between the proposed scheme and the Highland Main Line railway	Run 2 - 3.33% AEP to 0.5% AEP + CC	Increased capacity of the existing A9 culvert on WF52 and the lowering of the channel at the culvert outlet lead to increased flows downstream and increased water levels across the fields between the proposed scheme and the Highland Main Line railway embankment.	Compensatory storage area along the right bank of the channel with a spill across the right bank into the storage area. An excavated area has been included within the MXROAD export for inclusion in the model. The spill was included as a z-shape. This mitigation option was tested and finalised using the detailed WF52 model discussed in Annex A before being included within the main model.
Downstream of the relocated WF50 culvert between the proposed scheme and the Highland Main Line railway	All modelled events	Increased capacity of the existing A9 culvert on WF50 leads to increased flows downstream of the proposed scheme, and the change in alignment creates new areas of flooding. In some events the affect is likely amplified by the loss of floodplain area due to the increased road footprint.	A channel has been added to convey the flows from WF50 along the edge of the proposed scheme embankment to the culverts and wetland area around WF42. This channel has been modelled using a gully line as well as a 1D culvert element for the culverted section around Haugh of Kilmorich. A compensatory storage area has been included just downstream of WF50 with a spill from the channel. The storage area was included within the MXROAD export however an additional gully line was added along the downstream end to ensure that the storage area was self-draining. The spill was included as a z-shape. The ecological mitigation pond between the proposed scheme and the Highland Main Line railway near Culvert 42 has been re-designed to provide additional flood mitigation benefits. This area was included within the MXROAD export and an initial water level has been applied at a level below the top of the pond based on design information.

Diagram 9: Proposed mitigation measures



7 Modelled Events

7.1.1 Table 16 shows the AEP flood events and model scenarios that were simulated with the hydraulic models (main model and WF52 Detailed model). The table shows the final model scenarios only and does not include the large number of mitigation tests which have been completed. These are summarised in Annex B.

Table 16: Modelled events

Scenario	AEP Event				
	50% (2-year)	3.33% (30-year)	2% (50-year)	0.5% (200-year)	0.5% (200-year) + CC
Baseline – Run 1 Hydrology	✓	✓	✓	✓	✓
Baseline – Run 2 Hydrology		✓		✓	✓
Roughness Sensitivity* +/-20%					✓
Hydrological Inflow Sensitivity* +/-20%					✓
Downstream Boundary Sensitivity* +/-5%					✓
Guay Field Culvert Sensitivity*					✓
Proposed Scheme – Run 1 Hydrology	✓	✓	✓	✓	✓
Proposed Scheme – Run 2 Hydrology		✓		✓	✓
With Mitigation – Run 1 Hydrology	✓	✓	✓	✓	✓
With Mitigation – Run 2 Hydrology		✓		✓	✓
WF52 Detailed Model - Baseline (Run 2)		✓		✓	✓
WF52 Detailed Model – Proposed Scheme (Run 2)		✓		✓	✓
WF52 Detailed Model – With Mitigation (Run 2)		✓		✓	✓

*See Sensitivity Analysis in Section 8.1.28

8 Model Proving

Model Performance

8.1.1 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 for which the variation of the found solution between successive iterations is either zero or negligibly small and lies within a pre-specified tolerance limit.

8.1.2 As shown in Diagram 10, 1D Flood Modeller Pro convergence is good throughout the run duration. This convergence plot is generally typical for all the modelled events, except for some non-convergence occurring for a short time in the higher frequency events at the SX link on Kindallachan Burn (for around 30 minutes) and due to mode changes in the Dowally culvert (for around 20 seconds). Both issues occur well before the peak of the flood and therefore do not impact on the maximum flood peaks predicted by the model.

8.1.3 The cumulative mass error reports output from the TUFLOW 2D model have been checked for all simulated events. The accepted tolerance range recommended by the software manual is +/- 1% mass balance error. Diagram 11 shows that for the Run 1 0.5% AEP (200-year) plus CC flood event the cumulative mass error is well within this tolerance range for the duration of the run. This mass error diagnostic is typical for all events simulated.

8.1.4 Smooth variation of the change in volume through the model simulation can be another indicator of good convergence of the 2D model, however Diagram 11 shows that in this model there is considerable fluctuation in the change in volume. This effect is actually caused by fluctuations in the hydrological inflow hydrographs as a result of using a hydrograph shape based on a historic flood event and is not related to the model performance.

Diagram 10: Flood Modeller Pro 1D Model convergence plot – Baseline Run 1 - 0.5% AEP plus CC

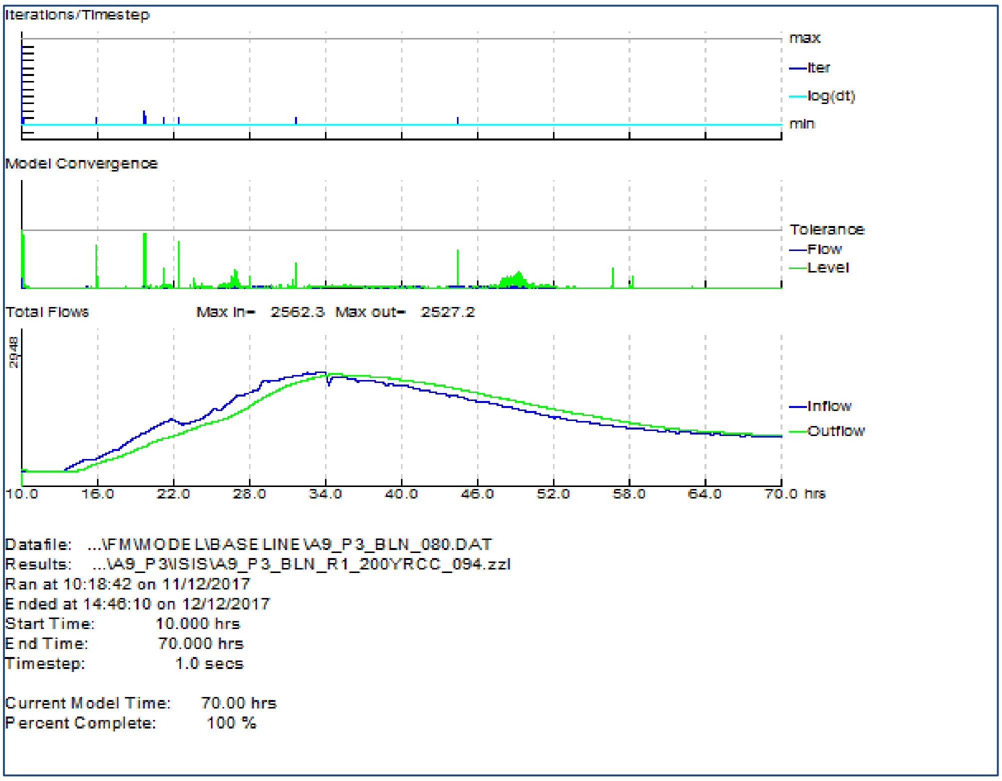
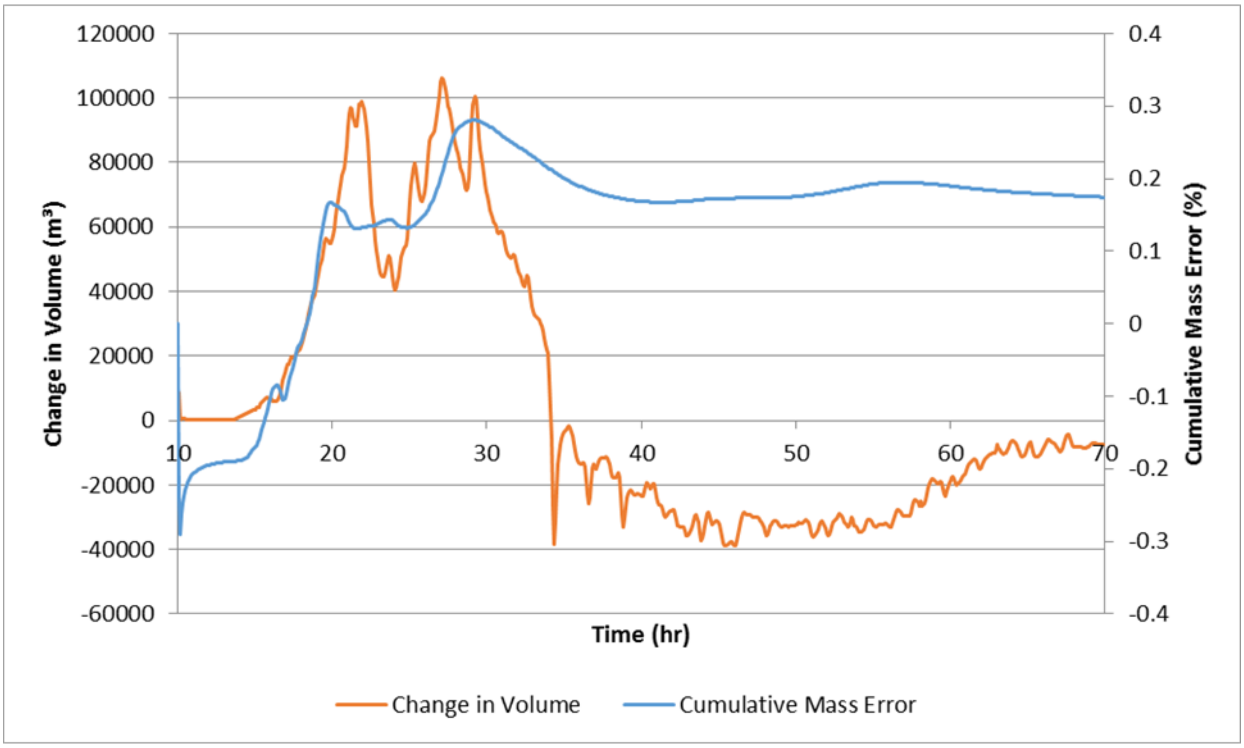


Diagram 11: Cumulative mass error and change in volume – Baseline Run 1 - 0.5% AEP plus CC



Calibration and Verification

Hydrology

8.1.5 Calibration of a hydraulic model requires accurate recorded flood flows with which to run the model and observed level data from the event to compare the model predicted water levels to. Both major rivers of the model have gauging stations upstream of, though reasonably close to, the beginning of the modelling; e.g., the Pitlochry station (River Tummel) is located approximately 8km upstream and the Pitnacree station (River Tay) is located approximately 7km upstream of the Tay/Tummel confluence. Flood hydrographs for three major historic flood events, 30 December 2015, 26 January 2008 and 14 December 2006, were extracted from 15-minute interval flow data provided by SEPA. The model was calibrated for the 2015 event and verified for the 2008 and 2006 events.

8.1.6 To enable this calibration/verification, the historic flood hydrographs recorded at the Pitnacree and Pitlochry gauges were applied at the upstream modelling extents of the two rivers, together with the residual inflows estimated for the intervening catchment between the two gauges and the downstream end of the model.

8.1.7 It is noted that the large floodplain area on the River Tay downstream of Pitnacree gauge and upstream of the model extent is not represented within the hydraulic model. Therefore, the model routed flows at the downstream end of the model were reconciled with the inflow hydrographs for the A9 Project 02 (Pass of Birnam to Tay Crossing) - DRMB Stage 2 hydraulic model which overlaps with the downstream end of the model. Inflows for the A9 Project 02 model were derived from the same historic flood events with flow records collected from the Caputh (Tay) and Hermitage (Braan) gauges during the calibration/verification of the A9 Project 02 model.

8.1.8 The above flows were reconciled by scaling the historic flood hydrograph at Pitnacree by a scaling factor of 0.85, (this is considered to partially compensate for the impact of the un-modelled floodplain extent between Pitnacree and the upstream end of the model, and is described further in Section 5 of Appendix A11.2 (Surface Water Hydrology Report). During the flow reconciliation, the Pitlochry historic flood hydrograph was not scaled because it has been observed the predicted flow at the downstream extent of the A9 Project 04 (Pitlochry to Killiecrankie) - DRMB Stage 3 hydraulic model of the River Tummel[3] (close to the upstream end the present model) was little different to that recorded at Pitlochry.

Calibration

8.1.9 Limited water level data was available for the calibration. The 30 December 2015 event had the most available data due to wrack mark observations which were collected in the areas around Kindallachan and Dowally, therefore this event was chosen for the calibration. Photographs of the winter 2015/16 flooding were made available by the local residents.

8.1.10 For the 2008 and 2006 events, the only available data were a number of photos taken during the events showing the flood extents.

8.1.11 For the 30 December 2015 flood event, the wrack marks were recorded by Jacobs during a site visit on 15 January 2016 and were indicated by debris left on fences after the flood event. They are all located to the east of the Highland Main Line railway embankment between Dowally and Haugh of Kilmorich, as shown in Diagram 12.

8.1.12 There are a number of uncertainties associated with using these wrack mark levels:

- The wrack marks were recorded approximately 2 weeks after the peak of the event, and could have been displaced between the time of the event and the information being collected.
- A number of wrack marks were removed from the analysis as the supporting photographs indicated that they were not necessarily associated with the highest water level and could have been caused by the receding limb of the flood.
- A survey of the wrack marks relative to the ordnance datum was not carried out, instead the depth of the marks relative to the ground was obtained on site and the 1m LiDAR DTM was used to determine the level relative to ordnance datum.

8.1.13 In order to achieve a good match between the modelled water levels and the levels at the wrack marks roughness values across the 2D domain and within the 1D cross sections were decreased by 4%, 8% and 12% from the original levels. The 8% decrease in roughness was found to achieve the best match with the observed data and was adopted into the baseline model. Diagram 13 shows the difference in water level between the modelled and observed levels with the 8% decrease in roughness. This is considered to be a good fit considering the uncertainties within the wrack mark data.

8.1.14 The comparison between the routed flow through the model at the downstream extent and the inflow to A9 Project 02 model is also shown in Diagram 13, which shows a close match.

[3] See Appendix A11.4 Hydraulic Modelling Report – DMRB Stage 3 Environmental Statement – A9 Dualling Programme Pitlochry to Killiecrankie

Diagram 12: Observed wrack mark locations and modelled flood extents for the 30 December 2015 event

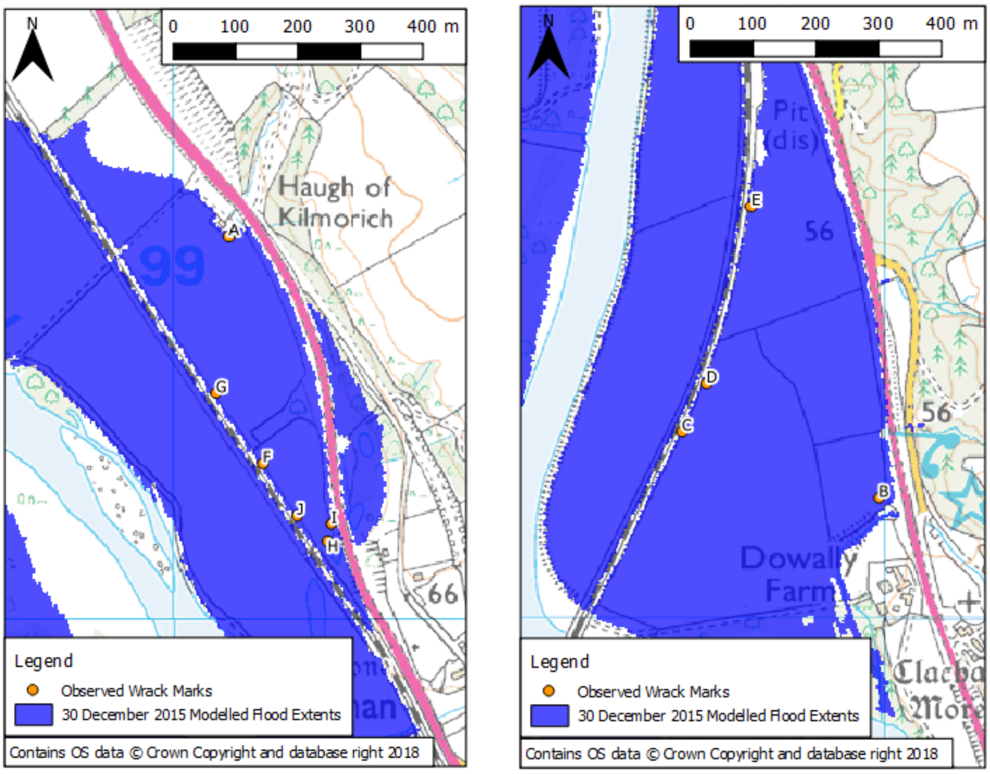
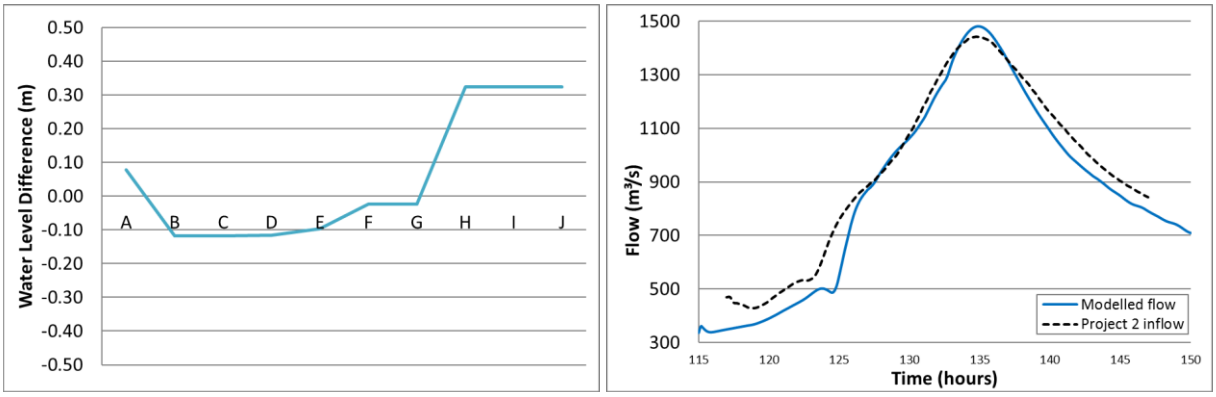


Diagram 13: Water level differences and flow comparison for the 30 December 2015 event



8.1.15 In addition to the wrack mark data, a photograph of the December 2015 flood extents was also used for calibration. The photograph presented in Diagram 14 shows considerable flooding in the fields between the existing A9 and Dowally to Kindallachan Side Road north of Guay Farmhouse. This flooding was not observed in the model results at the beginning of the calibration process.

8.1.16 Flooding mechanisms in this area were investigated to solve this discrepancy. Flooding to the fields as a result of Sloggan Burn overtopping its right bank was not considered a plausible explanation considering the large volume of water and flood extent observed. This was further confirmed by the model results for the design runs (Run 1 and Run 2) which predicts the onset of flooding from Sloggan Burn between a 2% AEP (50-year) event and a 0.5% AEP (200-year) event whilst the 30 December 2015 event is in the order of a 3.3% AEP (30-year) event.

8.1.17 A search of the field, following a suggestion from a local resident that there is a culvert under the existing A9 in this location (allowing floodplain connectivity on either side of the existing A9) was unable to find any evidence of this; although the photographic evidence indicates that the flooding in the field occurs simultaneously with the main floodplain.

8.1.18 Groundwater flooding has also been considered as a potential source of the flood water, with potential for hydraulic connectivity between the River Tay and east of the existing A9 via superficial gravel deposits. Monitoring has been undertaken with a borehole located within the field. The results of this monitoring have been inconclusive. In addition, groundwater flooding would be likely to have a slower response to flooding which does not match with the simultaneous nature of the flooding observed on either side of the A9.

8.1.19 Surface water flooding from woodlands to the east is also a possibility, with SEPA surface water flood maps indicating that much of the field is at high risk of surface water flooding from a 10% AEP (10-year) flood event. However, considering the extent and large flood volume observed it is reasonable to dismiss surface water flooding as a sole explanation for the observed flooding.

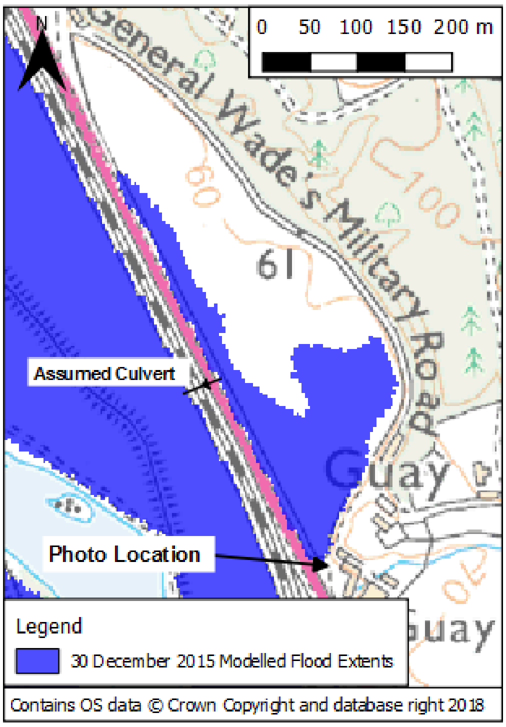
8.1.20 On the basis that it has not been possible to confirm the flood mechanism. Baseline hydraulic modelling of this area has therefore taken a conservative approach, with connectivity provided between the field and the floodplain west of the existing A9 through introduction of a culvert (model ID 'UnsurPotato') under the road embankment.

8.1.21 Invert levels were assumed based on LiDAR data and a culvert diameter of 500mm was chosen as this resulted in the best match with the observed flood extents; this, for the calibration event as well as for the two verification events.

8.1.22 Diagram 14 shows the observed flood extents (left), along with the modelled flood extents (right), including the assumed culvert under the existing A9.

8.1.23 A sensitivity test on the 0.5% AEP + CC results showed that removing this culvert from the model results in a less than 2mm increase in baseline water levels across the floodplain to the west of the A9. Thus, for the purpose of assessing the change in flood risk with the proposed scheme, it can be said that the inclusion of the culvert provides a more conservative approach.

Diagram 14: Photograph of flood extents looking north from Guay Farmhouse in the December 2015 event and the corresponding modelled extents



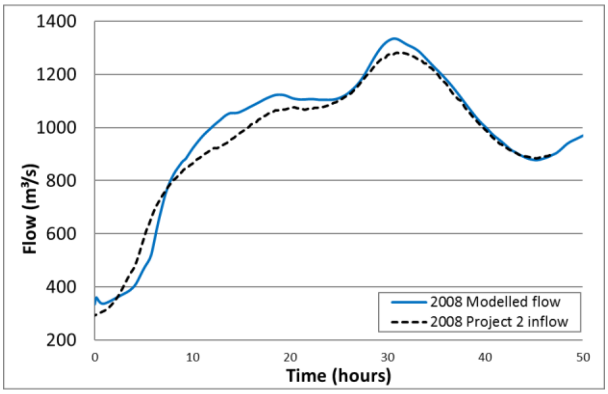
Verification

8.1.24 For the 26 January 2008 and 14 December 2006 events, no water level and wrack mark data was available. Instead a broad verification was undertaken based on anecdotal evidence using information available in the Perth and Kinross Council Biennial Reports for flooding incidences and additional photographic evidence received from local residents.

8.1.25 The comparison between the modelled flow at the downstream boundary and the A9 Project 02 inflow is shown in Diagram 15 for each event.

8.1.26 The photographic evidence demonstrated that there was generally good agreement between the modelled and observed flood extents. Diagram 16 shows historic photographs for the January 2008 event and their approximate location compared to the modelled flood extents. Diagram 17 shows the December 2006 flood extents looking south across the floodplain towards Dalguise. It is uncertain at which stage of the flood event the photographs were taken, however it appears there is a fairly good match between the observed and modelled extents.

Diagram 15: Flow comparison at the downstream model extent for the January 2008 and December 2006 events



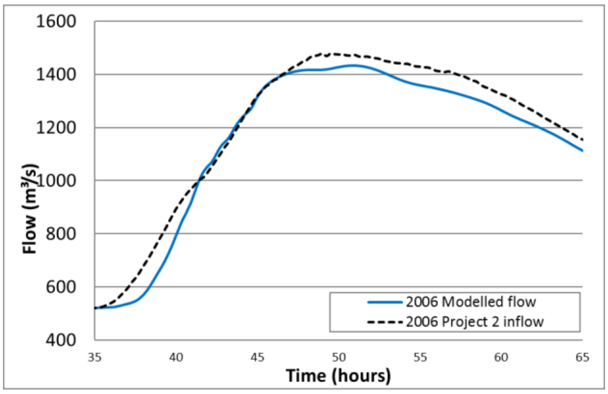
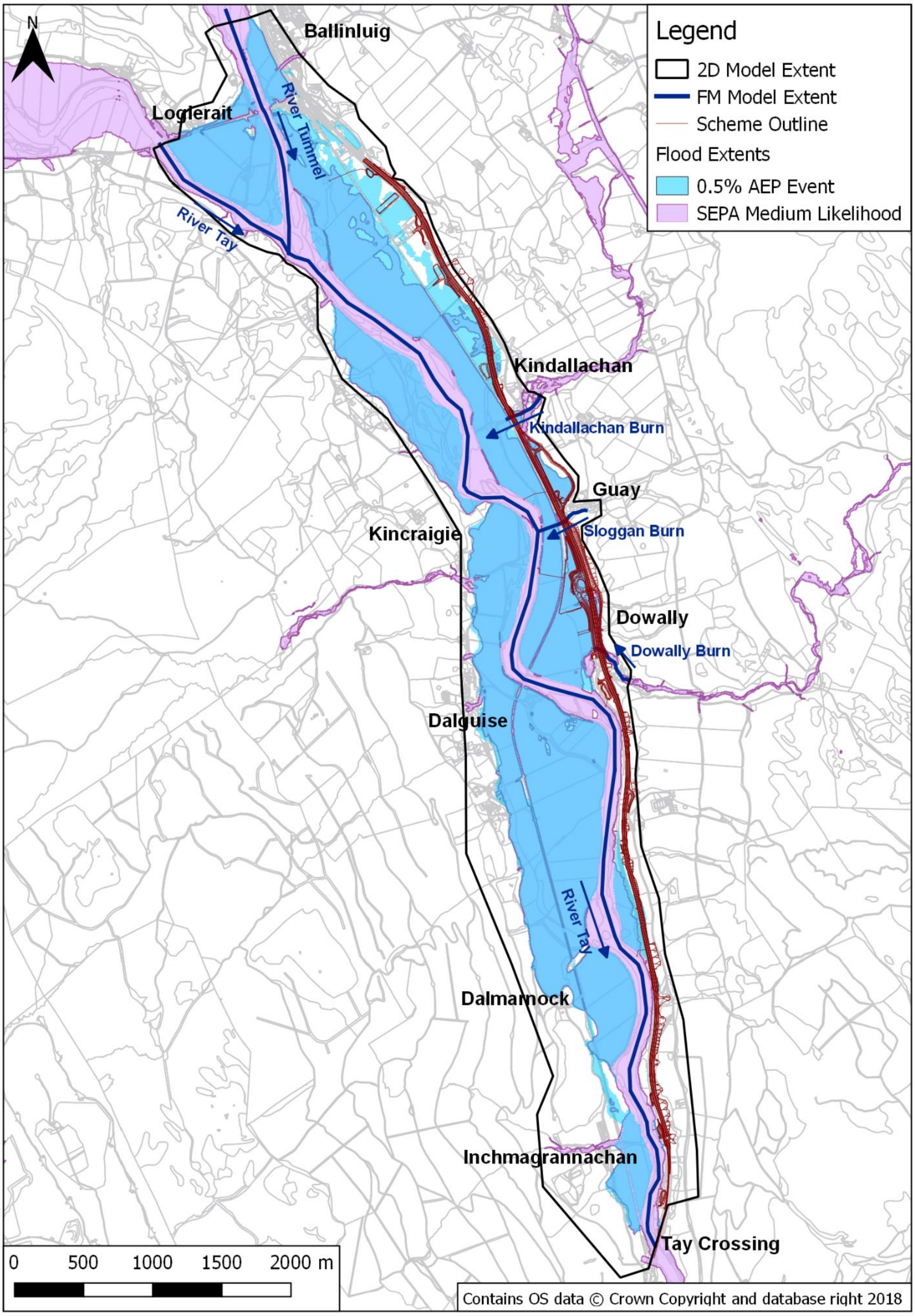


Diagram 16: Comparison of modelled flood extents with historic photos for the January 2008 flood event

Diagram 17: Photograph of the December 2006 flood event, marked up with a sketch of the modelled flood extents for this event

8.1.27 An additional 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 18 shows the comparison between the two flood extents. There is generally good agreement between the two extents however the model results show larger flood extents than the SEPA Flood Maps alongside the existing A9 between Ballinluig and Kindallachan. This difference can be attributed to the better and more detailed representation of the modelled area, particularly the floodplain connectivity beneath the Highland Main Line railway and the inclusion of the minor watercourse inflows.

Diagram 18: Modelled 0.5% AEP (200-year) flood event extent[4] vs. SEPA medium likelihood fluvial extent



[4] The modelled flood extent shown does not include the area covered by the 1D model domain.

Sensitivity Analysis

8.1.28 In order to test the model sensitivity to key hydraulic parameters a series of simulations were undertaken for the 0.5% AEP plus CC event under the baseline scenario. The assessed hydraulic parameters were: Manning's 'n' roughness coefficients, hydrological inflows and downstream boundary slope. A sensitivity test was also undertaken for the assumed culvert connectivity into the fields between the existing A9 and Dowally to Kindallachan Side Road north of Guay.

Roughness Sensitivity

8.1.29 In-channel and floodplain roughness coefficients (Manning's 'n') were changed by +20% and -20%. Table 17 shows the impact of changing the model roughness on the 1D in-channel water levels across the entire baseline model and in key locations which are near the proposed scheme. The results show that the in-channel water levels are highly sensitive to changes in roughness coefficients, however the variability is less than the freeboard requirements for the scheme of 600mm.

8.1.30 Diagram 19 shows the impact on the 2D maximum flood extents. There is little change in the 2D flood extents across large parts of the model however there is some variability in the location of the proposed scheme. The two locations where additional receptors could be affected are shown in the zoomed in areas. The 20% increase in roughness leads to overtopping of the existing A9 north of Guay, as well as increased flood risk to the buildings just south of Kindallachan Burn and at Westhaugh of Tulliemet.

8.1.31 As discussed in Section 4.1.5 and Section 4.1.22, roughness values have been chosen based on site observations, photographs and the calibration process and are considered reasonable.

Table 17: Roughness sensitivity results

Sensitivity	Water Level Difference (m)			Water Level Difference near the Scheme (m)			
	Max	Min	Average	River Tay node nearest the scheme	Kindallachan Burn A9 Culvert Inlet	Sloggan Burn A9 Culvert Inlet	Dowally Burn A9 Culvert Inlet
				TAY00_1991	TUL01_275	SLO01_182	DOW01_429
+20% Roughness	0.412	0.017	0.238	0.217	0.302	0.326	0.035
-20% Roughness	0.000	-0.471	-0.227	-0.202	-0.387	-0.021	0.000

Hydrological Inflow Sensitivity

8.1.32 The flows into the model were adjusted by +20% and -20%, for both the Flood Modeller Pro inflows and the TUFLOW 2D inflows. Table 18 shows the impact of changing model inflows on the 1D in-channel water levels and the 2D maximum flood extents are shown in Diagram 20. The model responses are found to be highly sensitive to changes in flow, and the variability in the flood extents and risk to additional receptors is very similar to that seen for the roughness sensitivity test, as can be seen by comparing Diagram 19 to Diagram 20.

Table 18: Flow sensitivity results

Sensitivity	Water Level Difference (m)			Water Level Difference near the Scheme (m)			
	Max	Min	Average	River Tay node nearest the scheme	Kindallachan Burn A9 Culvert Inlet	Sloggan Burn A9 Culvert Inlet	Dowally Burn A9 Culvert Inlet
				TAY00_1991	TUL01_275	SLO01_182	DOW01_429
+20% Flow	1.084	0.033	0.460	0.894	0.411	0.456	0.567
-20% Flow	-0.050	-1.064	-0.430	-1.034	-0.491	-0.321	-0.163

Downstream Boundary Condition Sensitivity

8.1.33 To test the model sensitivity to the downstream boundary condition, the stage-discharge relationship was modified by adjusting the flow by +5% and -5% for the same stage. Table 19 shows the effect on 1D water levels at the downstream boundary and at key locations near the proposed scheme. Water levels along the River Tay are affected for up to 7km upstream of the downstream boundary.

8.1.34 Diagram 21 shows the impact on the 2D maximum flood extents. The variability in flood extents is seen to be very small.

8.1.35 The results show that the model is slightly sensitive to the downstream boundary condition, however as discussed in Section 4.1.7, the downstream boundary has been extracted from the A9 Project 02 (Pass of Birnam to Tay Crossing) hydraulic model and is controlled by the downstream channel geometry represented within this model. Therefore, there is a high level of confidence in the boundary condition which has been applied.

Table 19: Downstream boundary sensitivity results

Sensitivity	Water Level Difference (m) at the Downstream Boundary	Water Level Difference near the Scheme (m)			
		River Tay node nearest the scheme	Kindallachan Burn A9 Culvert Inlet	Sloggan Burn A9 Culvert Inlet	Dowally Burn A9 Culvert Inlet
	TAY00_0000	TAY00_1991	TUL01_275	SLO01_182	DOW01_429
+5% Flow in Downstream Boundary Rating Curve	-0.228	-0.131	0.006	0	0
-5% Flow in Downstream Boundary Rating Curve	0.232	0.143	-0.005	0	0

Guay Field Culvert Sensitivity

8.1.36 As discussed in Section 8.1.15 the culvert with model ID 'UnsurPotato' connecting the River Tay floodplain to the fields between the existing A9 and Dowally to Kindallachan Side Road north of Guay is an assumed culvert which has been added to match observed flood extents but has not been observed on site.

8.1.37 In order to test the impact of this assumption on the model results, the baseline model has been run for the 0.5% AEP + CC event with this culvert removed. The results showed that whilst this makes a big difference to the flood extents in these fields and around Guay Farmhouse (see Diagram 22), there is a less than 2mm increase in water levels across the entire floodplain west of the existing A9. Including the culvert within the baseline model is a conservative approach for assessing flood risk impact from the proposed scheme as it returns slightly lower levels across the floodplain (west of the A9) for flood risk comparison.

Diagram 19: Roughness sensitivity 2D flood extents

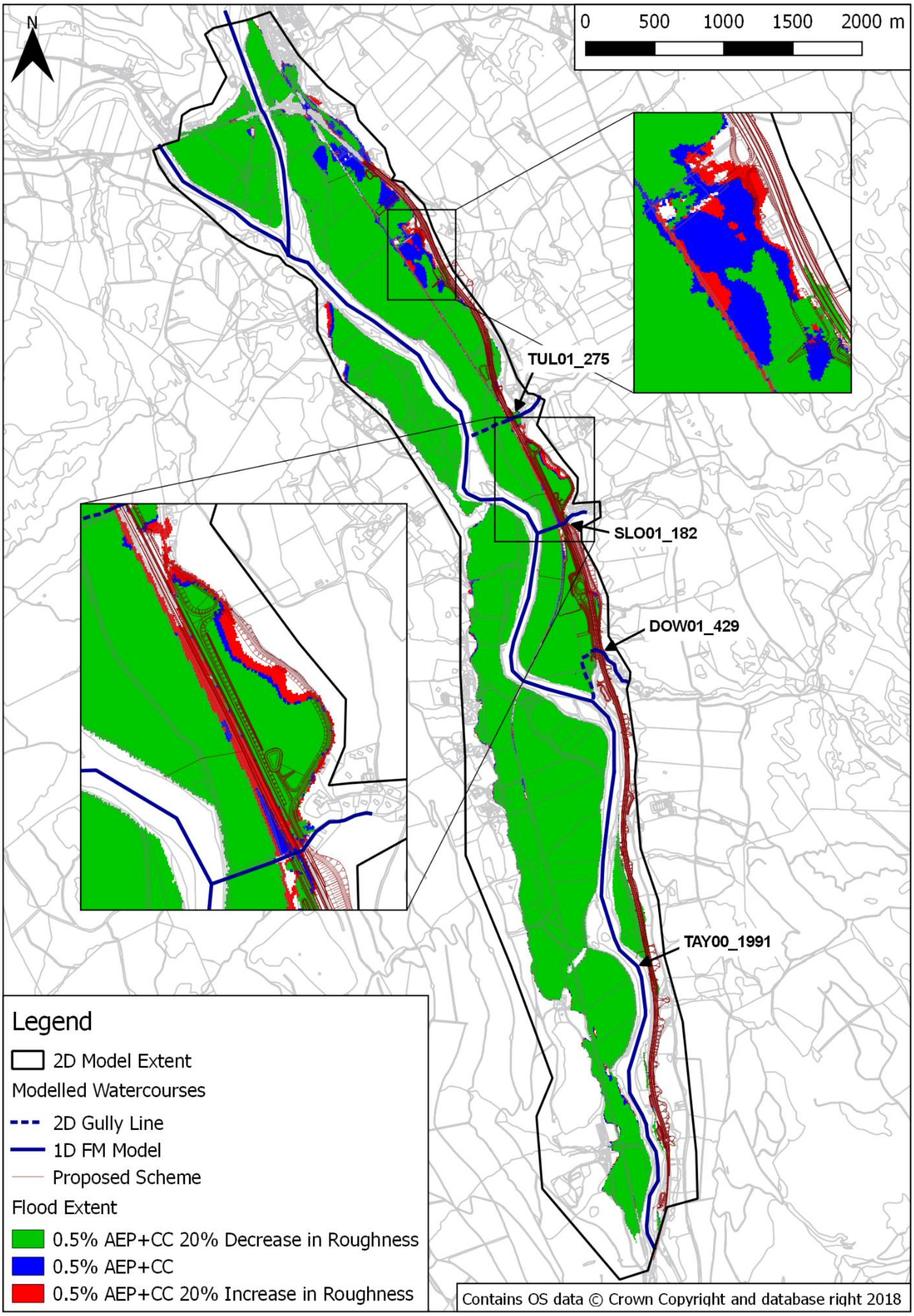


Diagram 20: Flow sensitivity 2D flood extents

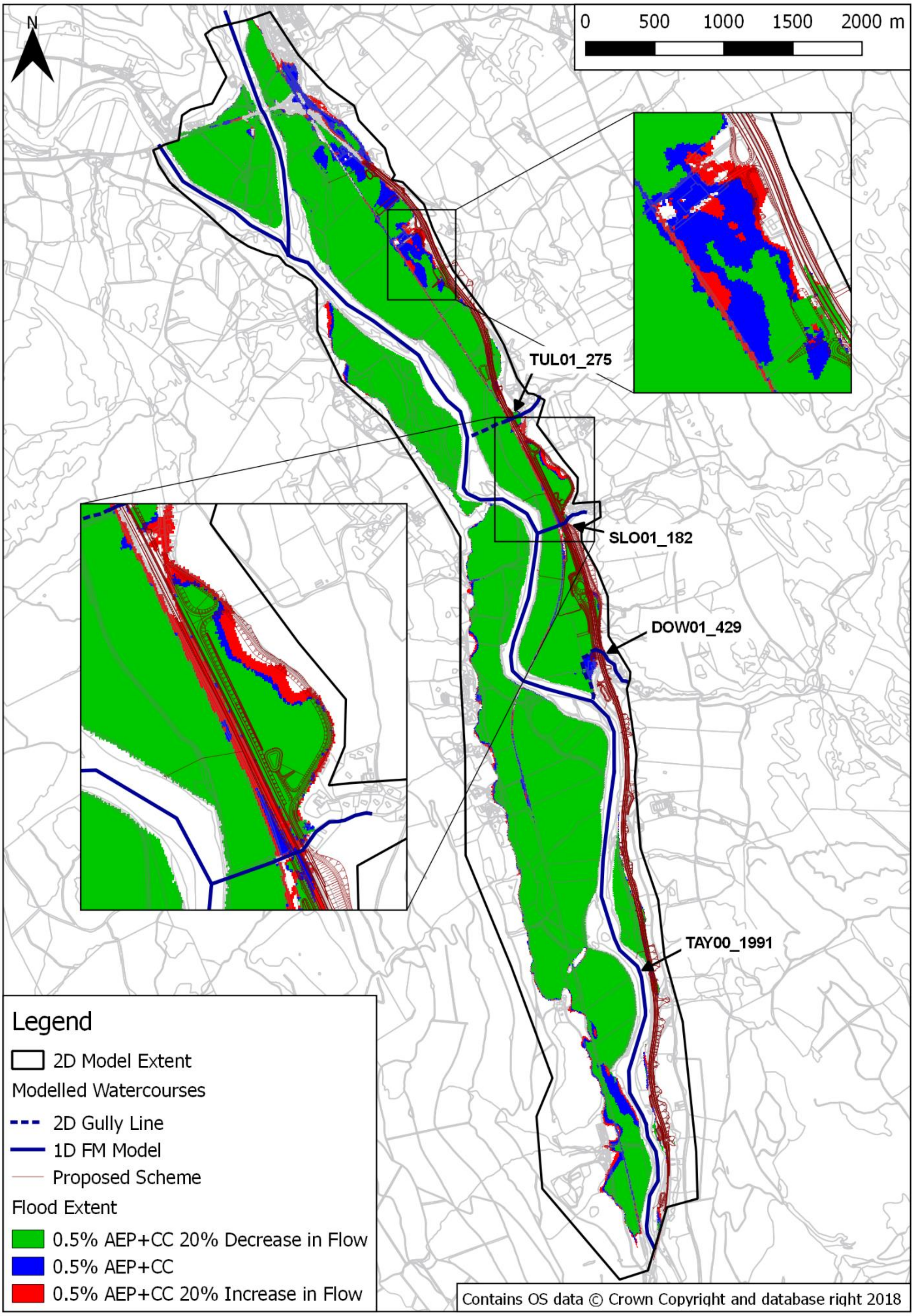


Diagram 21: Downstream boundary sensitivity 2D flood extents

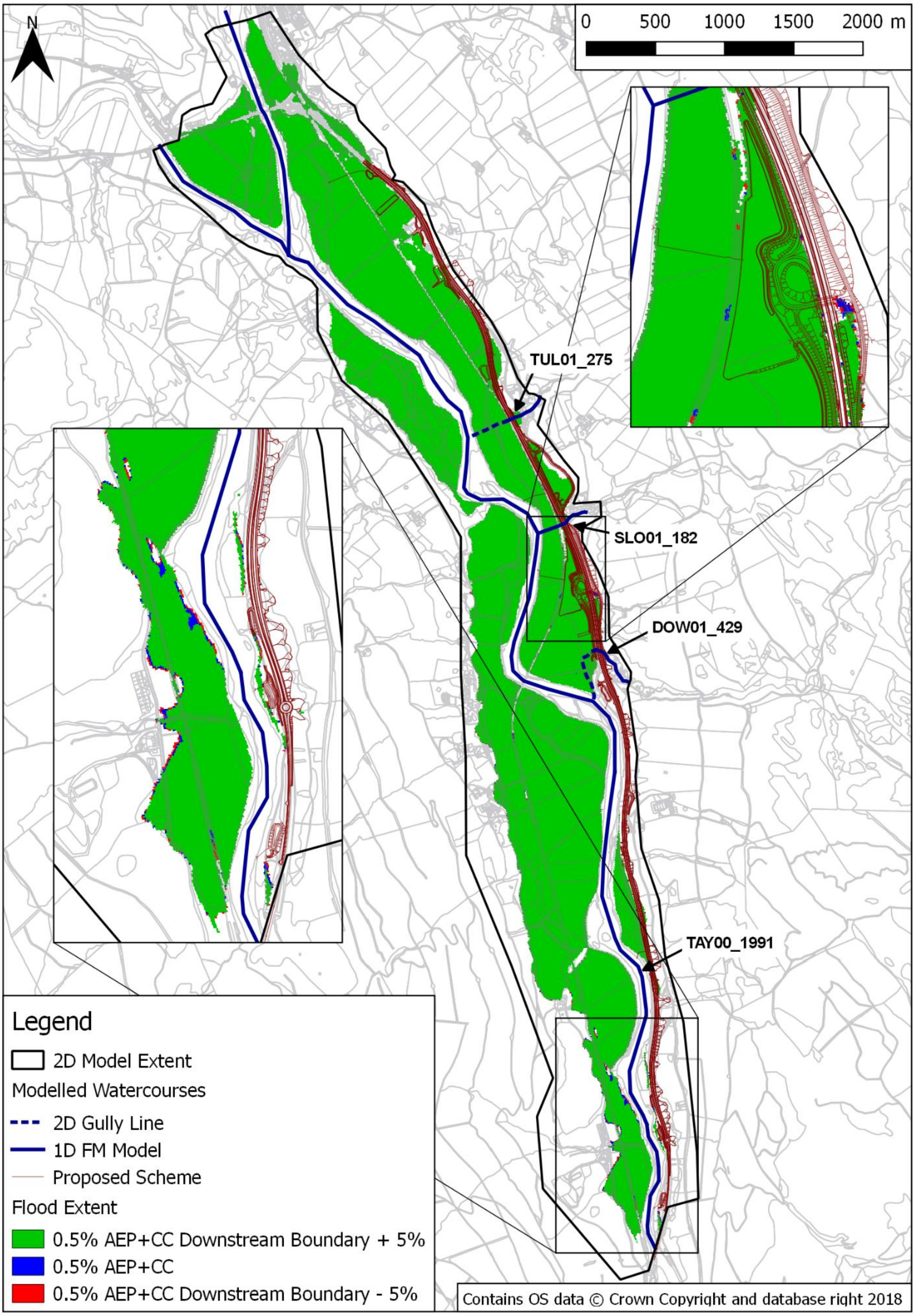
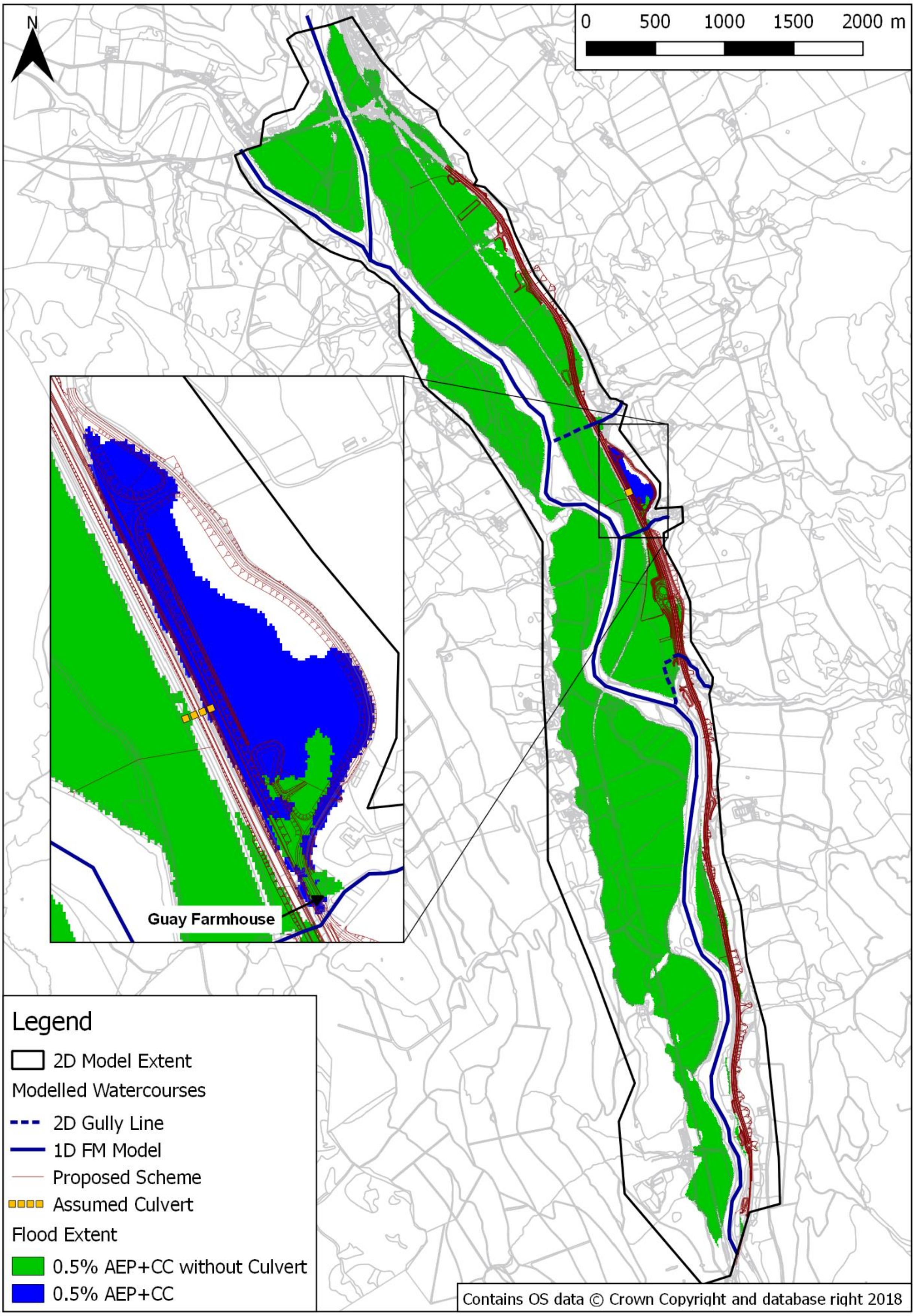


Diagram 22: Guay field culvert sensitivity 2D flood extents



9 Model Assumptions and Limitations

Introduction

9.1.1 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.

9.1.2 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.

9.1.3 The following sections summarise the key sources of uncertainty in addition to the limitations associated with the modelling.

1D Domain

Watercourse Schematisation

9.1.4 The representation of the watercourses diverges from standard 1D representation in a number of locations.

9.1.5 Firstly, the reaches of Kindallachan Burn and Dowally Burn downstream of the existing A9 have been represented within the 2D domain. This is considered to be an appropriate approach as for events larger than or equal to the Run 1 - 3.33% AEP event these reaches are completely submerged by floodplain flows from the River Tay.

9.1.6 Secondly, the minor watercourses crossing the existing A9 have been represented using 2D inflows connected to the 1D culverts by gully lines and with no explicit representation of the channels. This is considered to be appropriate as the key constraint on these watercourses is the culvert and additional detail was not needed. The only exception is WF52, for which a separate detailed model with 1D channel representation was found to be necessary and is discussed in Annex A.

9.1.7 In the proposed scheme scenario, a 1.8m long section of open channel between the main road and downstream side road culverts on Sloggan Burn has not been represented as an open channel, due to its small length in comparison with the 6m grid size in the 2D model. Instead the upstream and downstream culverts have been connected with a junction, and a spill and SX link provide connectivity to the 2D domain.

Channel Roughness

9.1.8 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) and have been adjusted as part of the calibration process. Sensitivity tests have been carried out to quantify the sensitivity to this parameter.

Representation of Structures

9.1.9 Hydraulic coefficients for structures have been applied using available guidance within the Flood Modeller Pro and TUFLOW software. The dimensions for watercourse structures have been based on detailed survey measurements for the baseline scenario and using the detailed structural drawings for the proposed scheme. An embedment depth between 0.15m and 0.3m has been applied at the culverts, in order to have a consistent approach between the baseline and with scheme scenarios.

9.1.10 The long culvert connecting Sloggan Burn to the River Tay has been represented using an orifice unit rather than a conduit unit due to model instability. This was considered to be a suitable representation as the culvert is submerged throughout most of the model run duration and levels are controlled by the water levels in the River Tay.

Downstream Boundary Conditions

9.1.11 The downstream boundary condition uses a stage-discharge rating relationship at Tay Crossing extracted from the A9 Project 02 (Pass of Birnam to Tay Crossing) hydraulic model. The sensitivity analysis discussed in Section 8 has shown that changes to the downstream boundary could have an effect on water levels alongside some sections of the scheme, however the variation is within the 600mm freeboard allowance for the scheme elevations and there is little impact on the flood extent. In addition, there is a high level of confidence in the condition which has been applied as it is controlled by the downstream channel geometry represented within the Project 02 model.

2D Domain

Floodplain Topography

9.1.12 The floodplain topography has been represented using 1m resolution LiDAR data in most areas, this is sufficiently detailed for the DMRB Stage 3 assessment. 5m resolution photogrammetry data has been used for a small area on the edge of the model domain. This area is not of critical importance for the assessment as ground levels rise steeply in this location and are almost entirely out of the flood extents.

9.1.13 Breaklines and elevation polygons have been used as required to better represent topographic features. Elevations for these features have been informed by the LiDAR or survey data.

9.1.14 Bank heights along the 1D/2D link have been defined using a combination of LiDAR and survey data as the top of bank was well represented in the DTM for the River Tay and River Tummel but not very well represented for the smaller watercourses. In two locations along the banks of the River Tay the side of the embankment has been slightly modified to create a gentler slope, as the sudden drop from the top of bank to the floodplain was causing local model instabilities in the floodplain. Careful review of the model results confirmed this modification does not have a significant effect on model results elsewhere.

Floodplain Hydraulic Friction

9.1.15 Hydraulic roughness coefficients across the 2D domain have been defined based on OS Mastermap land use data and standard guidance and have been adjusted as part of the calibration process. In a few locations along the river banks the roughness has been increased to improve the model stability, however sensitivity tests indicated that this does not have a significant impact on the model results.

Floodplain Structures

9.1.16 Floodplain structures have only been included where they were considered to have an impact on flood mechanisms. Levels and dimensions have come from survey data as much as possible, however some assumptions have had to be made based on LiDAR and site visit information.

9.1.17 In particular, the culvert providing connectivity between the Tay floodplain and the fields between the existing A9 and Dowally to Kindallachan Side Road north of Guay has been assumed based on historic flood data, as discussed in Section 8. The nature of any connectivity here is unknown but the model has been constructed based on the conservative assumption that the connectivity is present in the baseline scenario and will be removed when the scheme is put in place. The proposed mitigation reintroduces this connectivity to allow flow into the compensatory storage areas. Sensitivity tests have shown that the impact of this assumption across the rest of the model is minor.

9.1.18 In some locations 1D culvert representations were unstable and 2D fc-shapes have had to be used in their place. Parameters for these shapes have been chosen to match as closely as possible to the surveyed culvert data.

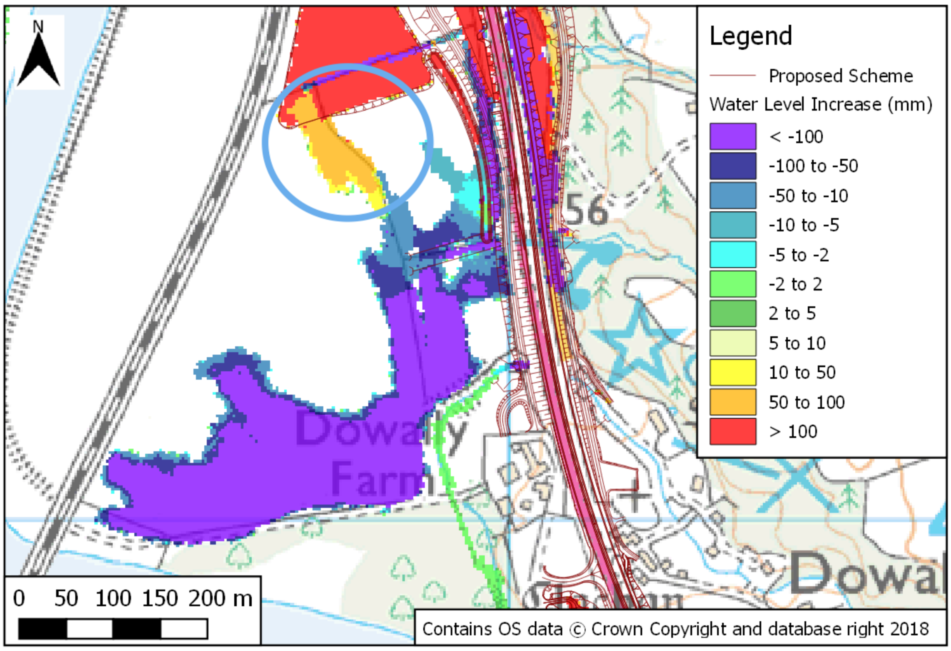
Grid Size

9.1.19 A 6m grid resolution has been used in the 2D domain, which samples the 1m LiDAR DTM data every 3m. This lowers the resolution of the representation of the ground model, but is suitable to represent most of the floodplain features across the model extents to an appropriate level of detail to support the Flood Risk Assessment of the Stage 3 of the DMRB process. Finer features have been incorporated into the grid using breaklines where this was considered to be appropriate.

9.1.20 For the smaller events, particularly the Run 2 events, many of the small drains which are not well-represented by the 6m grid become increasingly important. In locations where it was considered to be important for the flood mechanism these have been represented as gully lines within the 6m grid to ensure hydraulic connectivity, elsewhere the representation has been left entirely to the DTM.

9.1.21 One area where this is considered to be an issue is in the fields between the Highland Main Line railway and the existing A9 north of Dowally, shown in Diagram 23. The drain marked in black is not defined using a gully line and the connection into Dowally Burn at the downstream end is not represented. This was considered to be an acceptable approach for the large Run 1 events, however in the Run 2 events and the Run 1 50% AEP event it causes an over-estimation of the flood extents and water level increases of up to 60mm were observed in the circled area due to the proposed scheme and mitigation options. Calculations of the capacity of this drain suggest that the increased flow in the proposed scheme and mitigation scenario should be contained within the channel, further details are provided in Appendix A11.3 (Flood Risk Assessment).

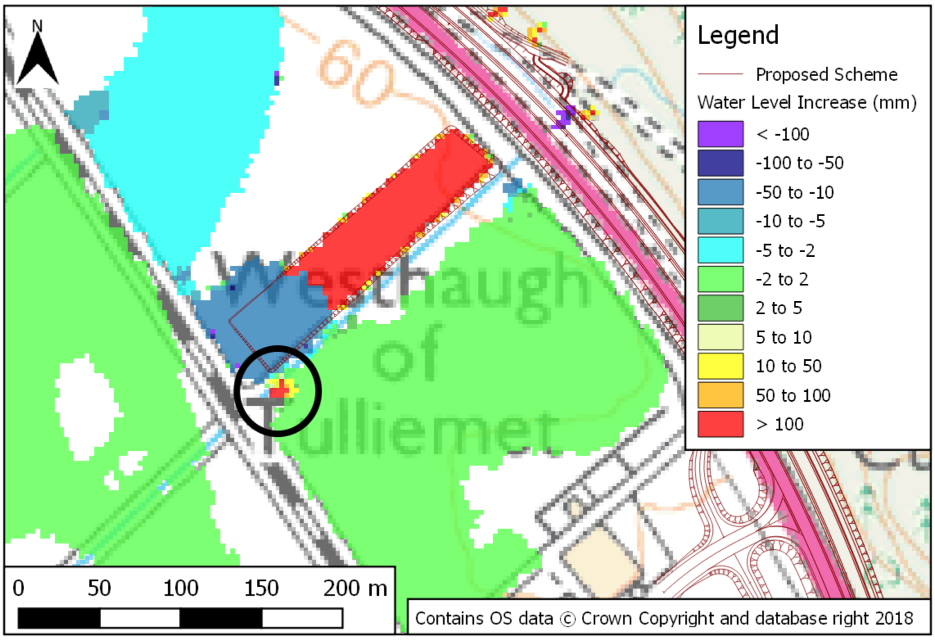
Diagram 23: Water level increases near Dowally in the With Mitigation scenario, Run 2 0.5% AEP + CC event



9.1.22 Around WF52 a more detailed, 2m cell size model has been constructed to resolve the uncertainties present within the main model which had 6m cell size, as discussed in Annex A. This model has been used for the Run 2 events only as in the large Run 1 events the flood mechanism in this area is dominated by floodplain flows coming from the River Tay.

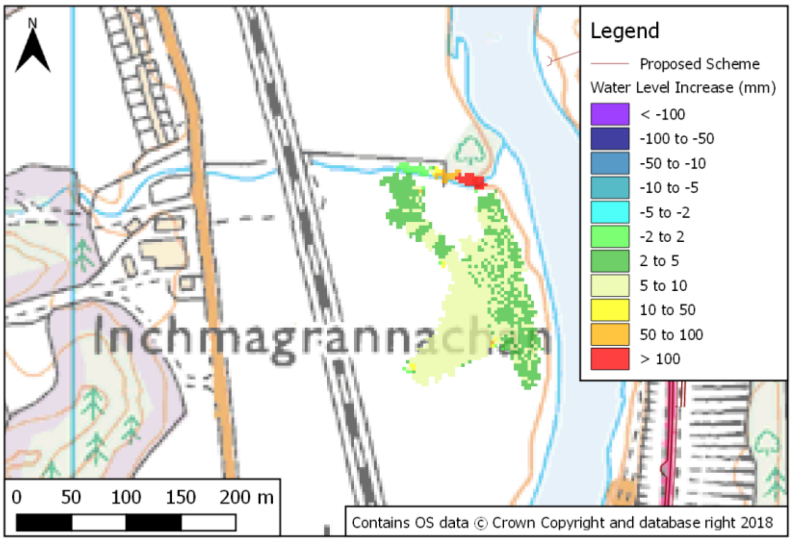
9.1.23 In the Run 1 - 2% AEP event for the main model a small area on the left bank of the WF52 channel, upstream of the Highland Main Line railway, is identified as potentially having up to 400mm increase in water level due to the proposed scheme and mitigation option, as circled in Diagram 24. The results of the detailed model indicate that this increase is related to the lack of detail within the main model and should not be considered an impact of the scheme.

Diagram 24: Erroneous water level increase from WF52 in the With Mitigation scenario, 2% AEP event



9.1.24 Similarly the small tributary which passes through Inchmagrannachan (shown in Diagram 25) is not explicitly represented within the model, and no connectivity is included between the bed of this channel and the River Tay. In the Run 2 events this leads to water ponding next to the 1D/2D link and water level increases of up to 200mm. This is considered to be the result of the schematisation and not a legitimate impact of the scheme. It was not considered necessary to refine the schematisation in this area as there was no risk to any receptors.

Diagram 25: Erroneous water level increase near Inchmagrannachan in the With Mitigation scenario, Run 2 0.5% AEP + CC event



Model Calibration

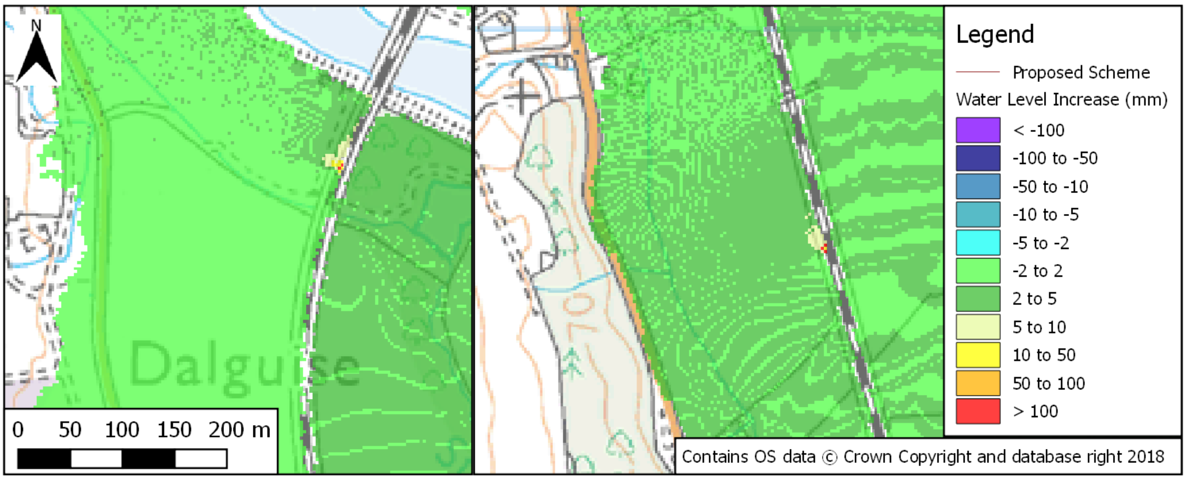
9.1.25 No gauged water levels were available within the model extent therefore the model calibration was carried out based on the limited information available, as discussed in Section 8. This consisted of wrack mark observations and historic photos, both of which were limited in coverage. Uncertainties in the wrack mark observations include whether observed marks could have potentially been displaced, and the reliance on depths above DTM levels rather than surveyed levels. The historic photographs have uncertainties around the timing of the photographs and whether the flood extents captured correspond to peak water levels.

Model Tolerance

9.1.26 For the above uncertainties and limitations, the comparison between the baseline and proposed scheme scenarios can be considered to be a like for like comparison. However, there is still a degree of uncertainty due to the inherent assumptions inside the Flood Modeller and TUFLOW software's solution schemes, such as the diffusion terms and other coefficients applied in the models. In particular, it is worth noting the water level convergence tolerance used within Flood Modeller Pro is 10 millimetres. As the scale of change that is being used as a measure of flood risk impact is in the order of millimetres, any interpretation at this order should be treated with caution.

9.1.27 There are a couple of areas, shown in Diagram 26, where it was considered that the increases in water levels seen in the proposed scheme scenario are related to the model tolerance rather than being a genuine effect of the scheme. These have been determined by taking into consideration the distance from the scheme, the local topography and flood mechanisms.

Diagram 26: Water level increases alongside the Highland Main Line railway in the Run 1 0.5% (left) and 3.33% (right) AEP events



10 Conclusion

10.1.1 In order to support the development of a Flood Risk Assessment for the Environment Statement of Stage 3 of the DMRB process, a hydraulic model was constructed to establish a baseline scenario for the flood risk along the River Tay between Ballinluig and Tay Crossing. A 9.9km long reach of the River Tay and 1.7km of the River Tummel were represented along with the three key tributaries, namely Kindallachan Burn, Sloggan Burn and Dowally Burn, and a number of minor watercourses which cross the proposed scheme.

10.1.2 A range of flood events from 50% to 0.5% AEP plus CC events were simulated using the model.

10.1.3 The baseline model was then adapted to represent the proposed scheme scenario in order to assess the impact of the proposed scheme on the flood risk. Where increases to flood risk were identified, mitigation measures were developed and incorporated into the proposed scheme and tested with hydraulic model simulations.

10.1.4 The assumptions and limitations associated with the hydraulic modelling are discussed in Section 9 of this report, which should be considered for any future use of the hydraulic model.

10.1.5 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.

11 References

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

Annex A: Minor Watercourse WF52 Individual Model

Introduction

As part of the hydraulic modelling undertaken between Ballinluig and Tay Crossing, minor watercourse WF52 was represented within the main model using the simple schematisation outlined in Section 4 of the main report. It was identified as a result of this modelling that the flood risk associated with WF52 was not well-defined using the simple schematisation. In order to provide sufficient detail on the baseline flood risk and the impacts to and from the proposed scheme a more detailed model was constructed for this area.

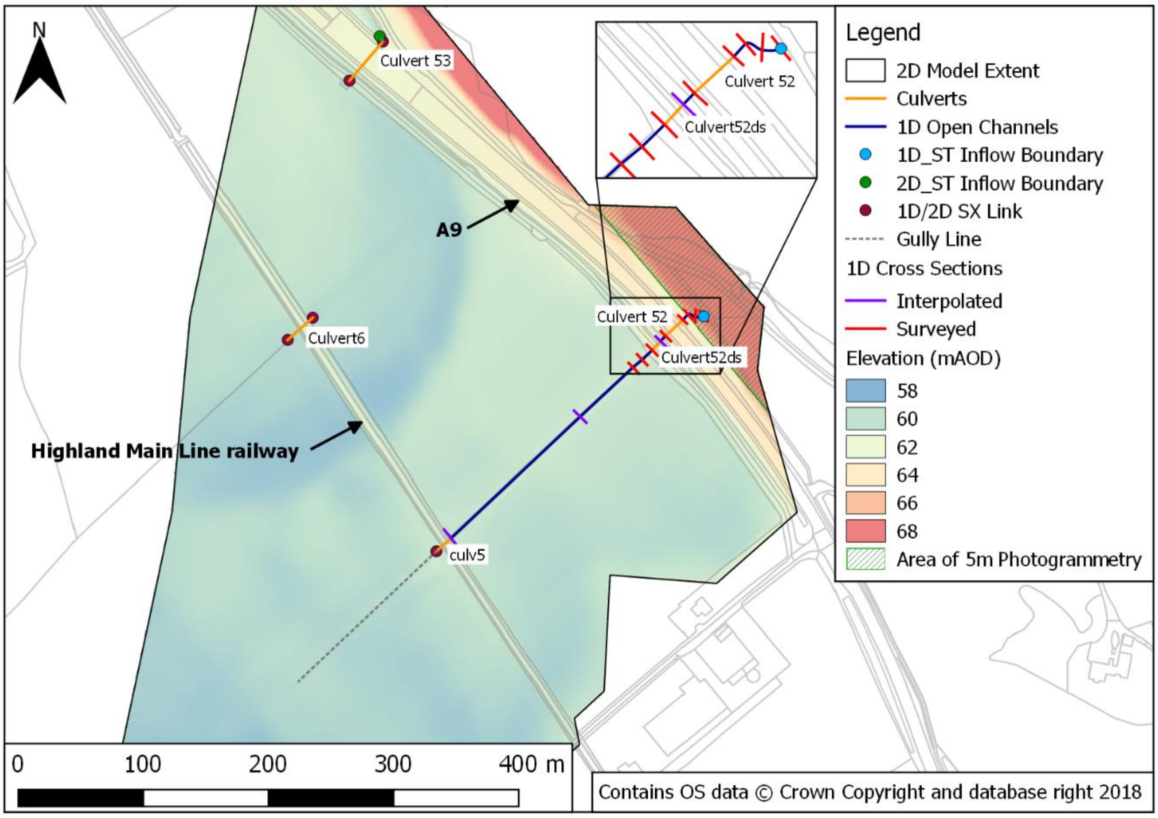
A small TUFLOW model was created using a 2m grid size and incorporating the channel for WF52 as a 1D ESTRY component. This model was constructed for the Run 2 events only, as for the Run 1 events the area is inundated by flooding from the River Tay and cannot be treated as an independent unit. This model will be referred to as the detailed model.

Baseline Modelling

Watercourse Schematisation

The 1D channel for WF52 has been defined in ESTRY from 21m upstream of the existing A9 culvert down to the culvert under the Highland Main Line railway, as shown in Diagram 27. The upstream section of this channel is based on surveyed cross section data, however no cross section data was available for the downstream section. Instead, cross sections have been interpolated between the final surveyed cross section and the surveyed level at the inlet to the railway culvert, assuming the same cross section shape throughout. An additional cross section was also added upstream of the track crossing (Culvert52ds) using the surveyed invert level at the culvert inlet and the shape of the upstream cross section.

Diagram 27: WF52 Baseline Schematisation



Downstream of the Highland Main Line railway no survey data was available. The channel continues for approximately 200m downstream of the railway (as seen in the LiDAR data) but is believed to discharge across the fields or into groundwater from this point, with no connectivity to the River Tay. Within the model this section of the channel has been represented in 2D with a gully line used to enforce the lowest levels from the LiDAR data on the model grid.

WF53 has also been included within the detailed model due to the interaction between the floodplains of the two watercourses. The watercourse and culvert have been represented exactly as in the main model, as this provided a sufficient level of detail in this location.

Hydraulic Roughness

An in-channel Manning's n roughness value of 0.05 has been used upstream of the track culvert (Culvert52ds), and a value of 0.04 has been used downstream of the track culvert. This is based on site photographs taken during the survey of the watercourse.

Hydraulic Structures

Table 20 lists the hydraulic structures included within the model. Levels and dimensions have been obtained from survey for all the structures.

Table 20: WF52 model hydraulic structures

Watercourse	Model ID	Structure	Baseline Model Schematisation
WF52	Culvert 52	Existing A9 culvert	0.59m diameter circular culvert
	Culvert52ds	Downstream track culvert	0.59m diameter circular culvert
	culv5	Highland Main Line railway culvert	0.30m diameter circular culvert*
WF53	Culvert 53	Existing A9 culvert	1.02m diameter circular culvert (1.15m diameter with 0.3m embedment)
Floodplain	Culvert6	Highland Mainline railway culvert	0.3m diameter circular culvert*

*The culvert is actually an irregular shape which has been represented within the model as circular with an equivalent diameter to provide the same cross sectional area.

Floodplain Schematisation

The 2D domain covers an area of 0.3km². The topography is represented using a 2m resolution square grid. As in the main model, the levels for the grid cells are based on a 1m resolution Digital Terrain Model (DTM) derived from LiDAR data, with the exception of an 8,000m² area in the north east, where the model was extended using the 5m resolution photogrammetry DTM, shown in Diagram 27. This area is high ground and is only just reached by the flood extents so has little impact on the results.

Z-shapes have been used to define the bank levels along the 1D channels. Where surveyed cross sections were available, the bank levels have been defined from survey, as this was an improvement over the accuracy of using LiDAR data alone. These were then extended downstream to the Highland Main Line railway culvert using LiDAR data. Along the section of open channel between the existing A9 and the downstream track, the surveyed cross section contained the top of the head wall structure rather than the top of bank. Using these levels would have overestimated the height of the banks, therefore in this location the bank levels were assumed as being 1m above the bed level which is the typical depth of the watercourse.

A gully line z-shape has been used to ensure that the lowest levels from the LiDAR are picked up by the model grid for a small section of channel downstream of the Highland Main Line railway.

Hydraulic roughness coefficients have been applied across each cell of the 2D domain depending on land use taken from OS Mastermap data. Roughness values adopted were taken from standard guidance (Chow, 1959).

Boundary Conditions

Two inflow boundaries have been applied to the model, using the hydrology inflows provided in Section 3 of the main report. The WF52 inflow has been applied using an ST boundary at the upstream end of the 1D channel, this is the combined inflow from three tributaries which feed into the existing A9 culvert. The WF53 inflow has been applied in exactly the same way as within the main model, using an ST boundary within the 2D domain linked to the upstream end of the culvert by a gully line.

No downstream boundary has been applied as the water ponds within the 2D domain and does not reach the edge of the model extent.

1D/2D Linking

The 1D channel has been linked along its length to the 2D domain at the bank crest level using HX connections. SX links have been used to connect the 1D channel to the 2D domain downstream of the Highland Main Line railway culvert on WF52, as well as the upstream and downstream ends of the WF53 A9 culvert and the floodplain culvert (Culvert 6).

Model Performance

The baseline model has been run for the 3.33% AEP, 0.5%AEP and 0.5% AEP + CC events for Run 2.

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

The results showed considerable flooding across the fields between the existing A9 and the Highland Main Line railway due to the limited capacity of the culvert beneath the railway. Further details are provided in Appendix A11.3 (Flood Risk Assessment).

Proposed Scheme Modelling

The proposed scheme has been incorporated into the WF52 model in the same way as for the main model, see Section 5 of the main report, and as shown in Diagram 28 thereafter. Proposed scheme elevations were input from the data exported from the MXROAD model, initial water levels were set to full within the SuDS pond, and land use types within the floodplain were updated based on the proposed scheme footprint.

The culverts under the proposed scheme have been updated as summarised in Table 14 of the main report. In particular, along WF52 the existing A9 culvert has been upsized to 1.003m diameter (equivalent diameter for 1.05m diameter culvert with 0.15m embedment) and extended downstream to replace the existing track culvert. The outlet level has been lowered and the channel has been regraded for approximately 75m downstream of the culvert to match the lowered level. Upstream of the existing A9 culvert a new pipe network connects into the three tributaries feeding into WF52. The combined flow of WF52 has now been applied as three independent 2D ST boundaries, in an identical schematisation to the main model.

The WF53 existing A9 culvert has also been upsized, as in the main model.

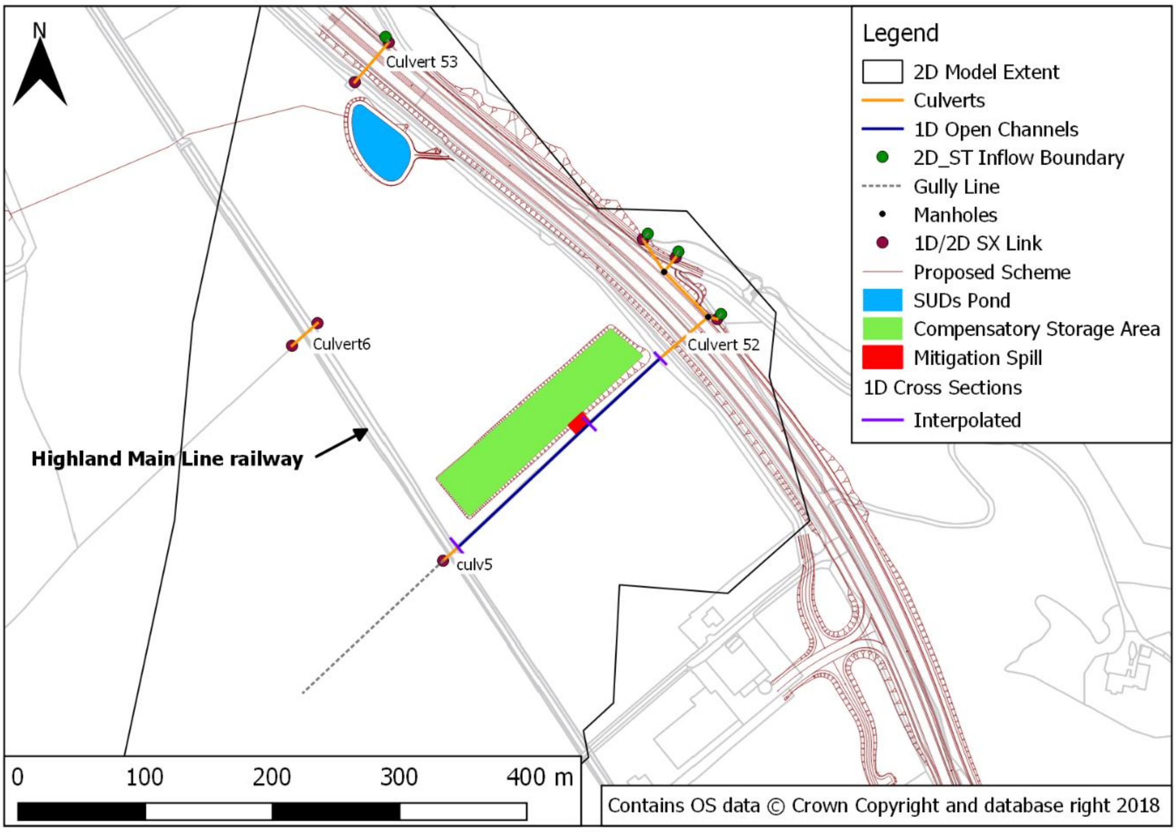
The proposed scheme model has been run for the 3.33% AEP, 0.5% AEP and 0.5% AEP + CC events for Run 2 and an increase in flood risk across the fields between the proposed scheme and the Highland Main Line railway and alongside the railway embankment was demonstrated, as discussed in Appendix A11.3 (Flood Risk Assessment).

With Mitigation Modelling

As discussed in Section 6 of the main report, a number of mitigation options have been tested to resolve the increased flood risk resulting from the increased capacity of the WF52 A9 culvert and the regrading of the channel. These are further summarised in Annex B.

The final mitigation option which has been included within the proposed scheme includes a compensatory storage area along the right bank of the WF52 channel and a spill across the right bank of the channel into this compensatory storage area, the locations are shown in Diagram 28. The compensatory storage area has been included in the model from the MXROAD export and the spill has been implemented using a z-shape to lower the levels along the 1D/2D link.

Diagram 28: WF52 Proposed Scheme and with Mitigation Layout



Conclusion

The detailed model of WF52 was able to provide an improved understanding of the baseline flood risk in the area and the impacts of the proposed scheme. Mitigation measures were then tested and a final mitigation option selected which offset the increased flood risk as a result of the scheme.

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.

Annex B: Log of Mitigation Tests

Table 21 lists all the mitigation measures which were tested using the hydraulic model to determine the final mitigation measures which have been incorporated into the proposed scheme and are discussed in Section 6 of the main report. Further details can also be found in Appendix A11.3 (Flood Risk Assessment) in particular the success or failure of the measures listed below in mitigating the impact of the proposed scheme.

Table 21: List of modelled mitigation measures

Location	Design Fix	Mitigation Measure
Ballinluig to Westhaugh of Tulliemet (excluding WF52, see below)	DF2 – DF6	Compensatory storage areas have been tested in a number of locations across this area: • Within the fields between the proposed scheme and the Highland Main Line railway • Within the fields east of the existing A9 near Ballinluig Junction • One the west bank of the River Tay near Balmacneil
WF52 (Options tested using detailed WF52 model)	DF6	Decreased diameter of culverts under the proposed scheme to reduce flow to the downstream channel and fields
	DF6	Increased diameter of the culvert under the Highland Main Line railway
	DF6	Compensatory storage areas on the left bank of the WF52 channel
	DF6	Compensatory storage area along the right bank of the WF52 channel
	DF7	Right bank storage combined with raised levels along the left bank of the channel
	DF7	Right bank storage combined with a spill from the channel into the storage
Westhaugh of Tulliemet to Kindallachan	DF2 – DF8	Compensatory storage areas have been tested in a number of locations across this area: • Within the fields south of Westhaugh of Tulliemet between the proposed scheme and the Highland Main Line railway • Within the fields downstream of WF50 • Within the fields around Haugh of Kilmorich • Within the triangular space where the proposed scheme and the Highland Main Line railway meet in the south • In the wetland on the east side of the proposed scheme north of Kindallachan Additional culverts were included within some of these runs to provide connectivity between the storage areas and the floodplain.
	DF2 – DF3	Viaduct a section of the proposed scheme between Kindallachan and Haugh of Kilmorich. This was modelled using a z-shape polygon to interpolate across the road, removing the road levels from the model topography for the viaduct section.
	DF2	Flood bund around Haugh of Kilmorich.
	DF6 – DF8	Channel from WF50 to WF45 with spill into compensatory storage area
Kindallachan to Guay	DF5	Compensatory storage areas have been tested in a number of locations across this area: • Within the field between the proposed scheme and Dowally to Kindallachan Side Road north of Guay • On the left bank of Sloggan Burn downstream of the Highland Main Line railway • Along the west bank of the River Tay near Kincraigie
	DF6	Open channel replacement of the existing culvert from Sloggan Burn to the River Tay. This option was tested using bank levels matched to the existing ground levels, as well as with bank levels raised to keep all flow within the banks in the Run 2 0.5% AEP + CC event.
	DF6 – DF8	Additional culvert parallel to the existing culvert from Sloggan Burn to the River Tay
	DF5	Culverts under the main road between Sloggan Burn and the fields between the proposed scheme and Dowally to Kindallachan Side Road north of Guay.
	DF5 – DF8	Flood wall along the right bank of Sloggan Burn.
Guay to Dowally	DF2 – DF8	Compensatory storage areas have been tested in a number of locations across this area: • Between the Highland Main Line railway and the proposed scheme south of Sloggan Burn

Location	Design Fix	Mitigation Measure
		• Along the east of the proposed scheme south of Guay • Within the fields around Dowally Farm • West of the B898 road near Glenalbert (offline storage with spill activated near peak of 0.5% AEP + CC event) • East of the B898 road near Glenalbert (modelled as both online storage and offline with spill activated near peak of 0.5% AEP + CC event) Additional culverts were included within some of these runs to provide connectivity between the storage areas and the floodplain.
	DF2	Walls along the banks of Dowally Burn downstream of the proposed scheme
	DF2	Blocking flow connectivity beneath the Highland Main Line railway through culvert culV8_c1
	DF2	Raised bank levels along the left bank of the River Tay between the Highland Main Line railway and Dowally Burn.
	DF2 – DF3	Viaduct a section of the proposed scheme between Balnabeggan and Dowally This was modelled using a z-shape polygon to interpolate across the road, removing the road levels from the model topography for the viaduct section.
Dowally to Tay Crossing	DF2 – DF6	Compensatory storage areas have been tested in a number of locations across this area: • West of the Highland Main Line railway near Dalguise • Along the west bank of the River Tay north of Dalmarnock • West of the Highland Main Line railway near Dalmarnock • West of the Highland Main Line railway near Inchmagrannachan • Adjacent to the proposed scheme near Ledpetty Lodge
	DF4	Additional culverts beneath the Highland Main Line railway near Dalguise