Annex A13.2.A: Watercourses in the Study Area

Table A1: List of watercourses within Study Area

Ref	Watercourse Name	Crossing Location		Significance Classification
		X	Y	
SWF02	Scretan Burn	269906	846015	Minor
SWF03	Cairnlaw Burn	270452	846148	Principal
SWF06	Kenneth's Black Wall	270865	846829	Principal
SWF07	Drain at Allanfearn	271432	847212	Minor
SWF08	Fiddler's Burn	272815	847672	Minor
SWF09	Tributary of Rough Burn (Newton Burn)	274138	848558	Minor
SWF12	Rough Burn	275258	848699	Principal
SWF13	Unnamed Burn Castle Stuart to Tornagrain	275994	849863	Minor
SWF14	Unnamed Burn Castle Stuart to Unknown	276319	850173	Minor
SWF15		276408	850253	Minor
SWF16	Tributary of Ardersier Burn	276931	850777	Principal
SWF17	Culblair Drain	277744	851617	Minor
SWF18	Indirect Tributary Drains of Ardersier Burn	278936	851771	Minor
SWF19	Balnagowan Burn	282743	853880	Minor
SWF22	Alton Burn	285224	854317	Minor
SWF23	River Nairn	288010	854495	Principal
SWF24	Indirect Tributary of the River Nairn	288983	854525	Minor
SWF26	Auldearn Burn	291360	856217	Principal

Annex A13.2.B: Cairnlaw Burn Hydraulic Model Report

Annex A13.2.C: Rough Burn Hydraulic Model Report

Annex A13.2.D: Tributary of Ardersier Burn Hydraulic Model Report

Annex A13.2.E: River Nairn Hydraulic Model Report

Annex A13.2.F: Auldearn Burn Hydraulic Model Report

JACOBS

Annex A13.2.G: Hydrology Report

Annex A13.2.H: Minor Watercourse Further Assessment

Annex A13.2.I: Surface Water Impact Assessment

Annex A13.2.J: Existing Structures Screening Assessment

A13.2.B Cairnlaw Burn Hydraulic Modelling Report

1 Introduction

Purpose

1.1 This annex provides detailed information on the hydraulic modelling relevant to Appendix 13.2 (Flood Risk Assessment).

1.2 The A96 Dualling Inverness to Nairn (including Nairn Bypass) scheme comprises the provision of approximately 31km of new dual carriageway, achieved through offline construction (hereafter referred to as the proposed Scheme). The existing A96 single carriageway would be de-trunked and reclassified as a local road to maintain local access. Due to the size and layout of the proposed Scheme, there are a number of flood risks, which may place the road and its users at risk of flooding. The proposed Scheme also has the potential to impact the level of flood risk elsewhere.

1.3 The proposed Scheme starts east of the roundabout for Inverness Retail Park, approximately 850m east of Raigmore Interchange, and continues approximately 30km east and ends at Hardmuir, 3.5km to the east of Auldearn. The proposed Scheme would incorporate:

- 22 watercourse crossings;
- provision of shared use paths suitable for Non-Motorised Users (NMU), approximately 30km in length;
- six grade separated junctions;
- 24 principal structures including a crossing of the River Nairn and three structures over the Aberdeen to Inverness Railway Line;
- local road diversions and provision of new private means of access; and
- utility diversions including major diversions for Scottish Gas Networks (SGN) and CLH Pipeline Systems (CLH-PS).

1.4 For key watercourse crossings a Flood Risk Assessment (FRA) was required to meet relevant local and national planning legislation and inform the design and planning process. Hydraulic modelling was required to support the FRA. This took the form of computational hydraulic models with associated catchment hydrology. The impact of the proposed Scheme on water level both upstream and downstream and the associated flood envelope was determined for a range of storm flood events at each watercourse crossing.

1.5 The key watercourse crossings for which a hydraulic modelling was carried out to support the FRA are:

- Cairnlaw Burn crossing (this report);
- Rough Burn crossing (Annex 13.2.C Rough Burn Hydraulic Modelling Report);
- Tributary of Ardersier Burn crossing (Annex D Tributary Of Ardersier Burn Hydraulic Modelling Report);
- River Nairn crossing (Annex 13.2.E River Nairn Hydraulic Modelling Report); and
- Auldearn Burn crossing (Annex 13.2.F Auldearn Burn Hydraulic Modelling Report).

1.6 This report details the methodology and the results of the hydraulic modelling carried out for Cairnlaw Burn and its tributaries, for the baseline, ‘with-scheme’ and ‘with-mitigation’ situations. This is a technical report, focused on the hydraulic modelling, and therefore the intended audience is those with a reasonable understanding and knowledge of hydraulic modelling principles, although no specific knowledge of particular software is needed.

Methodology

1.7 Most of the model was built primarily using a one-dimensional (1D) schematisation, with the river channel and its adjacent flood plain represented as a 1D component. Part of the model was built using a one-dimensional/two-dimensional (1D/2D) schematisation, where the 1D river channel is linked to the flood plain, which is represented by a 2D domain. The 1D component was constructed using the river modelling package Flood Modeller Pro (version 4.1), and the 2D component was constructed using TUFLOW (version 2013-12-AE-iSP-w64).

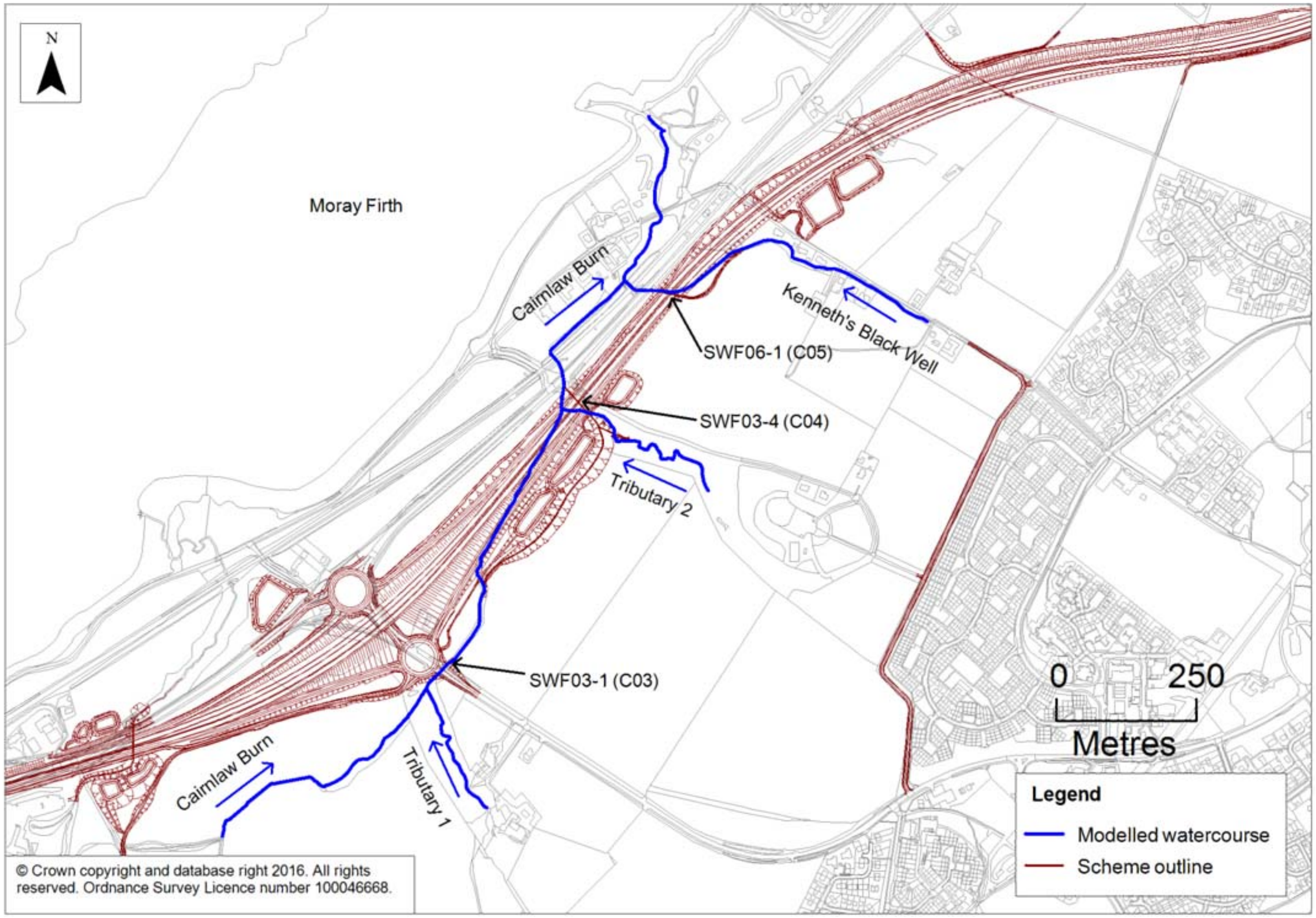
Study Area

1.8 Within the study area, Cairnlaw Burn flows from south-west to north-east, before discharging into the tidal Moray Firth, as show in Diagram 1. Three tributaries join Cairnlaw Burn, which are referred to in this report as Tributary 1, Tributary 2 and Kenneth's Black Well. The model includes approximately 1.7km of Cairnlaw Burn, 240m of Tributary 1, 260m of Tributary 2 and 620m of Kenneth's Black Well. There are two new crossings for the proposed Scheme within the Cairnlaw Burn study area, these have been named:

- SWF03-4 (C04); and
- SWF06-1 (C05).

1.9 There is one proposed Scheme culvert which is an extension of an existing highway culvert (SWF03-1 (C03)).

Diagram 1: Cairnlaw Burn study area



2 Input Data

2.1 The data used to construct the hydraulic model for Cairnlaw Burn is summarised in Table 1.

Table 1: Data Used to Build the Hydraulic Model

Data	Description	Source
Photogrammetry/ LiDAR	2014 composite DTM: Car-based LiDAR data for existing A96 carriageway 10m horizontal resolution photogrammetry data Used to extend cross sections (see Section 4 (Flood Plain Schematisation - 1D domain)) and represent the topography for the area to the north of Kenneth's Black Well (see Section 4 (Flood Plain Schematisation - 2D domain))	Blom Aerofilms
OS maps	Mastermap data 1 to 10,000 Scale Raster	Transport Scotland
Channel survey	In-channel cross sections and hydraulic structures See Section 4 (Watercourse Schematisation - 1D Domain)	Jacobs Site survey 2015 and 2016
A96 proposed Scheme topography	MXROAD ASCII grids	Jacobs 2016
Watercourse photographs	Site visit – in-channel watercourse photographs	Jacobs Site survey 2015 and 2016 Site inspection 2015
Hydrological analysis	Hydrological analysis carried out for Cairnlaw Burn See Section 3 (Hydrology)	Jacobs 2016

3 Hydrology

3.1 The details of the analysis carried out to produce inflows for the hydraulic model are provided in a separate hydrology report (Annex 13.2.G (Surface Water Hydrology Report)) which was undertaken for the DMRB Stage 3 assessment.

3.2 There are five point inflows into the model. One at the upstream extent of Cairnlaw Burn, one at the upstream extent of each tributary and one inflow part way along Cairnlaw Burn (see locations in Diagram 2). For these locations, inflows have been estimated for the 50%, 20%, 10%, 3.33%, 2%, 1%, 0.5% and 0.1% Annual Exceedance Probability (AEP) flood events.

3.3 The peak inflows were produced using the Flood Estimation Handbook (FEH) statistical method. The hydrograph shape was derived from the FEH rainfall-runoff model hydrograph shapes. These hydrographs used a theoretical critical storm duration of 5.4 hours calculated at the downstream modelling extent. The same hydrograph shape and critical storm duration was used for all inflows. During the modelling, a critical storm duration analysis was carried out and confirmed that the storm duration of 5.4 hours was critical at key proposed Scheme locations.

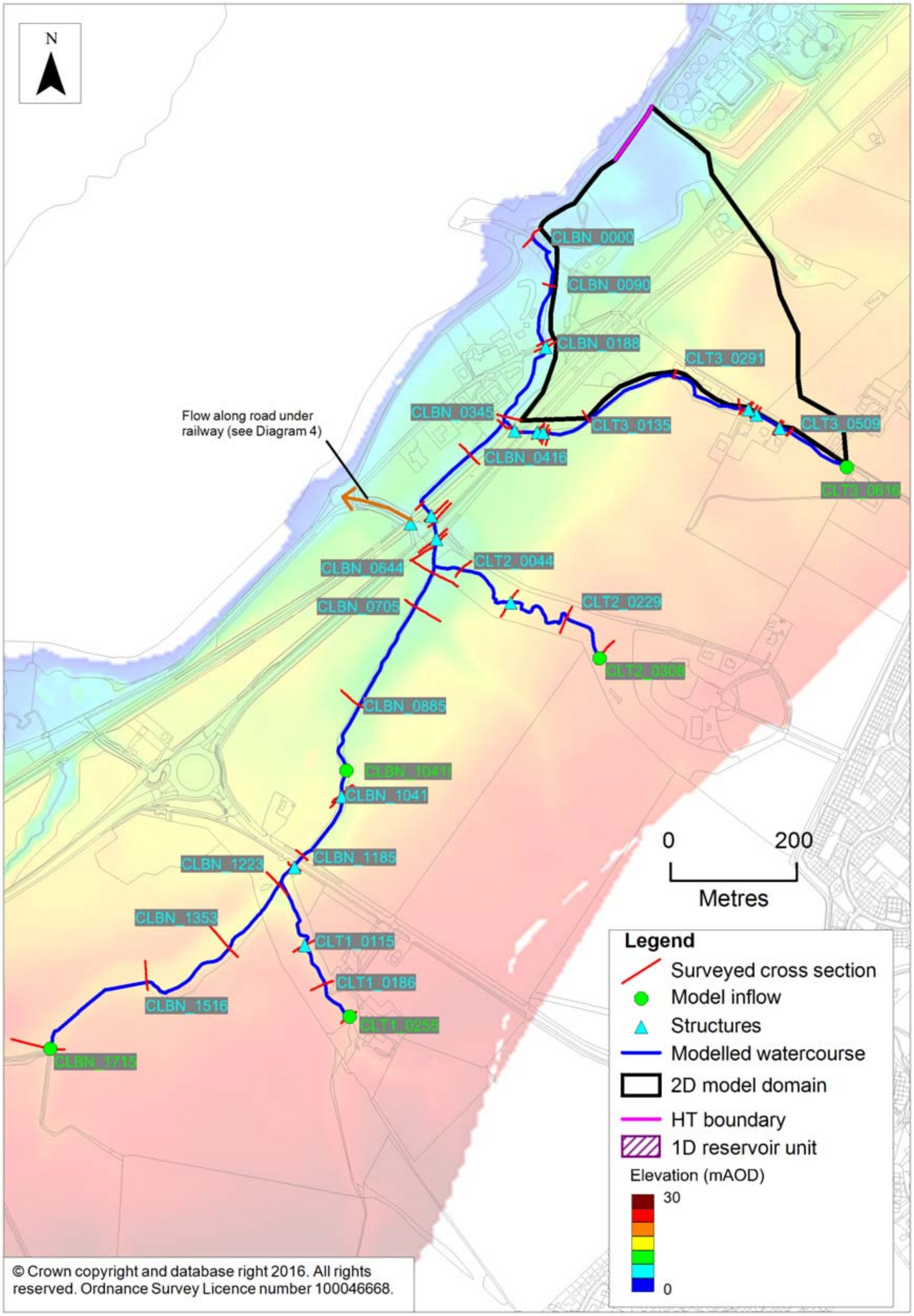
3.4 In order to assess the impact of Climate Change (CC), a 20% uplift of the hydrological inflows was applied on the 0.5% AEP event. This climate change uplift factor is based on current standard practice (SEPA 2015). In addition the tidal downstream boundary was adjusted as described in Section 4 (Watercourse Schematisation - 1D Domain).

3.5 Peak inflows of the modelled watercourses are shown in Table 2 for all the events simulated.

Table 2: Hydrological Inflow Peak Values and Locations

Location	Peak Flow (m^3/s)								
	AEP 50%	AEP 20%	AEP 10%	AEP 3.33%	AEP 2%	AEP 1%	AEP 0.5%	AEP 0.5% + CC	AEP 0.1%
Cairnlaw Burn upstream model extent	0.76	1.07	1.30	1.73	1.96	2.32	2.74	3.30	4.06
Part way along Cairnlaw Burn	0.20	0.28	0.34	0.46	0.52	0.62	0.73	0.88	1.08
Tributary 1 upstream model extent	0.99	1.39	1.69	2.24	2.54	3.01	3.57	4.28	5.27
Tributary 2 upstream model extent	0.08	0.11	0.14	0.18	0.21	0.24	0.29	0.35	0.43
Kenneth's Black Well upstream model extent	1.42	1.99	2.42	3.22	3.65	4.33	5.12	6.15	7.56

Diagram 2: Cairnlaw Burn Baseline Model Schematisation



4 Baseline Modelling

Watercourse Schematisation - 1D Domain

In-Channel Geometry

4.1 Surveyed cross section data has been used to inform the in-channel geometry of the modelled watercourses. The location of the surveyed cross-sections is shown in Diagram 2. To aid model performance on all modelled watercourses, interpolated cross sections were added between the surveyed cross sections. The spacing of the interpolated cross sections ranged from 5m to 50m. Table 3 shows the Flood Modeller nodes associated with the modelled watercourses.

Table 3: Flood Modeller Nodes

Reach	Upstream Node	Downstream Node
Cairnlaw Burn	CLBN_1715	CLBN_0000d
Tributary 1	CLT1_0255	CLT1_0010
Tributary 2	CLT2_0308	CLT2_0044
Kenneth's Black Well	CLT3_0616	CLT3_0000

In-Channel Hydraulic Friction

4.2 Hydraulic roughness (Manning's 'n' coefficient) values were determined primarily using the photographs taken during the survey. Generally, cobbles can be seen in the bed of Cairnlaw Burn with trees on the banks. However, the Cairnlaw Burn channel is vegetated at the upstream model extent. Tributary 1 and Kenneth's Black Well feature cobbles on the bed and heavy vegetation on the banks. The bed and banks of Kenneth's Black Well are vegetated. The Manning's 'n' coefficients used in the model are shown in Table 4. Roughness values adopted were taken from standard guidance (Chow 1959).

Table 4: Manning's 'n' Coefficients – 1D Domain

Flood Modeller Nodes	Watercourse	Bed Manning's 'n'	Bed Material	Banks Manning's 'n'	Banks Material
CLBN_1715 to CLBN_1516	Cairnlaw Burn	0.06	Vegetated channel	0.055	Long grass and bracken
CLBN_1353 to CLBN_0000		0.05	Cobbles	0.055 0.1	Long grass and bracken Heavy vegetation/trees
CLT1_0255 to CLT1_0010	Tributary 1	0.05	Cobbles	0.055 0.1	Long grass and bracken Heavy vegetation/trees
CLT2_0308 to CLT2_0044	Tributary 2	0.1	Heavily vegetated channel	0.1	Heavy vegetation/trees
CLT3_0616 to CLT3_0000	Kenneth's Black Well	0.05 0.032	Cobbles Masonry lined channel	0.055 0.1	Long grass and bracken Heavy vegetation/trees

In-Channel Hydraulic Structures

4.3 Thirteen hydraulic structures were included in the model, as detailed in Table 5. Their locations are shown in Diagram 2.

Table 5: In-Channel Hydraulic Structures

Watercourse	Structure	Flood Modeller Node	Specification	
Cairnlaw Burn	C1032 Barn Church Road crossing	CLBN_1185u	**Type:** **Upstream bed level:** **Downstream bed level:** **Length:** **Width:** **Springing height:** **Crown height:**	Symmetrical conduit (arch) 13.085mAOD 13.000mAOD 22.570m 3.900m 0.750m 1.770m
Cairnlaw Burn	Pipe crossing	CLBN_1045B	**Type:** **bed level:** **Width:** **Height:**	Arch bridge (flat soffit) 11.395mAOD 11.621m 1.586m
Cairnlaw Burn	Twin culverts under existing A96	CLBN_0589	**Type:** **Left upstream bed level:** **Left downstream bed level:** **Right upstream bed level:** **Right downstream bed level:** **Length:** **Width:** **Springing height:** **Crown height:**	2x sprung arch conduits 6.557mAOD 6.329mAOD 6.557mAOD 6.329mAOD 26.410m 1.534m 0.280m 0.767m
Cairnlaw Burn	Aberdeen to Inverness Railway Line crossing	CLBN_0552u	**Type:** **Upstream bed level:** **Downstream bed level:** **Length:** **Width:** **Height:**	Full arch conduit 6.145mAOD 6.255mAOD 23.480m 3.200m 1.325m
Cairnlaw Burn	Milton Road crossing	CLBN_0195	**Type:** **Bed level:** **Width:** **Springing height:** **Crown height:**	Arch bridge 3.350mAOD 4.734m 1.820m 2.215m
Tributary 1	Informal footbridge partially blocked	CLT1_0115	**Type:** **Bed level:** **Width:** **Height:**	Orifice and spill 15.900mAOD 0.320m 0.100m
Tributary 2	Pipe crossing	CLT2_0136B	**Type:** **Bed level:** **Width:** **Height:**	Arch bridge (flat soffit) 10.686mAOD 7.520m 1.157m
Kenneth's Black Well	Drive crossing	CLT3_0491B	**Type:** **Bed level:** **Width:** **Height:**	Arch bridge (flat soffit) 16.151mAOD 1.960m 1.204m
Kenneth's Black Well	Drive crossing	CLT3_0449B	**Type:** **Bed level:** **Width:** **Height:**	Arch bridge (flat soffit) 15.880mAOD 1.342m 1.119m
Kenneth's Black Well	Twin culvert drive crossing	CLT3_0434	**Type:** **Left upstream bed level:** **Left downstream bed level:** **Right upstream bed level:** **Right downstream bed level:** **Length:** **Diameter:**	2x circular conduits 15.799mAOD 15.653mAOD 15.756mAOD 15.701mAOD 5.000m 1.010m

Watercourse	Structure	Flood Modeller Node	Specification	
Kenneth's Black Well	Weir immediately upstream of the existing A96	CLT3_0054spU	**Type:** **Upstream bed level:** **Downstream bed level:** **Width:**	Spill unit 10.368mAOD 6.734mAOD 4.1m
Kenneth's Black Well	Existing A96 crossing	CLT3_0048u	**Type:** **Upstream bed level:** **Downstream bed level:** **Length:** **Width:** **Height:**	Rectangular conduit 6.734mAOD 6.088mAOD 34.320m 3.080m 1.430m
Kenneth's Black Well	Aberdeen to Inverness Railway Line crossing	CLT3_0009	**Type:** **Bed level:** **Width:** **Springing height:** **Crown height:**	Arch bridge 6.029mAOD 2.185m 3.309m 0.912m

Boundary Conditions – 1D Domain

4.4 The upstream and downstream boundary conditions applied to the 1D domain are described in Table 6. Inflow locations are shown in Diagram 2.

4.5 Cairnlaw Burn discharges into Moray Firth, which is tidal. Therefore a tidal downstream boundary was required. Extreme tide levels were calculated for the downstream end of the model. Test runs were carried out to assess how the extreme tide levels would impact on water levels at the proposed Scheme. In addition, tests were carried out to assess the flooding caused by a joint fluvial and coastal event. The results of both these tests showed that the proposed Scheme would not be impacted by extreme high tides. Therefore, a mean high water spring curve was used for the downstream boundary and coastal only flooding, or joint fluvial coastal flooding has not been modelled.

4.6 The downstream boundary was created using Admiralty Tide Tables for Inverness (United Kingdom Hydrographic Office 2006), the closest secondary port. A typical mean spring tide curve was extracted for this port. For the climate change scenario, as well as increasing the inflows (see Section 3 (Hydrology)), an uplift in water level was applied to the downstream boundary to account for sea level rise. The increase in sea level was calculated by Jacobs Hydrology using the UK Climate Projections website (UK Climate Projections 2009). The uplift value was calculated for 2055 for the medium emission scenario. This gives an increase in sea level of 0.151m. The mean spring tide curve was increased by this amount.

Table 6: Boundary Conditions – 1D Domain

Type of Boundary	Flood Modeller Node	Description
FEH Boundary	CLBN_1715	Scaled FEH boundary. Applied at the upstream end of the Cairnlaw Burn.
FEH Boundary	CLBN_1041In	Scaled FEH boundary. Applied part way along Cairnlaw Burn.
FEH Boundary	CLT1_0255	Scaled FEH boundary. Applied at the upstream end of the Tributary 1.
FEH Boundary	CLT2_0308	Scaled FEH boundary. Applied at the upstream end of the Tributary 2.
FEH Boundary	CLT3_0616	Scaled FEH boundary. Applied at the upstream end of the Kenneth's Black Well.
Head-Time downstream boundary	CLBN_0000d	Spring tide curve for Inverness. Applied at the downstream extent of Cairnlaw Burn.
Head-Time downstream boundary	ROAD_0000d	Spring tide curve for Inverness. For flow path along road under the existing A96 (see Section 4 (Flood Plain Schematisation - 1D domain)).

Flood Plain Schematisation - 1D domain

4.7 Most of the flood plain in the Cairnlaw Burn model is represented in 1D with the surveyed cross sections. At some locations it was necessary to extend the cross sections using the 2014 photogrammetry data. Hydraulic roughness values were assigned for long grass (0.055) and trees (0.1) on the flood plain.

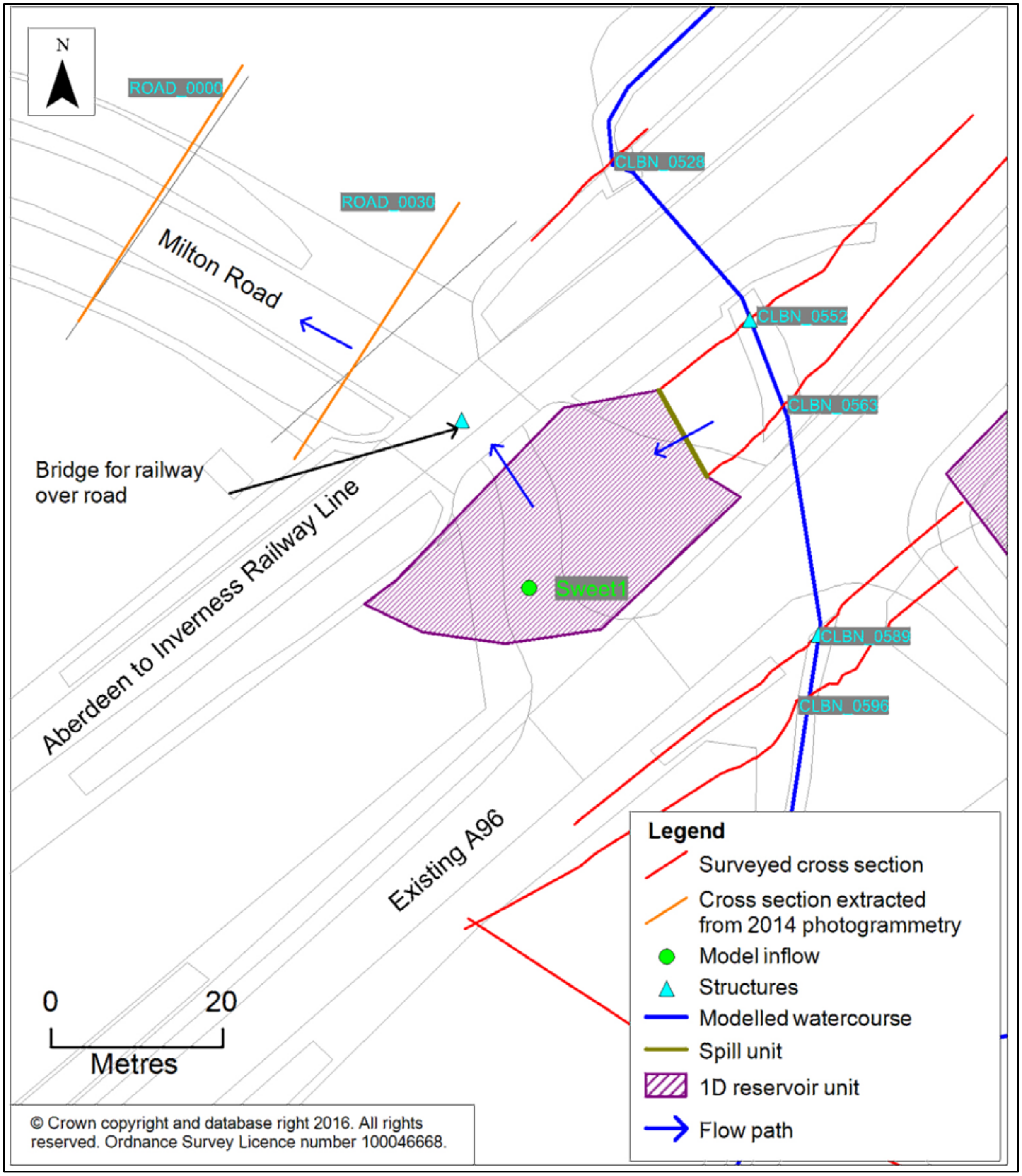
4.8 In three areas it was seen that water would pond in the flood plain. In each of these areas a reservoir unit was added in the 1D model. The geometry for these reservoirs was extracted from the 2014 photogrammetry data. The locations of these reservoir units are (as shown in Diagram 2):

- right bank of Cairnlaw Burn, upstream of the existing A96 twin culvert;
- left bank of Cairnlaw Burn, downstream of the existing A96 twin culvert and upstream of the Aberdeen to Inverness Railway Line crossing; and
- left bank of Kenneth's Black Well;

4.9 The reservoirs are connected to the channel by lateral spills along the banktop. The spill geometry was extracted from the channel survey data.

4.10 It was seen that the reservoir unit on the left bank of Cairnlaw Burn would overtop, with water able to flow along Milton Road, a local road under the Aberdeen to Inverness Railway Line. This was schematised as shown in Diagram 3. An orifice unit was added to represent the bridge for the Aberdeen to Inverness Railway Line crossing. Dimensions for this structure were estimated from Google Street View. Two cross sections, extracted from the 2014 photogrammetry data, were added downstream of the orifice. The topography shows that the overtopping water would flow into Moray Firth; therefore a tidal downstream boundary was applied at the end of this section. The same mean spring tide curve, used for the main model downstream boundary, was applied (see Section 4 (Watercourse Schematisation - 1D Domain)). A nominal (sweetening) flow was applied to the reservoir to prevent the cross sections from being dry before the overtopping occurred.

Diagram 3: Flow Path Along Milton Road



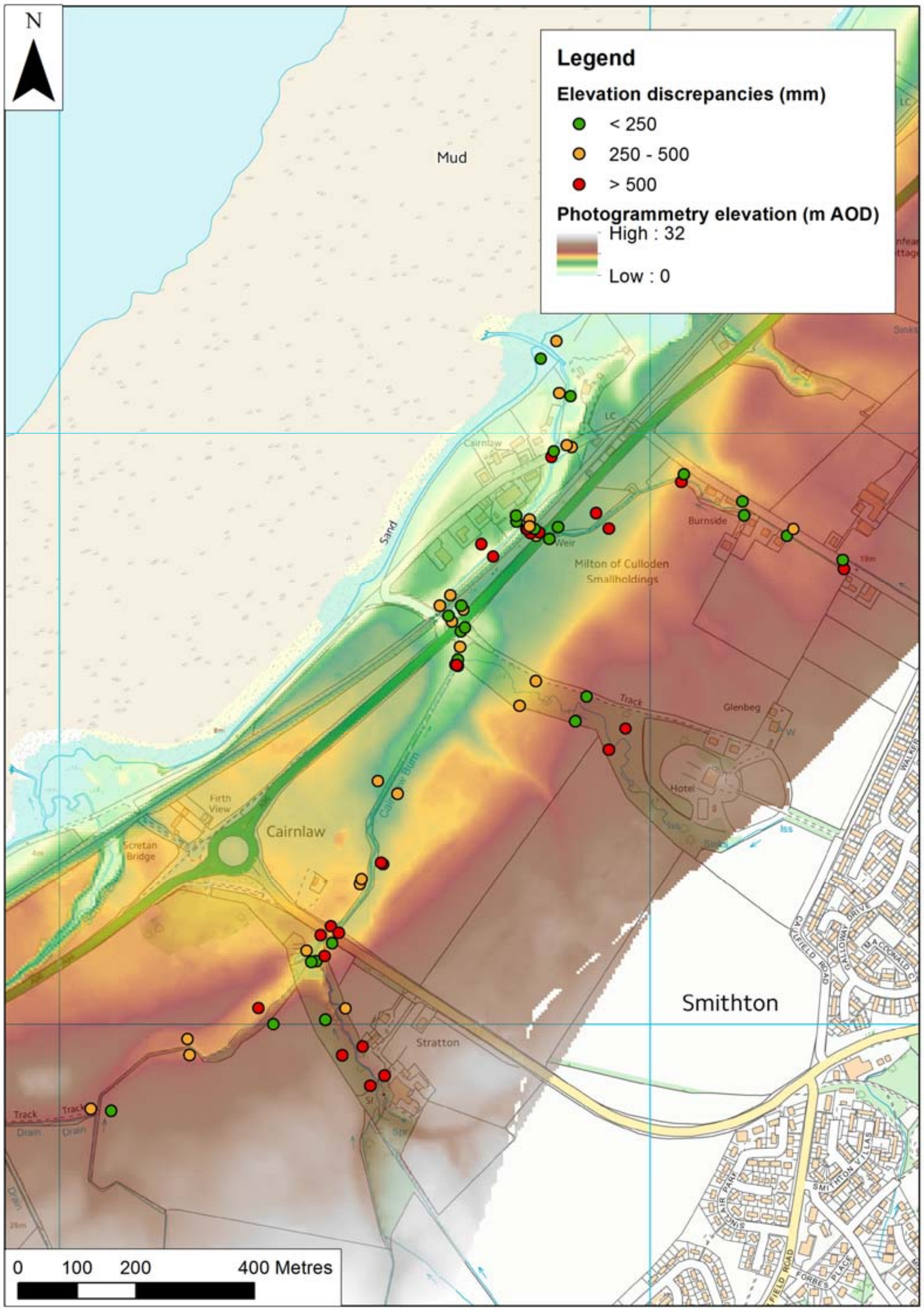
Flood Plain Schematisation - 2D domain

Flood Plain Topography

4.11 As shown in Diagram 2, a 2D domain was utilised on the right bank of Kenneth's Black Well. This was required to simulate the flood mechanism at this location, which features extended flow down the hillside with flow splits in plan. The 2D domain covers an area of 0.14km^2. The topography is represented using a 5m resolution square grid. The levels for the grid cells are based on a Digital Terrain Model (DTM) derived from 2014 photogrammetry data.

4.12 Diagram 4 shows a comparison between the channel survey data and the 2014 photogrammetry data. The photogrammetry data has been used for the 2D domain on Kenneth's Black Well. The comparison shows that there is generally good agreement between the survey sections and the floodplain DTM. There is one location towards the downstream end of Kenneth's Black Well where there is a greater than 500mm difference between the two datasets. However at this location there is no out of bank flooding in any event and the model only uses the more accurate channel survey data. Across the rest of the model the photogrammetry data is only used for a small number of 1D cross section extensions and its use is deemed acceptable in this context.

Diagram 4: Photogrammetry Elevation Discrepancies



Flood Plain Hydraulic Friction

4.13 Hydraulic roughness coefficients were applied over each grid cell of the 2D domain, as shown in Table 7, using land use categories taken from OS Mastermap data. Roughness values adopted were taken from standard guidance (Chow 1959).

Table 7: Manning's 'n' Coefficients – 2D Domain

Land Use	Manning's n
Roads, tracks and paths	0.025
Rail	0.050
Buildings, manmade structures	1.000
Trees, rough grassland	0.100
Embankments, cliff	0.050
Open Land, general surface	0.055
Water, inland water	0.020

Boundary Conditions – 2D Domain

4.14 No inflow has been applied directly in the 2D domain. Table 8 describes the downstream boundary condition used in the 2D domain. Its location is shown in Diagram 2.

Table 8: Boundary Conditions - 2D Domain

Type of Boundary	TUFLOW Feature	Description
Stage-Time	HT Boundary	Boundary for overtopping from Kenneth's Black Well. Flood water flows into Moray Firth. Used spring tide curve from 1D model. Uplifted HT boundary for climate change scenario (see Section 4 (Watercourse Schematisation - 1D Domain)).

1D/2D Linking

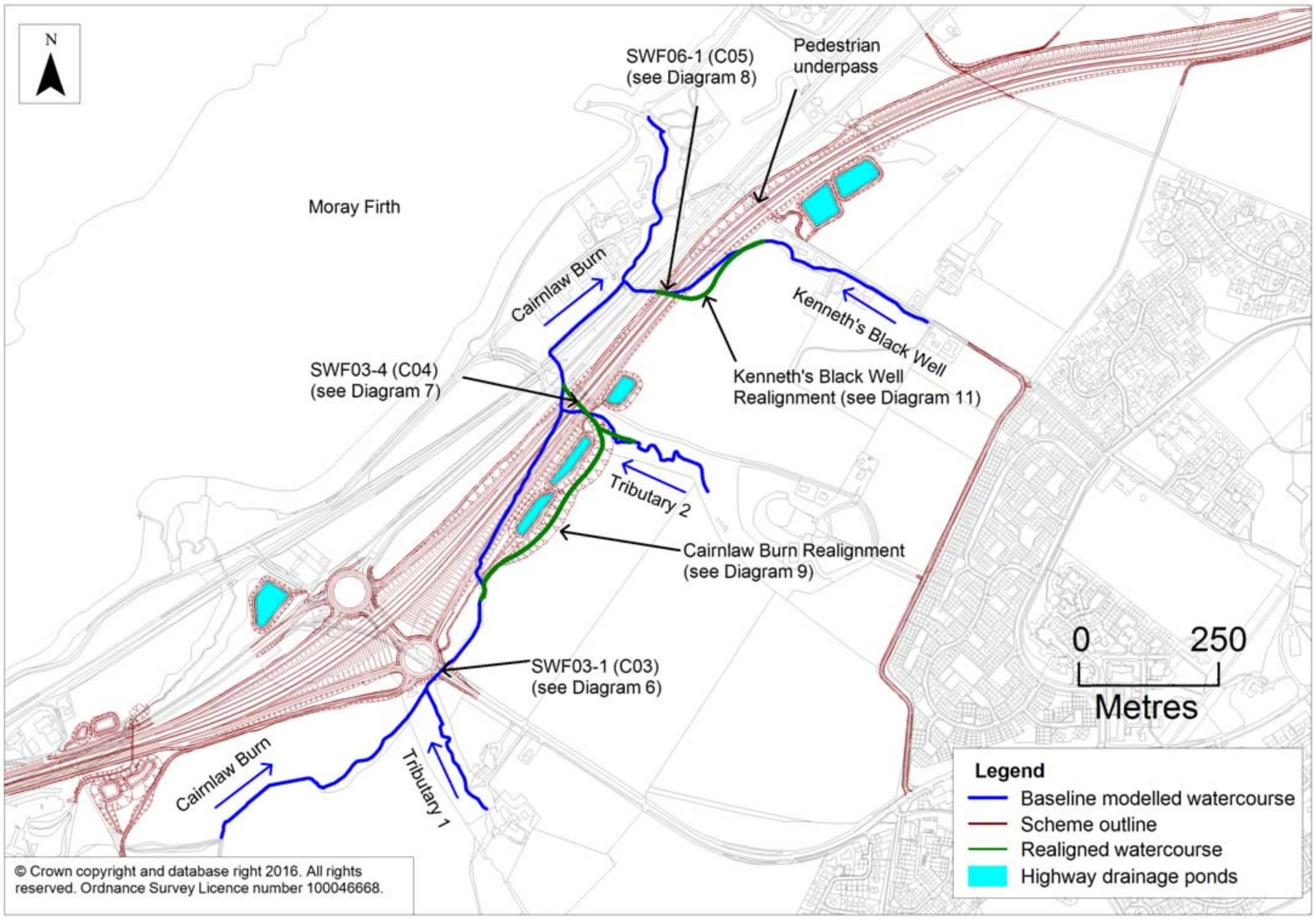
4.15 The 1D and 2D domains were linked on the right bank of Kenneth's Black Well for overtopping and on the right bank of Cairnlaw Burn for return flow. Generally the link was defined using the 2014 photogrammetry data which provides the variation between surveyed sections. However, for a short section of the watercourse (CLT3_0291 to CLT3_0135) bank top modification was required, using the channel survey data to define the link.

5 'With-Scheme' Modelling

Proposed Scheme Arrangement

5.1 As shown in Diagram 5, the proposed Scheme, within the Cairnlaw Burn study area, consists of a new offline dual carriageway with associated infrastructure. There is one extended culvert (SWF03-1 (C03)) and two new culverts (SWF03-4 (C04) and SWF06-1 (C05)). In addition there are three areas of watercourse realignment and a number of highway drainage ponds incorporated within the proposed Scheme.

Diagram 5: 'With-Scheme' Arrangement



Modelling Approach

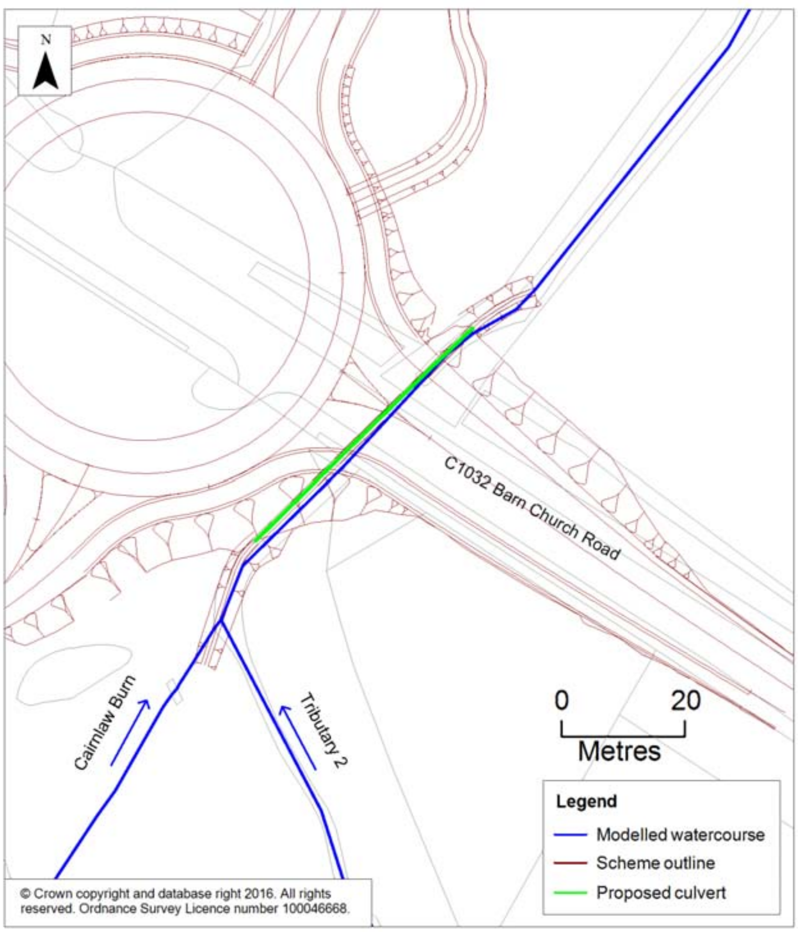
5.2 As in the baseline, the 'with-scheme' model was built primarily using a 1D schematisation with a small 2D domain adjacent to Kenneth's Black Well.

1D Model Updates

SWF03-1 (C03)

5.3 Structure SWF03-1 (C03) is an extension of the existing culvert under C1032 Barn Church Road (Diagram 6). The culvert inlet and outlet tie into the toe of the proposed Scheme embankments. There is a 16m extension on the upstream side, of the existing culvert, and a 9m extension on the downstream side. The existing channel bed levels, at the required locations, have been used for the invert levels. The culvert has a linear profile from the upstream to the downstream. The culvert shape and roughness values have been retained from the baseline model. As this is a modification of an existing culvert there is no requirement to include a mammal crossing.

Diagram 6: Structure SWF03-1 (C03) Model Schematisation



SWF03-4 (C04)

5.4 Structure SWF03-4 (C04) is a new culvert under the proposed Scheme on Cairnlaw Burn (Diagram 7). The culvert inlet and outlet tie into the toe of the proposed Scheme embankments. The invert levels for the inlet and outlet were matched to the bed levels of the channel, defined by the realignment of Cairnlaw Burn (see paragraph 5.13). The culvert has been modelled as rectangular type, using a symmetrical culvert unit. The inlet is assumed to have a square headwall.

5.5 The dimensions of the culvert were determined using an iterative modelling approach, with the following criteria:

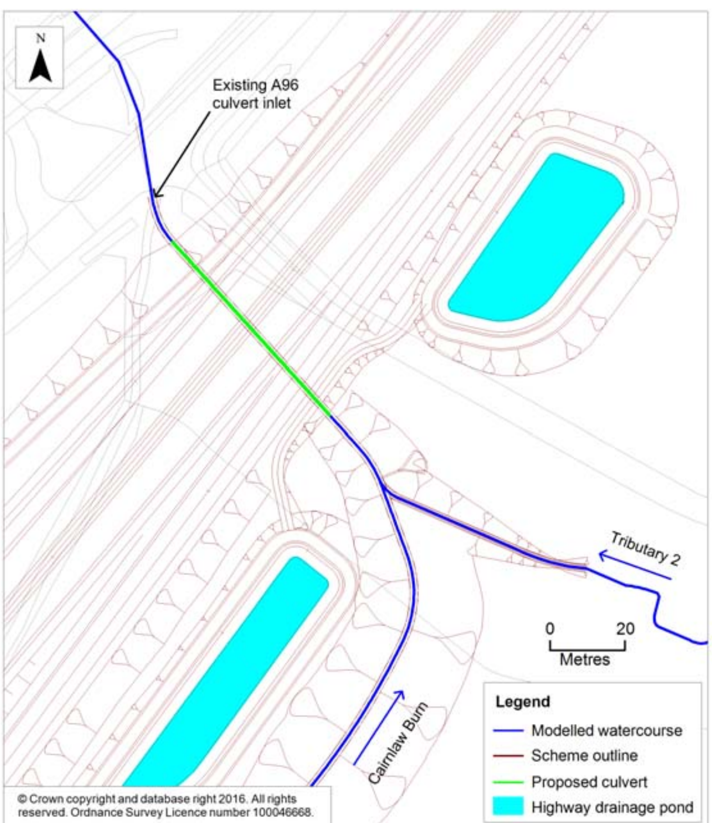
- no change in pass forward flow so that the existing A96 twin culvert, downstream of the new culvert, remain the hydraulic control for water level upstream;
- freeboard of 600mm within the culvert, above the 0.5% AEP + CC event maximum water level, to allow floating debris to pass through; and
- mammal crossing to be included (see paragraph 5.18).

5.6 The modelling showed that a culvert 4m wide and 3.2m high would be required to achieve the criteria.

5.7 The Roughness within the culvert was set to a Colebrook- White Friction value of 0.001m (Manning's 'n' equivalent; N = 0.012) for new concrete wall and soffit and 1.36m (Manning's 'n' equivalent; N = 0.04) for the culvert invert, to match the upstream bed roughness.

5.8 The highway drainage ponds in the vicinity of this culvert have not been included in the 'with-scheme' model as they are sufficiently remote from the maximum modelled flood extent.

Diagram 7: Structure SWF03-4 (C04) Model Schematisation



SWF06-1 (C05)

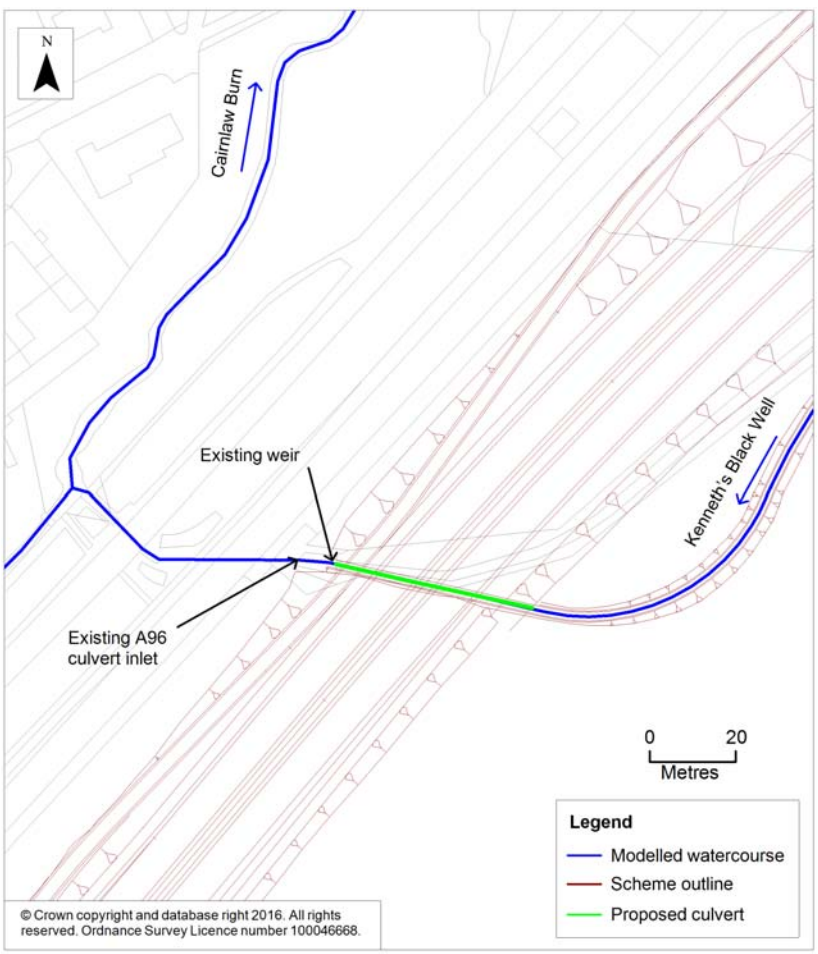
5.9 Structure SWF06-1 (C05) is a new culvert under the proposed Scheme on Kenneth's Black Well (Diagram 8). The culvert inlet and outlet tie into the toe of the proposed Scheme embankments. At the downstream end of the culvert an existing weir structure (see Table 5) is to be retained. The invert levels for the inlet and outlet were matched to the bed levels of the channel, defined by the realignment of Kenneth's Black Well (see paragraph 5.17). The culvert has been modelled as rectangular type, using a symmetrical culvert unit and the inlet is assumed to have a square headwall.

5.10 To achieve the criteria listed in paragraph 5.5, the modelling showed that a culvert 4m wide and 1.6m high would be required.

5.11 The Roughness within the culvert was set to a Colebrook-White Friction value of 0.001m (Manning's 'n' equivalent; N = 0.012) for new concrete wall and soffit and 1.36m (Manning's 'n' equivalent; N = 0.04) for the culvert invert, to match the upstream bed roughness.

5.12 As this is a new culvert, a mammal crossing was required to be modelled within the structure (see paragraph 5.18).

Diagram 8: Structure SWF06-1 (C05) Model Schematisation



Cairnlaw Burn Realignment

5.13 The proposed Scheme requires a realignment of Cairnlaw Burn onto a 515m reach of new channel (Diagram 9). New cross sections were added to the model along this reach. The bed levels of the new cross sections were defined using a linear gradient between cross section CLBN_1041 from the baseline model at the upstream and cross section CLBN_0589 at the downstream end of the realignment. The old section of Cairnlaw Burn channel, between model node CLBN_1041In1 and CLBN_0596 was removed from the model. A trapezoid channel shape was used in cross section with a 2m wide bed and linear, bankside slopes (a typical section is shown in Diagram 10). Channel width at the bank tops was taken from the design drawings. The levels of the bank tops were taken from the MXROAD ASCII grids and the 2014 photogrammetry as required.

5.14 The highway drainage ponds in the vicinity of the Cairnlaw Burn realignment have not been included in the 'with-scheme' model as they are sufficiently remote from the maximum modelled flood extent.

5.15 The reservoir unit in the baseline model, on the right bank of Cairnlaw Burn (see Section 4 (Flood Plain Schematisation - 1D domain)) was removed as this flood plain area will be lost to the proposed Scheme.

Diagram 9: Cairnlaw Burn Realignment Model Schematisation

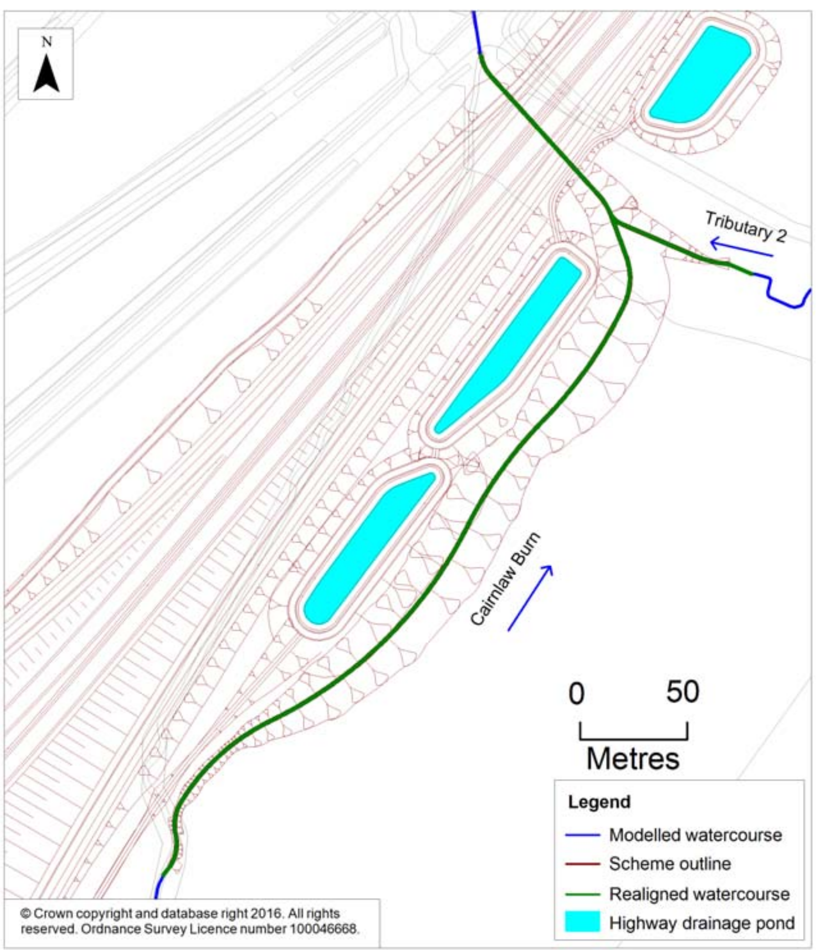
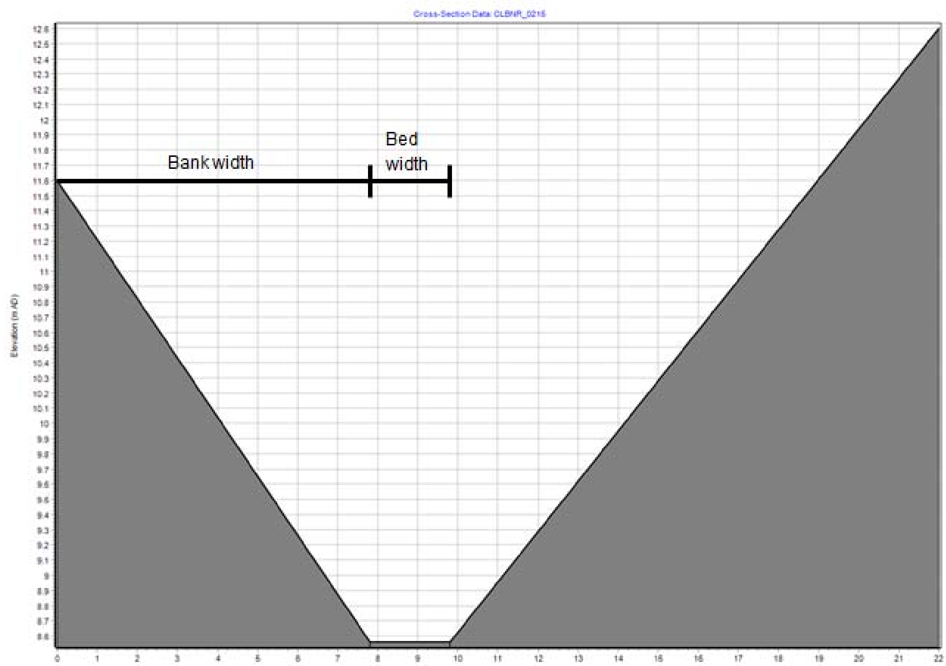


Diagram 10: Typical Realignment Cross Section



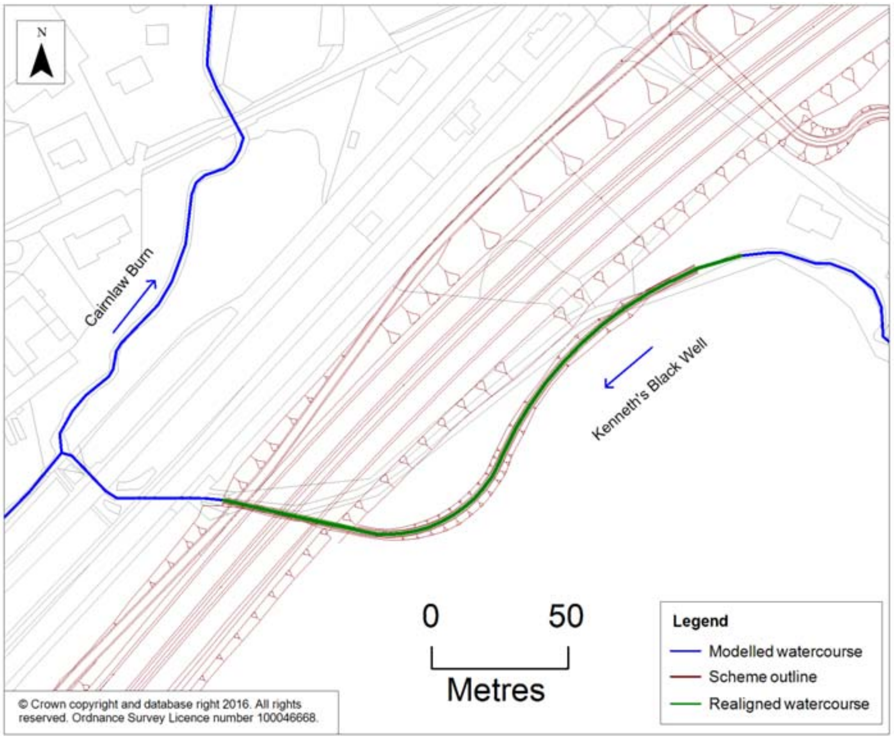
Tributary 2 Realignment

5.16 Channel realignment was required at the downstream end of Tributary 2 to allow the tributary to connect to the realigned Cairnlaw Burn (Diagram 9). A new cross section, located on the right bank of Cairnlaw Burn, was created for Tributary 2. The cross section shape followed the method described in paragraph 5.13. The bed level for the new section was defined by extending the bed slope from the retained upstream channel. A roughness value of “n” = 0.04 was used.

Kenneth’s Black Well Realignment

5.17 The proposed Scheme requires a realignment of Kenneth’s Black Well onto a 255m reach of new channel (Diagram 11). The bed levels of the new cross sections were defined using a linear gradient between cross section CLT3_0291 from the baseline model at the upstream end, and cross section CLT3_0048 at the downstream end of the realignment. The old section of the Kenneth’s Black Well channel, between model node CLT3_0291In1 and CLT3_0059, was removed from the model. The cross section shape followed the method describe in paragraph 5.13. The level of the bank tops were taken from the MXROAD ASCII grids and the 2014 photogrammetry as required. A channel roughness value of “n” = 0.04 was used for the new sections.

Diagram 11: Kenneth's Black Well Realignment Model Schematisation



Mammal Crossings

5.18 Mammal crossings were required for each new culvert. The mammal ledge is required to be 170mm above the 4% AEP event maximum water level and to have headroom of 600mm. The mammal crossing takes the form of a ledge on either side of the culvert. However, it was not possible to model this using the symmetrical unit or any other unit available within the Flood Modeller software. Therefore a simplified approach was taken. The width of the culverts was reduced to account for the loss of cross sectional area caused by mammal crossings.

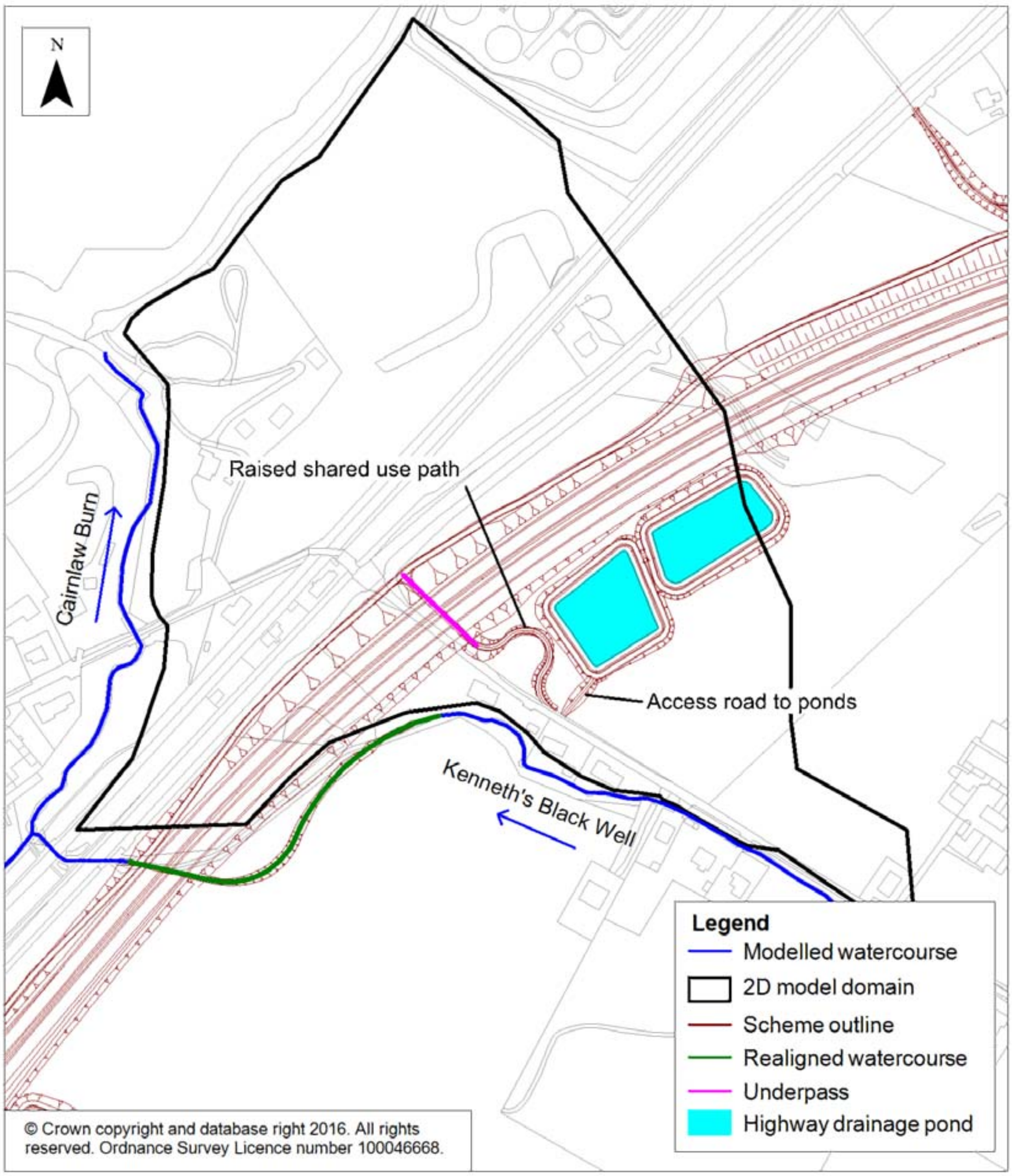
2D Model Updates

5.19 As in the baseline model the flood plain on the right bank of Kenneth's Black Well was modelled in 2D (Diagram 12). The design features were added to the 2D model. The proposed Scheme road elevations were exported from the MXROAD software as ASCII grids, for inclusion in the hydraulic model. Within the proposed Scheme footprint the ASCII grids replaced the existing ground elevation. The design requires there to be no connection between the flood plain and the highway drainage ponds. The ponds were included in the model as z-shapes with nominally high level to ensure no wetting of these areas.

5.20 A new shared use path (pedestrian and cycle) passes under the proposed Scheme. This underpass was modelled as a 4m wide, 2.5m high rectangular culvert using a 1D element within the 2D model. The invert levels for the upstream and downstream were taken from the existing ground levels in the 2014 photogrammetry data. Standard values were used for the height and width contraction coefficients and the entry and exit loss coefficients (BMT WBM 2010). The roughness of the culvert internal surfaces were defined as new, smooth concrete with Manning's "n" = 0.012.

5.21 As shown in Diagram 12, there is an access road to the highway drainage ponds. The DMRB Stage 3 design shows that this access road is on a raised embankment. This would block the existing flow through the field at this location. Therefore, this feature was removed from the MXROAD ASCII. In addition part of the shared use path is raised above the existing ground levels. This was also removed from the MXROAD ASCII. The final proposed Scheme arrangement will utilise access tracks for these ponds that are not embanked above ground level or are relocated outside the modelled flood extent.

Diagram 12: Kenneth's Black Well 2D Model Schematisation



6 Modelled events

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

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

Table 9: Modelled Events

Scenario	AEP Event								
	50%	20%	10%	3.33%	2%	1%	0.5%	0.5% + CC	0.1%
Baseline	✓	✓	✓	✓	✓	✓	✓	✓	✓
'With- Scheme'	✓	✓	✓	✓	✓	✓	✓	✓	✓
Roughness Sensitivity (1D and 2D)							✓		
Hydrological Inflow Sensitivity							✓		
Downstream Boundary Sensitivity (1D and 2D)							✓		
'With-Scheme'								✓	
'With-Mitigation' Measures				✓			✓	✓	✓
'With-Mitigation' Measures – 50% blockage of new culverts								✓	
'With-Mitigation' Measures – 90% blockage of new culverts								✓	

7 Model Proving

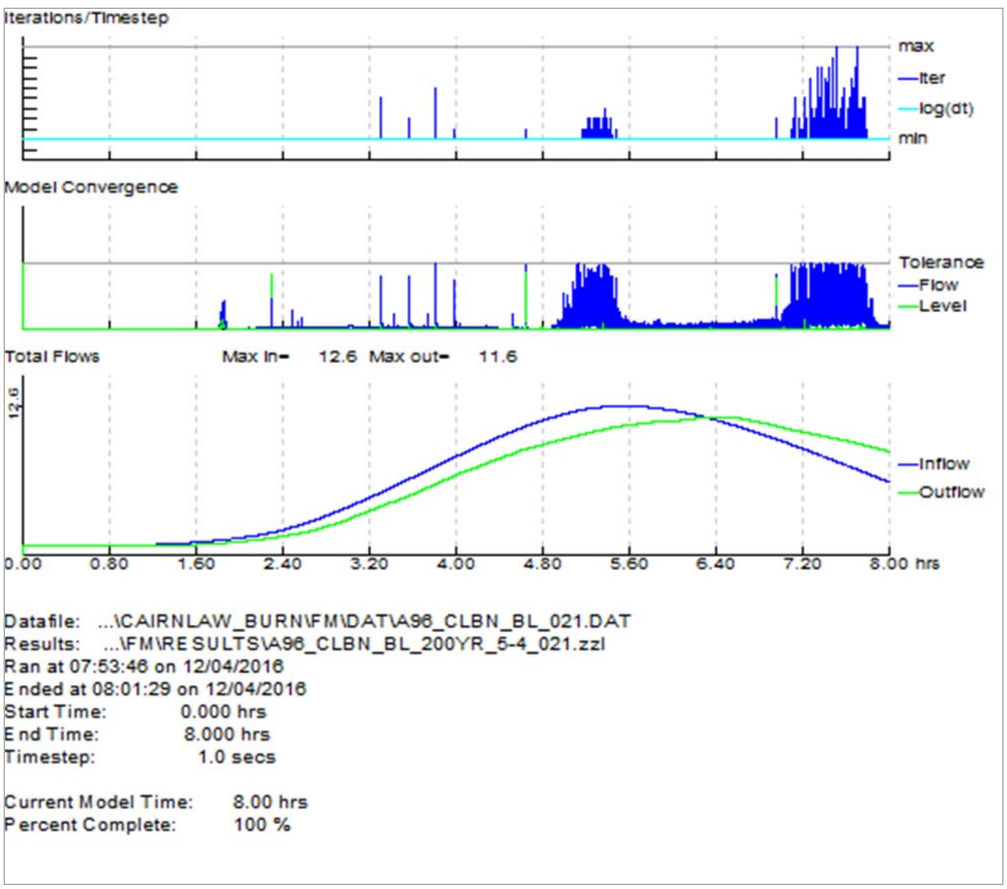
Introduction

7.1 The following sections discuss the model performance and the verification process. In addition, details relating to the additional runs carried out to test the sensitivity of the model to key variables are also discussed.

Model Performance

7.2 Run performance has been monitored throughout the model build process and then during each simulation carried out, to ensure a suitable model convergence was achieved. Convergence refers to the ability of the modelling software to arrive at a solution that is close to the exact solution within a pre-specified error tolerance. The convergence of the 1D model was checked. As shown in Diagram 13 below, there are no 1D non-convergence issues. This convergence plot is typical for the events modelled.

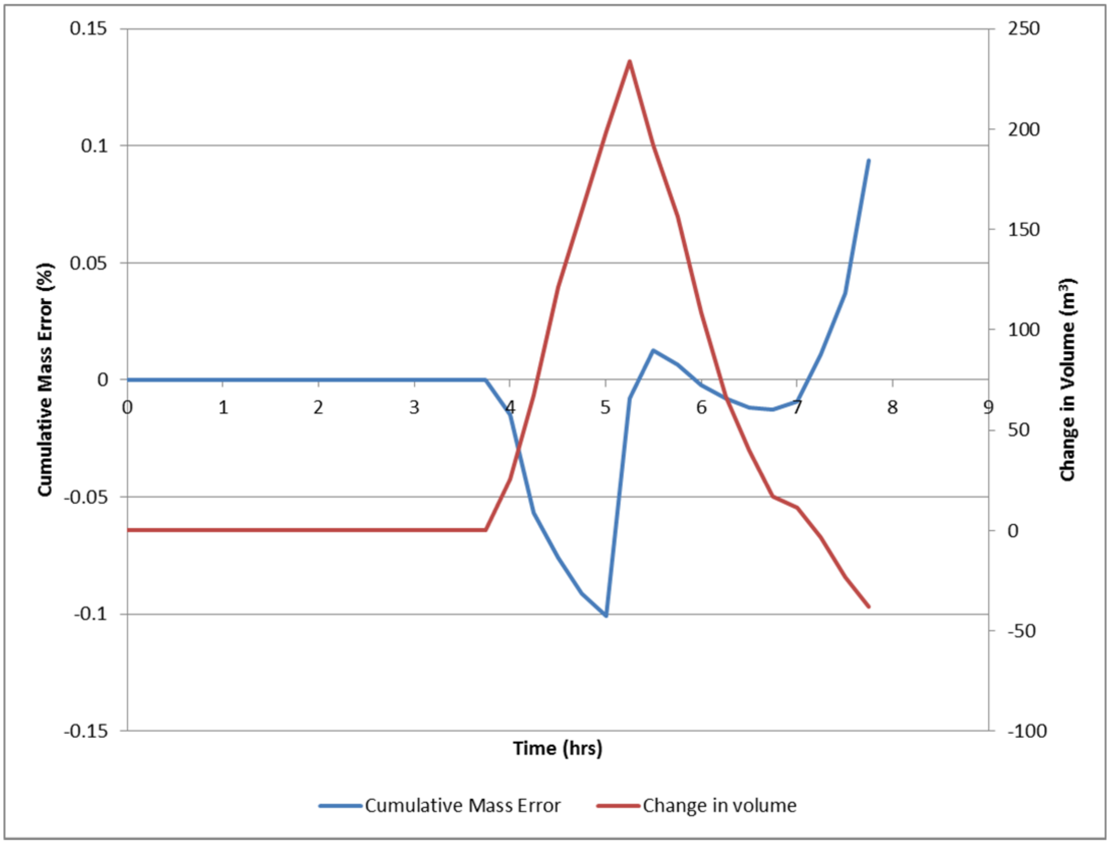
Diagram 13: 1D Model Convergence – 0.5 % AEP Event



7.3 The cumulative mass error reports output from the TUFLOW 2D model have been checked. The recommended tolerance range is +/- 1% Mass Balance error. The change in volume through the model simulation has also been checked and has been found to progress smoothly, which is also an indicator of good convergence of the 2D model.

7.4 Diagram 14 shows that the cumulative mass error is within the tolerance range for the whole simulation and that the change in volume follows a smooth progression. This Mass error diagnostic is typical for all events modelled.

Diagram 14: 2D Cumulative Mass Error and Change in Volume – 0.5 % AEP Event



Calibration and Verification

<u>Calibration</u>

7.5 There are no gauges on Cairnlaw Burn or its tributaries within the extent of the model. Therefore, it was not possible to calibrate the model. However, data is available for a high level verification of the model results.

<u>Verification Using Historic Data</u>

7.6 There were two types of historic data available for verifying the Cairnlaw Burn model: flood incident records and flood remark data (see Diagram 15).

7.7 The flood incident data is shown in Table 10. One incident point describes the general flood risk on Kenneth's Black Well; this is well matched by the model results. A second incident point shows 2012 flooding on the C1032 Barn Church Road. However the model suggests that flood water is able to pass though the culvert on the C1032 Barn Church Road, without flooding. Cairnlaw Burn is deeply incised at this location, therefore, although the flood incident data states that the source of the observed flooding is fluvial, it is suggested that this incident may be blockage related or surface water flooding.

7.8 Table 11 shows the flood remark data. The modelling shows a good match with one key flood remark record. Two remarks cannot be reconciled, and comments are provided to suggest why this may be the case.

7.9 The model results show overtopping of the existing A96, due to flooding originating from Kenneth's Black Well, from the 2% AEP event onwards, and some spilling onto Milton Road between the existing A96 and the Aberdeen to Inverness Railway Line crossing, from the 0.5% AEP +CC event onwards. The historic data does not show any evidence of this.

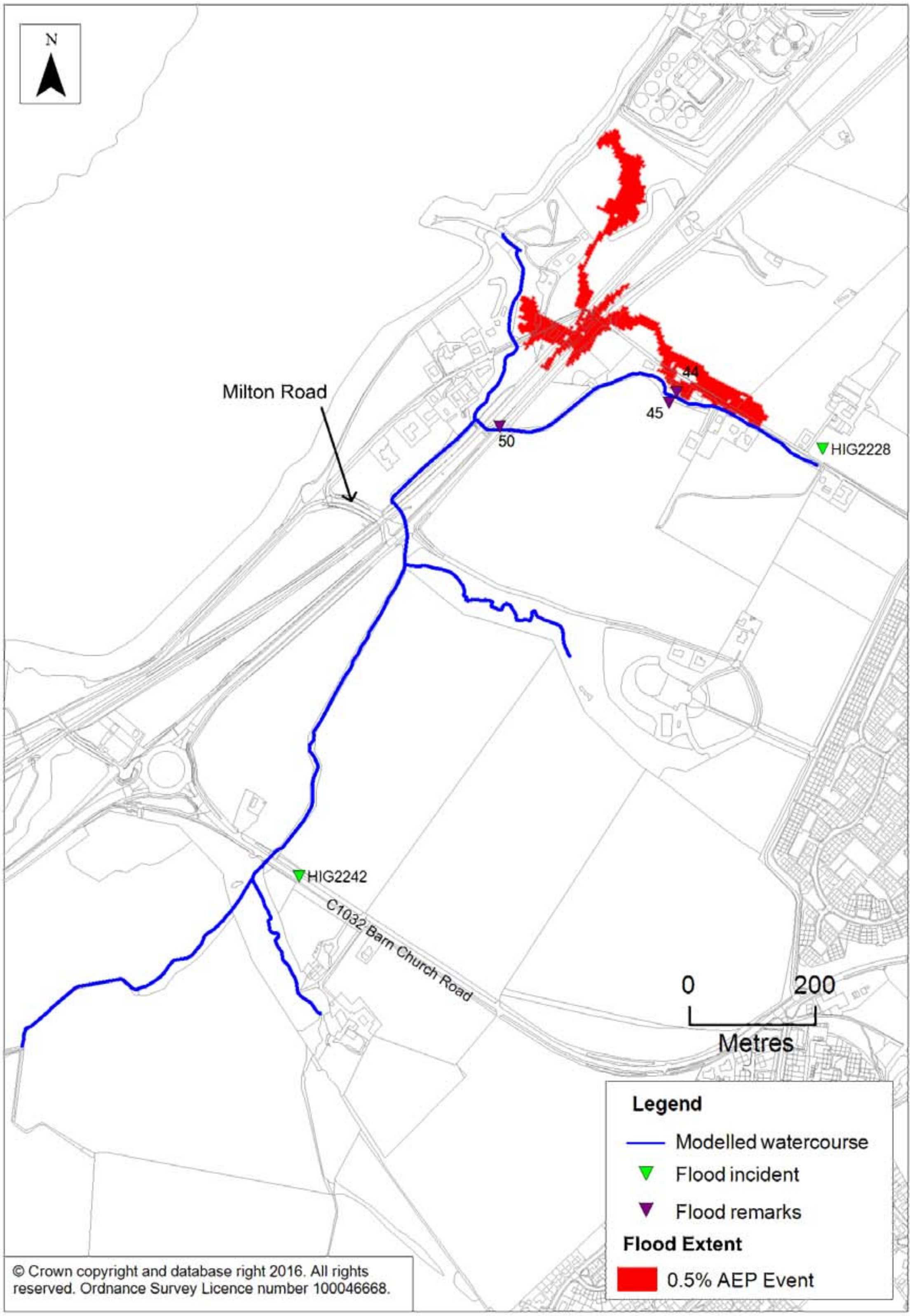
Table 10: Flood Incident Records

Reference	Easting	Northing	Date	Scale of Flooding	Description	Model Verification
HIG2242	270505	846124	20-01-2012	Unknown	Water flowing down embankment and damaged the roadside drainage at the manhole and damaged the road gully	Not shown by modelling. Suggest this incident may be blockage related or emanate from the minor drainage network that is not included in the model
HIG2228	271336	846803	08-09-2002	Property level	Significant flooding in 2002 originated from… [Kenneth's Black Well] …at various pinch-points / Restrictions along this length. Significant loss of cross-section and capacity at access bridges to: No, 4B, Fassfearn, Faylea from Service ducts and undersized culverts.	Assume that this refers to the whole of Kenneth's Black Well. Model shows overtopping onto flood plain from 3.33% AEP event onwards, caused by restrictions at drive access bridges. Flood record is matched by modelling

Table 11: Flood Remark Data

ID	Comment	Model Verification
44	Fields and garden area behind house flooded Retaining wall destroyed by floods one year, now replaced with gabion baskets	• Matched by modelling
45	Flooding to rear of houses and in field	• Not shown by modelling • Flood remark point is on high ground suggest this remark may be unreliable
50	Burn reported to have washed away part of railway line in flood	• Not shown by modelling • suggest this remark may be blockage related

Diagram 15: Location of Flood Incidents



Verification Using SEPA Flood Maps

7.10 Flood extent maps are available from the Scottish Environment Protection Agency (SEPA). These maps show the fluvial flood extent for different likelihoods of flooding (high, medium and low). The SEPA medium likelihood of flooding is equivalent to a 0.5% AEP event. Therefore a comparison has been made with the modelled baseline 0.5% AEP event flood extents.

7.11 For the 1D only section of the model it was not required to produce a full flood extent for comparison purposes. Instead the extent of flooding was mapped at selected surveyed cross section. The green circles in Diagram 16 show the flood extent of the modelled 0.5% AEP event, at selected model cross sections. These generally show a good match with the SEPA flood map. The flooding shown on Milton Road by the SEPA flood map is not predicted in the modelled 0.5% AEP event. However, the model does predict flooding at this location for the 0.5% AEP +CC event (see paragraph 8.4).

7.12 As the flood plain on the right bank of Kenneth's Black Well has been modelled in 2D full flood extent maps were readily available, and a more detailed comparison has been made (Diagram 17). The SEPA map shows a good match to the 0.5% AEP modelled event for flooding on the existing A96 and on the downstream side of the existing A96. However, towards the upstream model extent of Kenneth's Black Well there is flooding on the right bank, which is not shown by the SEPA flood maps. The SEPA flood maps show flooding on Kenneth's Black Well, immediately upstream of the existing A96 crossing. The model results at this location show that for the 0.5% AEP event there is some flooding on the left bank of Kenneth's Black Well, in the extended 1D cross sections upstream of the culvert, which is in line with the SEPA flood maps. However, on the right bank the surveyed banktop level contains the maximum 0.5% AEP water level and the SEPA flood outline is not replicated.

7.13 Differences with the SEPA flood mapping are expected as the FRA modelling presented in this report is based on a finer level of detail along with refined catchment hydrology analysis.

Verification Conclusion

7.14 In conclusion, the model shows a good general match with the verification data. A number of points cannot be reconciled. However, it is suggested that these are not significant and that the model has been developed with as much detail as possible within the scope of the present study. The model is thought to be an appropriate representation of the existing situation, for the purpose of flood risk assessment of the proposed Scheme.

Diagram 16: Modelled 0.5 % AEP Event Flood Extent vs. SEPA Medium Likelihood Fluvial Extent

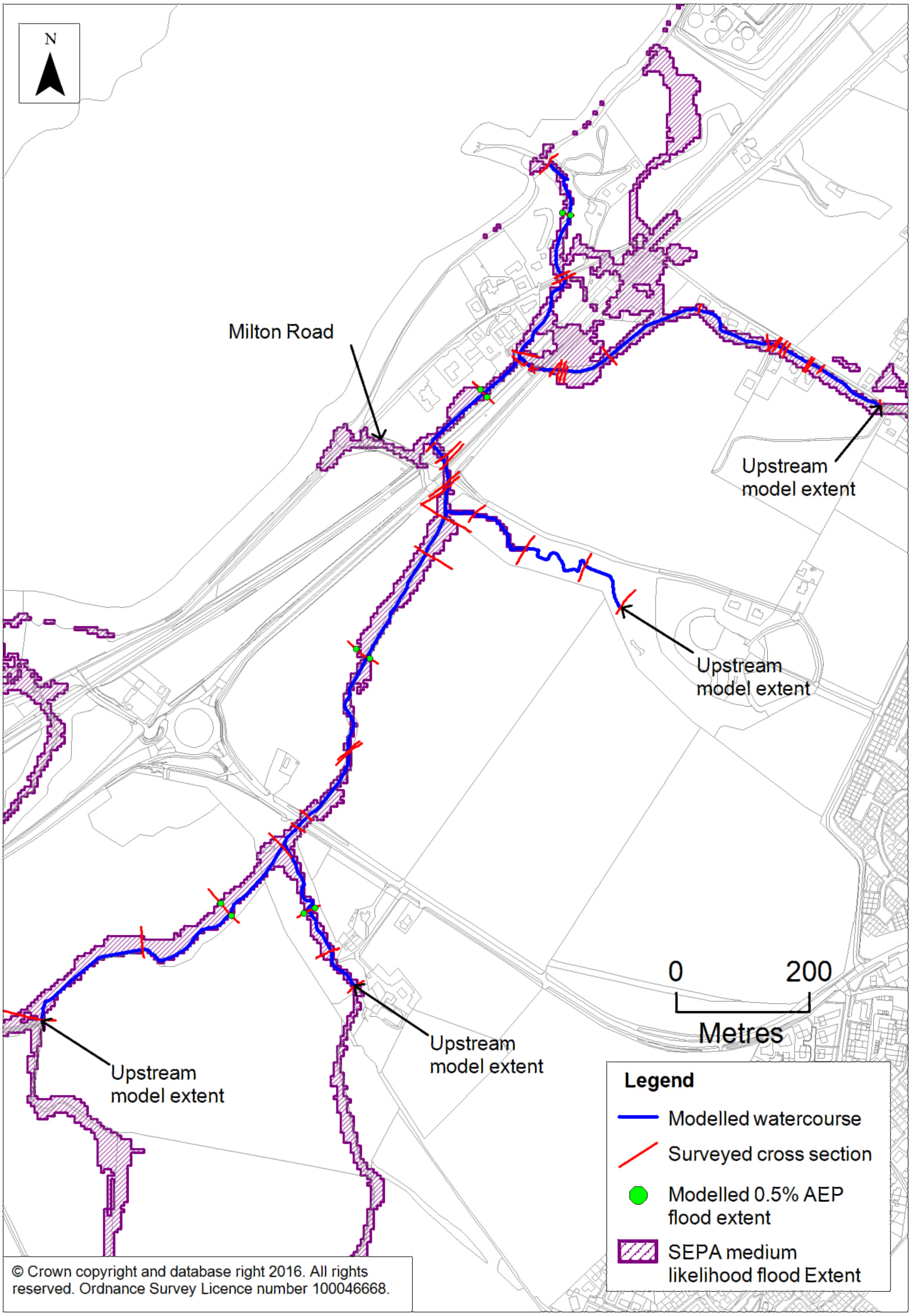
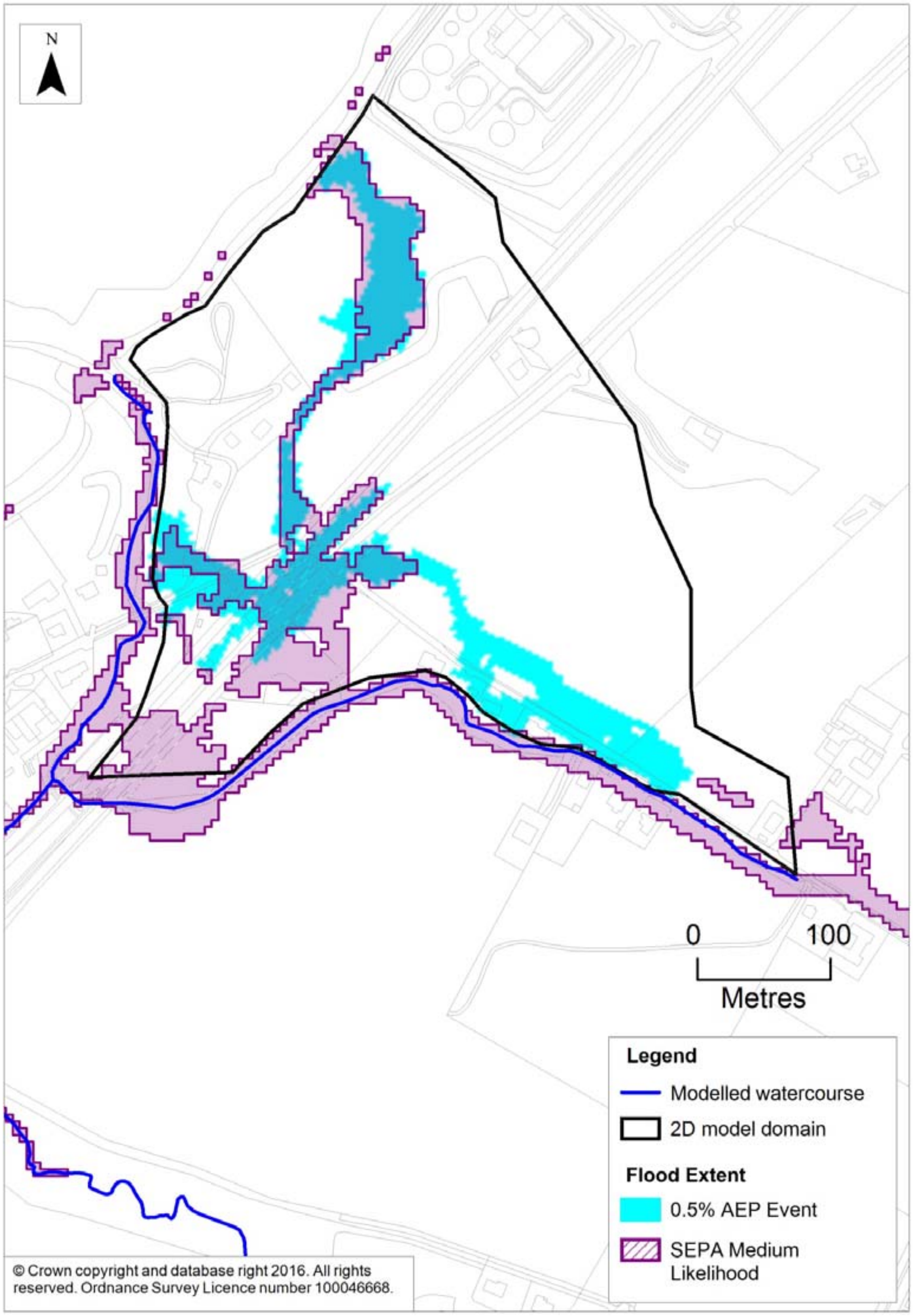


Diagram 17: Kenneth's Black Well: Modelled 0.5 % AEP Event Flood Extent vs. SEPA Medium Likelihood Fluvial Extent



Sensitivity Analysis

Roughness Sensitivity

7.15 In-channel and flood plain roughness coefficients (Manning's 'n') were changed by +20% and -20%. Table 12 shows the impact of changing the model roughness. Results are presented for the whole of Cairnlaw Burn and its tributaries and also at key locations relevant to the proposed Scheme. The results show that the in-channel water levels are moderately sensitive to changes in roughness.

Table 12: Roughness Sensitivity Results

Sensitivity	Water Level Difference (m)					
	Max	Min	Average	CLBN_1223 SWF03-1 (C03)	CLBN_0589 SWF03-4 (C04)	CLT3_0048 SWF06-1 (C05)
+20% Roughness	0.136	-0.054	0.044	0.055	0.021	0.038
-20% Roughness	-0.164	0.084	-0.054	-0.054	-0.029	-0.010

Hydrological Inflow Sensitivity

7.16 The flows into the model were adjusted by +20% and -20%. Table 13 shows the impact of changing the model inflows. Results are presented for the whole of Cairnlaw Burn and its tributaries and also at key locations relevant to the proposed Scheme. The results show that the in-channel water levels are generally moderately sensitive to changes in flow but at the proposed Scheme crossing location SWF03-4 the model is very sensitive to a reduction in flow.

Table 13: Flow Sensitivity Results

Sensitivity	Water Level Difference (m)					
	Max	Min	Average	CLBN_1223 SWF03-1 (C03)	CLBN_0589 SWF03-4 (C04)	CLT3_0048 SWF06-1 (C05)
+20% Flow	0.577	0.000	0.093	0.073	0.119	0.138
-20% Flow	-0.509	0.000	-0.145	-0.070	-0.509	-0.123

Downstream Boundary Condition Sensitivity

7.17 The stage in the downstream boundaries in the 1D and 2D models was adjusted by +0.5m and -0.5m. The results show that the changes to the downstream boundary only affect the downstream end of the model. Table 14 shows the response at the downstream end of the model (Flood Modeller CLBN_0000). The location at which there is no change in water level as a result of changing the downstream boundary has been identified. Distances from this location, in relation to the downstream end of the model (tailwater distance) and in relation to the proposed Scheme, are shown in Table 14.

Table 14: Downstream Boundary Sensitivity Results

Sensitivity	Water Level Difference (m)		
	Water Level Difference (m) at CLBN_0000	Tailwater Distance (m)	Distance to proposed Scheme (m)
+0.5m Downstream boundary slope	0.455	140	240
-0.5m Downstream boundary slope	-0.179	140	240

8 Model Results

Baseline Scenario

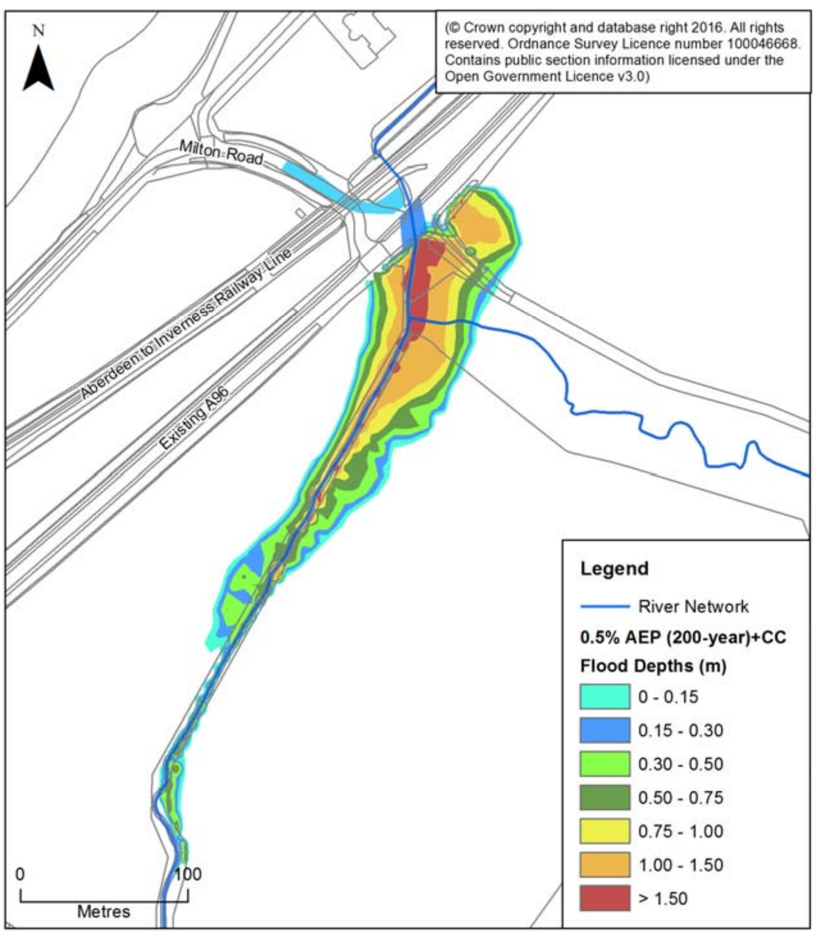
8.1 In-channel maximum water levels have been inspected at key locations in relation to the proposed Scheme and Table 15 shows in-channel maximum water levels for the 0.5% AEP +CC (Climate Change) event. The in-channel water levels at key locations for all modelled events are shown in Section A.1 (Maximum Water Level Tables and Long Sections). Below is a discussion of the results for each reach.

Cairnlaw Burn

8.2 The results show that upstream of the C1032 Barn Church Road culvert water is contained within the river valley and no properties are flooded.

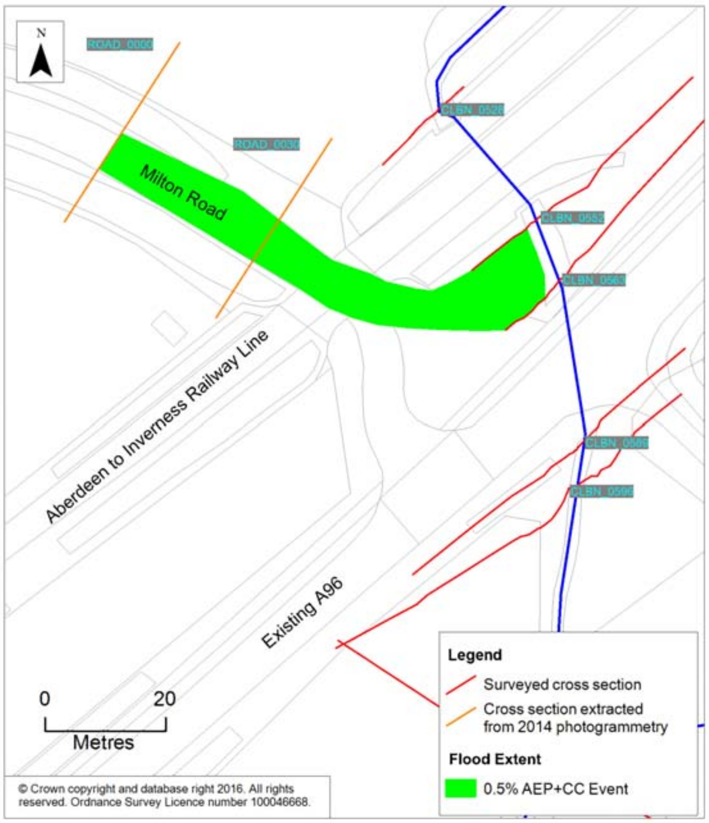
8.3 The existing A96 twin culvert, which is situated downstream from the Tributary 2 confluence, causes backing up on Cairnlaw Burn. Cairnlaw Burn begins to overtop its banks during the 50% AEP flood event due to restricted channel capacity. When the burn reaches the existing A96 culvert, water begins to back up due to the culvert constriction during the 10% AEP flood event. From the 2% AEP event onwards, water backing up from the twin culvert overtops into a low spot on the right bank of Cairnlaw Burn. From the 0.5% AEP event onwards there is water overtopping the existing A96 and returning into channel immediately downstream (Diagram 18).

Diagram 18: Cairnlaw Burn Flood Depths



8.4 Between the existing A96 twin culvert and the Aberdeen to Inverness Railway Line crossing water overtops on the left bank and flows down Milton Road, as described in paragraph 4.10. The onset of this overtopping occurs at the 0.5% AEP +CC event, with 0.3m^3/s overtopping at the event peak. The 0.5% AEP +CC flood extent for this location is shown in Diagram 19 below.

Diagram 19: Milton Road Flood Extent



Tributary 1

8.5 An informal footbridge causes an interruption to flow on Tributary 1, in all events. For the 0.5% AEP event onwards there is some out of bank flooding on the downstream sections of Tributary 1, but it is all contained within the wider river valley. There are no properties at risk in the existing situation.

Tributary 2

8.6 Tributary 2 is a steep watercourse with a small catchment. There is no out of bank flooding in any events and no properties are at risk of flooding.

Kenneth's Black Well

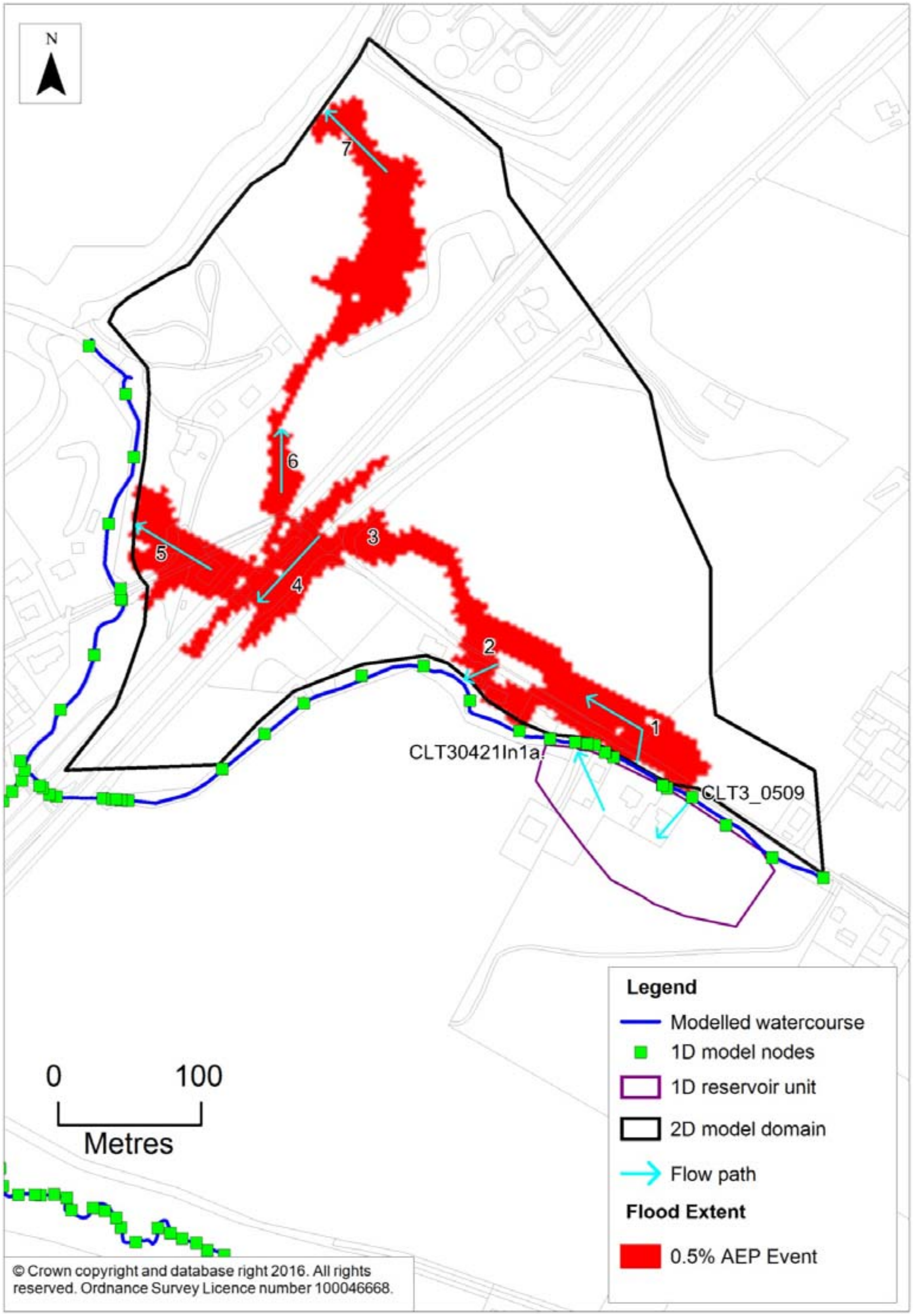
8.7 On the left bank of Kenneth's Black Well there is out of bank flooding, which affects properties adjacent to the watercourse (see Diagram 20). Water overtops from model nodes CLT3_0509 to CLT3_0449 and the onset of flooding is the 3.33% AEP event. Water returns back into Kenneth's Black Well, at model nodes CLT3_0443c to CLT30421In1a.

8.8 There is out of bank flooding on the right bank of Kenneth's Black Well. The flood mechanisms are shown in Diagram 20 and described as follows:

1) Out of bank flooding on the right bank flows through fields parallel to Kenneth's Black Well. The onset of flooding is the 3.33% AEP event.
2) From the 2% AEP event onwards some water returns to Kenneth's Black Well.
3) Water backs up in the corner of field adjacent to the existing A96 in all events. The maximum depth reached here is approximately 0.7m in the 0.1% AEP event.
4) From the 2% AEP event onwards, water overtops onto the existing A96 and flows along the highway, filling a localised depression.
5) Water returns to Cairnlaw Burn from the 2% AEP event onwards. There is some flooding of properties in this area.
6) From the 1% AEP event onwards, there is a flow split at the existing A96 with some water flowing north and ponding.
7) Water flows into Moray Firth from the 0.5% AEP event onwards.

8.9 Extent maps for the flooding originating from Kenneth's Black Well are shown in Section A.2 (Flood Extent Maps (2D domain only)) for all modelled flood events. As discussed in the previous sections, out of bank flooding for the rest of the model is limited to the to the river valley and represented by the 1D model domain, and therefore extent maps have only been produced for Kenneth's Black Well.

Diagram 20: Kenneth's Black Well Flood Mechanism, a description of flood mechanism for location numbers is given in the text



Comparison of Baseline and 'With-Scheme' Scenarios

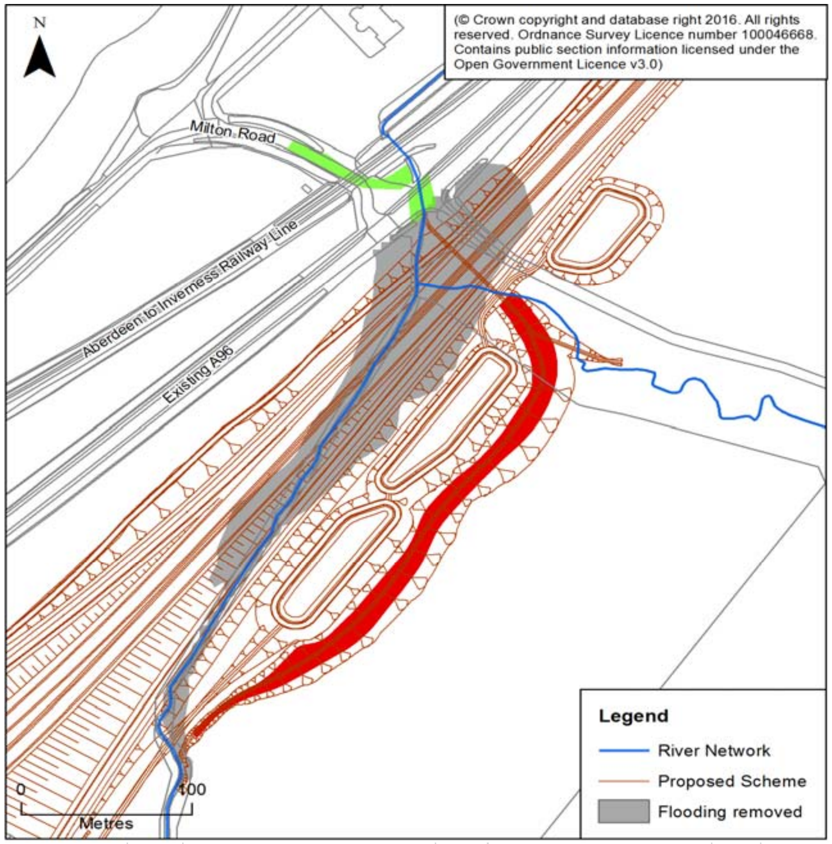
8.10 Table 15 shows the changes for in-channel maximum water level between the baseline and the 'with-scheme' scenarios, for the 0.5% AEP +CC event. Where the proposed Scheme has removed the baseline nodes from the model, no comparison was made.

8.11 The results show that at 167m upstream of the extended C1032 Barn Church Road culvert there is no change in in-channel maximum water level as a result of the proposed Scheme. Immediately upstream of the proposed Scheme there is an increase in maximum water level of 44mm in the 0.5% AEP +CC event. This increase extends for 108m upstream of the extended culvert. The changes are due to the change in gradient through the culvert, caused by the extension. The extended culvert does not change pass forward flow on the downstream side of the culvert.

8.12 118m downstream of the extended culvert there is an increase of 371mm in the 0.5% AEP +CC event. This location is immediately upstream of the Cairnlaw Burn realignment. This in-channel maximum water level increase is due to the increase in channel length and the resultant slackening of the gradient caused by the realignment. The increased water levels remain in channel and do not increase flooding on the flood plain.

8.13 For the reach downstream of the Cairnlaw Burn realignment there is an increase in in-channel maximum water level of 3mm upstream of the existing A96 twin culvert. The same increase is also seen on the existing A96 spill unit. This additional water increases maximum water levels on Milton Road by 7mm. Increases in maximum water level from the baseline continue to the downstream end of Cairnlaw Burn. Diagram 21 shows the changes in water level in the vicinity of the Cairnlaw Burn realignment.

Diagram 21: Cairnlaw Burn 'With-Scheme' Depth Difference



Potential flood impact							
	Increase in peak flood level 0.5% AEP (200-year) > 100 mm		Increase in peak flood level 0.5% AEP (200-year) 10 - 50mm		Reduction in peak flood level 0.5% AEP (200-year) 10 - 50mm		Reduction in peak flood level 0.5% AEP (200-year) >100mm
	Increase in peak flood level 0.5% AEP (200-year) 50 - 100 mm		Negligible change in peak flood level 0.5% AEP (200-year) <+/- 10 mm		Reduction in peak flood level 0.5% AEP (200-year) 50 - 100mm		

8.14 There are no changes in in-channel maximum water levels on Tributary 1 as a result of the proposed Scheme.

8.15 On Tributary 2 there is a small reduction in maximum water level as a result of the proposed Scheme at model node CLT2_0136d. This change is associated with the realignment at the confluence of Tributary 2 and Cairnlaw Burn. The peak water level at this location remain in channel and do not increase flooding on the flood plain

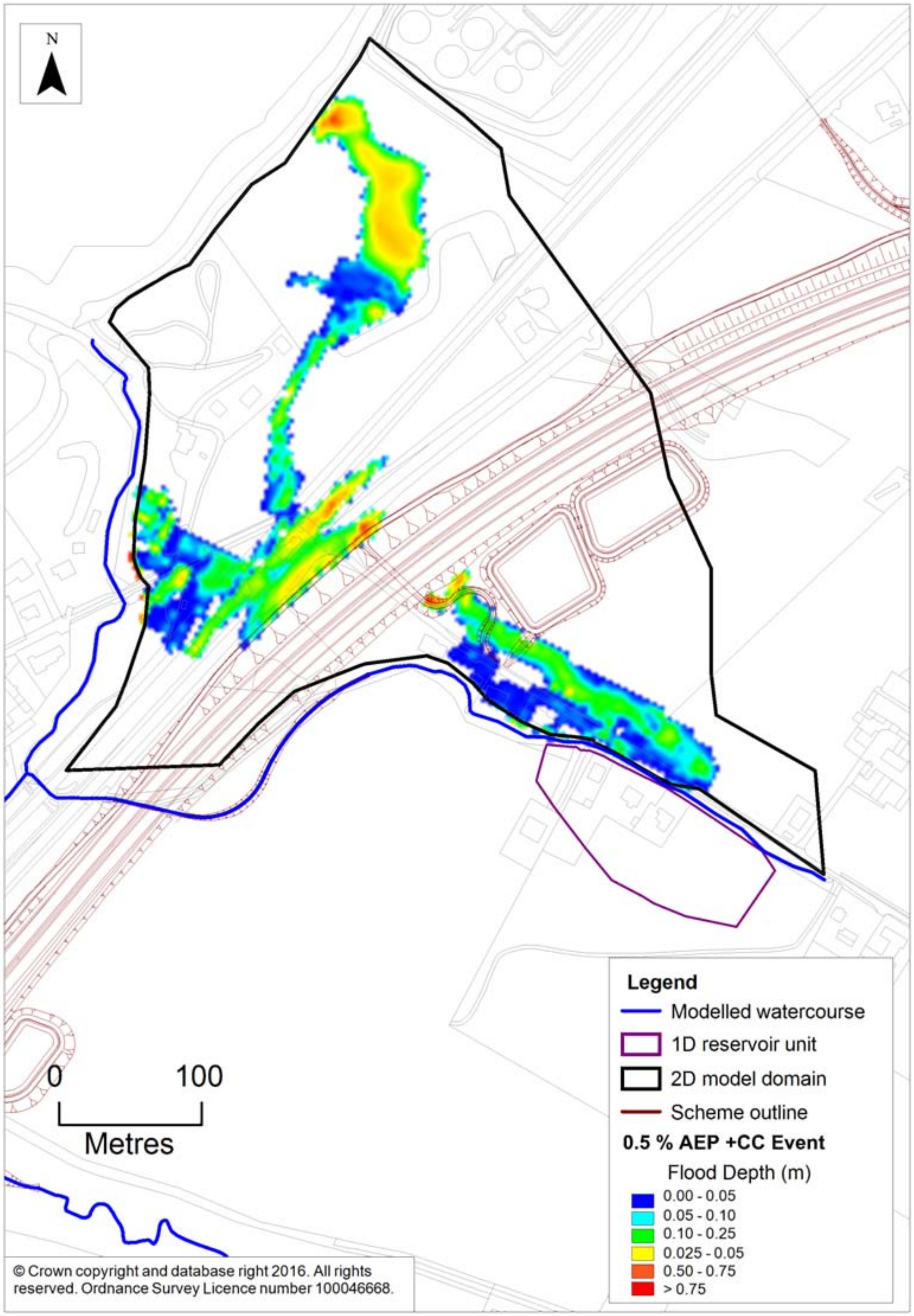
8.16 On Kenneth's Black Well there are both increases and decreases in water levels of less than 20mm as a result of the proposed Scheme. Peak water levels remain in channel and do not increase flooding on the flood plain. The new culvert does not change the pass forward flow downstream of the culvert.

8.17 Diagram 22 shows the depth on the flood plain adjacent to Kenneth's Black Well for the 0.5% AEP event. It can be seen there is a significant flood risk to the shared use underpass under the proposed Scheme. The flood risk to the properties on the left bank, in the 1D reservoir unit, remains the same as in the baseline.

Table 15: In-Channel Maximum Water Level at Key Locations for the 0.5% AEP +CC Event. See Diagram 2 for Model Node Locations.

Model Node	Description	Baseline Water Level (mAOD)	'With-Scheme' Water Level (mAOD)	Change in Water Level (m)
CLBN_1353	Cairnlaw Burn. 167m upstream of C1032 Barn Church Road	15.221	15.221	0.000
CLBN_1223	Immediately upstream of the proposed Scheme at C1032 Barn Church Road	14.572	14.616	0.044
CLBN_1185	Cairnlaw Burn. Upstream of C1032 Barn Church Road	14.280	-	-
CLBN_1163	Cairnlaw Burn. Downstream of C1032 Barn Church Road	13.901	-	-
CLBN_1045	Cairnlaw Burn. 118m Downstream of C1032 Barn Church Road	12.384	12.755	0.371
CLBN_0705	Cairnlaw Burn. 115m upstream of existing A96 twin culvert	9.241	-	-
CLBN_0589	Cairnlaw Burn. Upstream of existing A96 twin culvert	9.232	9.235	0.003
CLBN_0528	Cairnlaw Burn. Downstream of Aberdeen to Inverness Railway Line crossing	7.471	7.473	0.002
CLBN_0332	Cairnlaw Burn. Downstream of Kenneth's Black Well confluence	6.187	6.190	0.003
CLBN_0000	Cairnlaw Burn. Downstream extent of model	2.550	2.551	0.001
CLT1_0115d	Tributary 1. 115m upstream of Cairnlaw Burn confluence	16.573	16.573	0.000
CLT2_0136d	Tributary 2. 136m upstream of Cairnlaw Burn confluence	10.977	10.940	-0.037
CLT2_0044	Tributary 2. 44m upstream of Cairnlaw Burn confluence	9.237	-	-
CLT3_0291	Kenneth's Black Well. 240m upstream of existing A96 crossing	14.077	13.994	-0.083
CLT3_0135	Kenneth's Black Well. 88m upstream of existing A96 crossing	12.200	-	-
CLT3_0013	Kenneth's Black Well. Downstream of existing A96 crossing	7.681	7.682	0.001

Diagram 22: Kenneth's Black Well, 0.5% AEP Event 'With-Scheme' Maximum Flood Depths



9 With-Mitigation Measures Modelling

9.1 'With-scheme' results show that the proposed Scheme increases flood risk to the existing A96 on Cairnlaw Burn, immediately downstream from SWF03-4 (C04), and to Milton Road. To mitigate this, culvert SWF03-4 (C04) was reduced in size to 1.5m wide by 1.25m high. As a result of this throttling, model results show an increase in maximum water level upstream of the proposed Scheme culvert, which causes water to spill on to the proposed Scheme drainage ponds on either side of the channel, from the 0.5% AEP event onwards. Reservoir units were added at the pond locations to allow for the spilling. A conservative assumption was taken that the ponds would be full to the lowest level at the perimeter of the pond during a flood event greater than the 3.33% AEP.

9.2 On Kenneth's Black Well the out of bank flooding on the right bank causes a risk to the proposed Scheme. Therefore measures were taken to mitigate this. An additional aim of the mitigation was to reduce the flood risk to properties on the left bank of Kenneth's Black Well and on the downstream side of the existing A96, providing a legacy benefit from the proposed Scheme works.

9.3 The solution to mitigate out of bank flooding on Kenneth's Black Well is shown in Diagram 23. A bypass channel was added in the fields on the opposite side of the road from Kenneth's Black Well. This required the model to be extended upstream from its original baseline extent. An additional existing road culvert was added, with a short section of open channel upstream. On the upstream side of the culvert there is a flow spilt between the main channel and the bypass channel. Flow in the bypass channel continues in open channel to a culvert alongside a private property. There is then 230m of open channel before a right angled bend and another culvert under the road. The culvert returns flow to the main channel. The open channel was modelled with a nominal 4m x 2m trapezoid arrangement. The upstream culvert used a 1.2m x1.2m box culvert sized to accommodate all the water that was spilling onto the flood plain in the existing situation 0.5% AEP event. The downstream culvert, which crosses under the road and outfalls into Kenneth's Black Well was sized to a 2m x 1m box culvert in order to pass the design event without surcharge.

9.4 Since the with-Scheme scenario was modelled there has been a change to the highway drainage ponds (Diagram 24).

- On the left bank of Cairnlaw Burn there is now one pond instead of two.
- On the right bank of Cairnlaw Burn the pond has moved to the north-east further away from the channel.

The floodplain in this area is modelled with a series of reservoir units linked by lateral spill alignments.

Diagram 23: Kenneth's Black Well Mitigation Measures

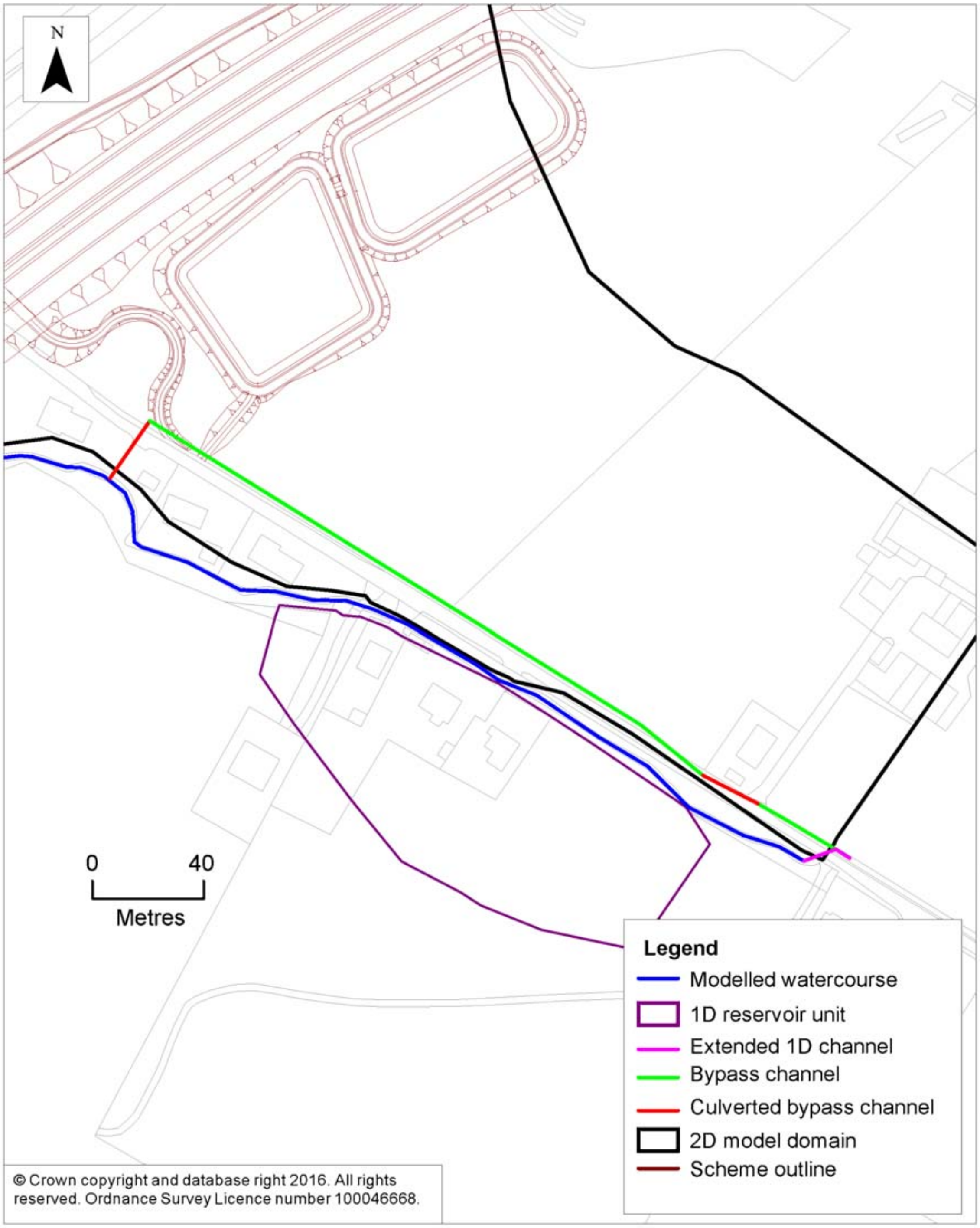
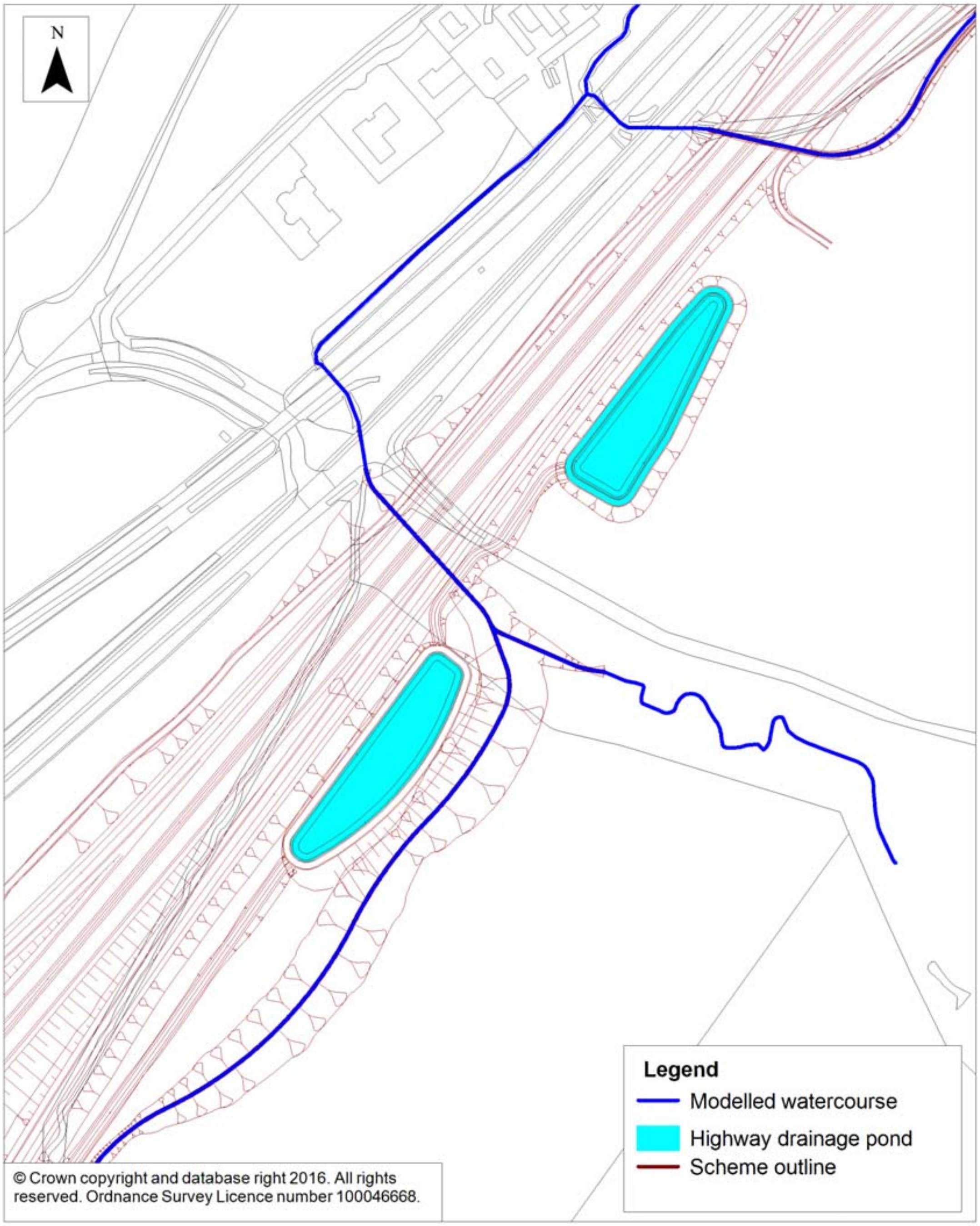


Diagram 24: Updated Drainage Ponds



10 Model Results – With-Mitigation Measures

Comparison of Baseline and With-Mitigation Scenarios

Cairnlaw Burn, Tributary 1 and 2

10.1 Table 16 and Table 17 show the changes of in-channel maximum water level between the baseline and the 'with-mitigation' scenarios, for the 0.5% and the 0.5% AEP +CC events respectively. Where the proposed Scheme has removed the baseline nodes from the model, no comparison was made.

10.2 The mitigation model results show that the maximum increases in water level, in the upstream section of Cairnlaw Burn and on Tributary 1 are the same as seen in the 'with-scheme' model, 0.044m for the 0.5% AEP +CC event, occurring immediately upstream of the Barn Church Road (CLBN_1223).

10.3 At the existing A96 twin culvert (CLBN_0589) there are reductions in maximum water level of 24mm in the 0.5% AEP event and 75mm in the 0.5% AEP +CC event. This reduction is caused by throttling from the reduced size of the proposed Scheme culvert, which is upstream of the existing A96 culvert. This throttling also leads to a reduction in the amount of water overtopping the existing A96.

10.4 The onset of flooding into Milton Road (see Diagram 19) has now changed to a 0.1% AEP event.

10.5 As the proposed Scheme culvert (SWF03-4 (C04)) is acting as a throttle, water levels are increased upstream and the culvert is surcharging. Therefore there is now no freeboard within the culvert or an allowance for a mammal crossing. The increased maximum water level upstream of the culvert does not lead to overtopping of the proposed Scheme highway (Diagram 25).

10.6 Water overtops on the left bank of Cairnlaw Burn, upstream of the throttled culvert. The water level exceeds the level of the access track to the pond, as shown in Diagram 25. This occurs from the 0.5% AEP flood event.

10.7 The upstream increases in maximum water level, caused by reducing the size of the proposed Scheme culvert on Cairnlaw Burn, are also seen on Tributary 2 extending 60m upstream from the confluence in the 0.5% AEP +CC event. However, all water remains in channel and there is no increased flood risk to properties on Tributary 2 which remain more than 160m distant and, due to the steep hillslope, are elevated above any water level change by more than 4m.

10.8 Downstream of the Aberdeen to Inverness Railway Line crossing, a reduction in maximum water level, caused by throttling culvert SWF03-4 (C04), is also seen.

Kenneth's Black Well

10.9 On Kenneth's Black Well the mitigation measures divert some water into the bypass channel. The bypass channel is activated in the smallest event modelled, the 3.33% AEP. In the 0.5% AEP +CC event 57% of the peak flow is carried by the bypass channel. The additional capacity results in there being no out of bank flooding on the either the right bank (2D model) or the left bank (1D reservoir unit) in the 3.33%, 0.5% and 0.5 AEP +CC events.

10.10 In the 0.1% AEP event there is some minimal out of bank flooding on Kenneth's Black Well (Diagram 26). However the magnitude of flooding is reduced significantly from the baseline results.

10.11 The properties on Kenneth's Black Well and those on the downstream side of the existing A96, which were at risk as a result of out of bank flooding from Kenneth's Black Well in the baseline scenario, are no longer flooding. In addition the proposed Scheme is not at risk.

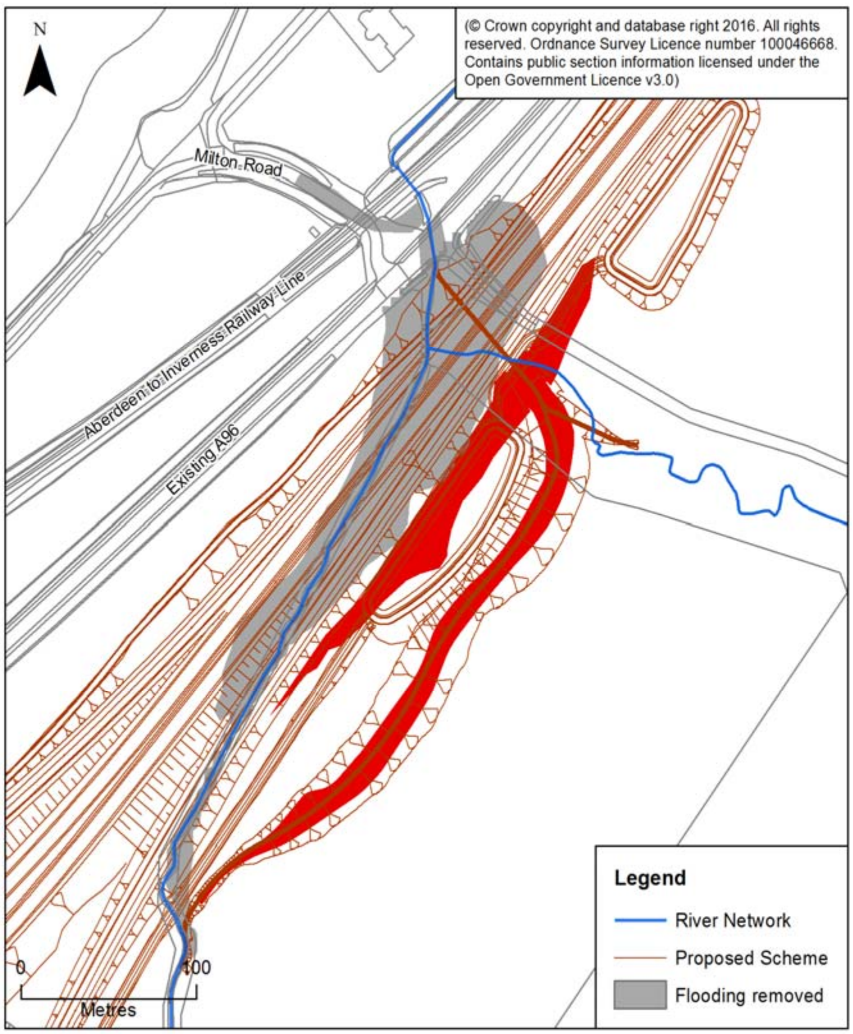
10.12 Where the bypass channel outfalls to Kenneth's Black Well, there is an increase of in-channel flow, due to water which had previously been flowing across the flood plain, being added to Kenneth's Black Well. However it is seen that there is no increase in modelled maximum water level on Kenneth's

Black Well. This is because of the effect of the high capacity re-aligned channel, which improves the hydraulic performance of the lower reach and reduces maximum water level at the cross sections adjacent to the bypass outfall, which are retained as per the existing situation.

10.13 There is an increase in flow from Kenneth's Black Well into Cairnlaw Burn as a result of the mitigation. However, due to the throttling of the proposed Scheme culvert on Cairnlaw Burn, significant increases in maximum water level are not seen in the downstream sections of Cairnlaw Burn. In the 0.5% AEP event there is an increase in maximum water level of 16mm downstream of the Kenneth's Black Well confluence. However peak water level remains in channel and there is no increased flood risk to properties. In the 0.5% AEP +CC event there is a reduction in maximum water level on the downstream section of Cairnlaw Burn. This is due to the impact of the culvert throttling in place on Cairnlaw Burn.

10.14 The 'with-mitigation' in-channel maximum water levels at key locations for all modelled events are shown in Section A.1 (Maximum Water Level Tables and Long Sections).

Diagram 25: Cairnlaw Burn 'With-Mitigation' Depth Difference



Potential flood impact							
	Increase in peak flood level 0.5% AEP (200-year) > 100 mm		Increase in peak flood level 0.5% AEP (200-year) 10 - 50mm		Reduction in peak flood level 0.5% AEP (200-year) 10 - 50mm		Reduction in peak flood level 0.5% AEP (200-year) >100mm
	Increase in peak flood level 0.5% AEP (200-year) 50 - 100 mm		Negligible change in peak flood level 0.5% AEP (200-year) <+/- 10 mm		Reduction in peak flood level 0.5% AEP (200-year) 50 - 100mm		

Diagram 26: Kenneth's Black Well, 0.1% AEP Event 'With-Scheme' Maximum Flood Depths

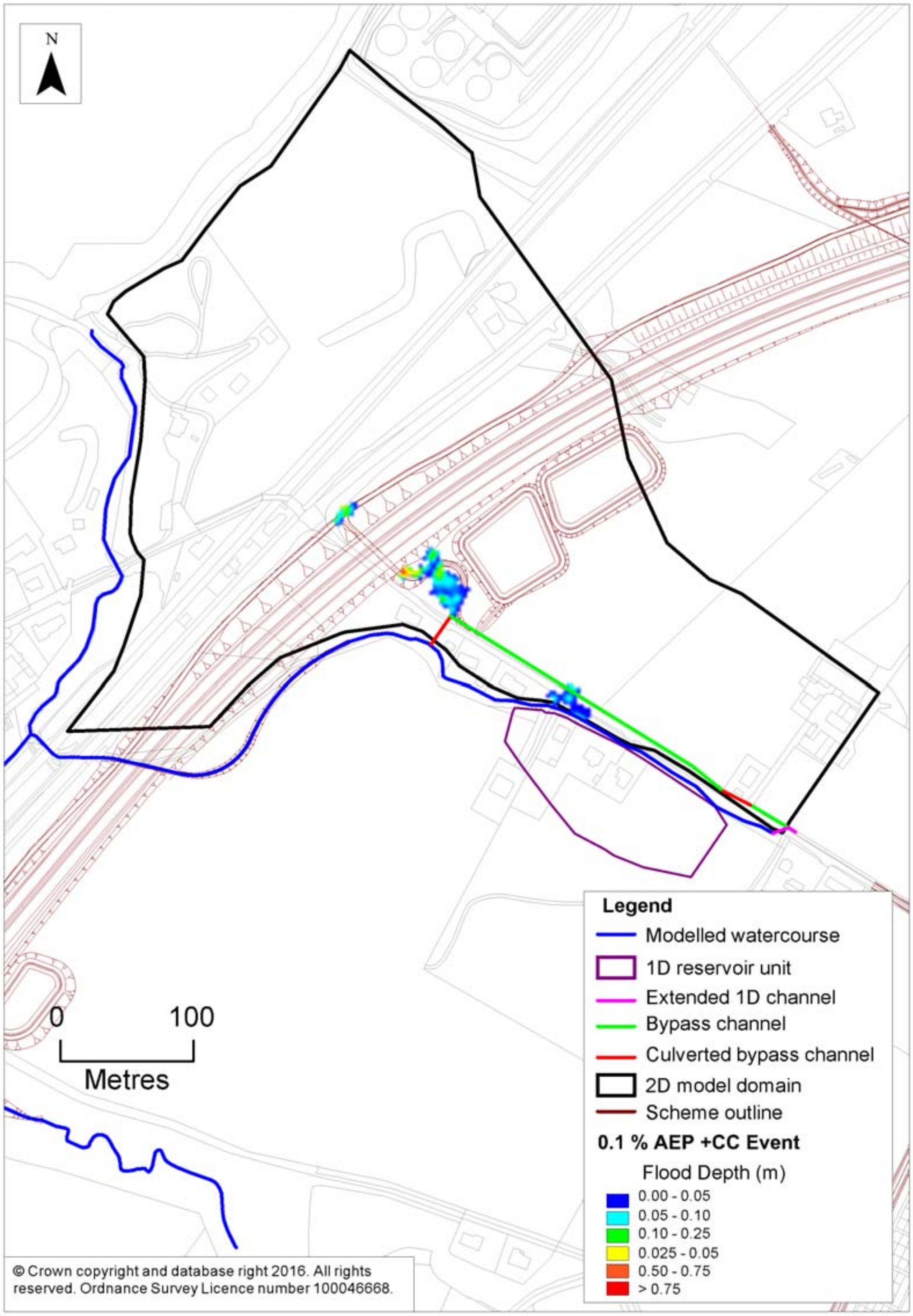


Table 16: In-channel maximum water level at key locations for the 0.5% AEP Event

Model node	Description	Baseline water level (mAOD)	'With-mitigation' water level (mAOD)	Change in water level (m)
CLBN_1353	Cairnlaw Burn. 167m upstream of C1032 Barn Church Road	15.194	15.195	0.001
CLBN_1223	Immediately upstream of the proposed Scheme at C1032 Barn Church Road	14.499	14.521	0.022
CLBN_1185	Cairnlaw Burn. Upstream of C1032 Barn Church Road	14.153	-	-
CLBN_1163	Cairnlaw Burn. Downstream of C1032 Barn Church Road	13.840	-	-
CLBN_1045	Cairnlaw Burn. 118m Downstream of C1032 Barn Church Road	12.305	12.641	0.336
CLBN_0705	Cairnlaw Burn. 115m upstream of existing A96 twin culvert	9.121	-	-
CLBN_0589	Cairnlaw Burn. Upstream of existing A96 twin culvert	9.112	9.088	-0.024
CLBN_0528	Cairnlaw Burn. Downstream of Aberdeen to Inverness Railway Line crossing	7.378	7.364	-0.014
CLBN_0332	Cairnlaw Burn. Downstream of Kenneth's Black Well confluence	6.087	6.104	0.017
CLBN_0000	Cairnlaw Burn. Downstream extent of model	2.404	2.409	0.005
CLT1_0115d	Tributary 1. 115m upstream of Cairnlaw Burn confluence	16.518	16.519	0.001
CLT2_0136d	Tributary 2. 136m upstream of Cairnlaw Burn confluence	10.956	11.041	0.085
CLT2_0044	Tributary 2. 44m upstream of Cairnlaw Burn confluence	9.117	-	-
CLT3_0291	Kenneth's Black Well. 240m upstream of existing A96 crossing	14.019	13.987	-0.032
CLT3_0135	Kenneth's Black Well. 88m upstream of existing A96 crossing	12.174	-	-
CLT3_0013	Kenneth's Black Well. Downstream of existing A96 crossing	7.572	7.667	0.095

Table 17: In-Channel Maximum Water Level at Key Locations for the 0.5% AEP +CC Event

Model Node	Description	Baseline Water Level (mAOD)	With-Mitigation Water Level (mAOD)	Change in Water Level (m)
CLBN_1353	Cairnlaw Burn. 167m upstream of C1032 Barn Church Road	15.221	15.221	0.000
CLBN_1223	Immediately upstream of the proposed Scheme at C1032 Barn Church Road	14.572	14.616	0.044
CLBN_1185	Cairnlaw Burn. Upstream of C1032 Barn Church Road	14.280	-	-
CLBN_1163	Cairnlaw Burn. Downstream of C1032 Barn Church Road	13.901	-	-
CLBN_1045	Cairnlaw Burn. 118m Downstream of C1032 Barn Church Road	12.384	12.752	0.368
CLBN_0705	Cairnlaw Burn. 115m upstream of existing A96 twin culvert	9.241	-	-
CLBN_0589	Cairnlaw Burn. Upstream of existing A96 twin culvert	9.232	9.157	-0.075
CLBN_0528	Cairnlaw Burn. Downstream of Aberdeen to Inverness Railway Line crossing	7.471	7.412	-0.059
CLBN_0332	Cairnlaw Burn. Downstream of Kenneth's Black Well confluence	6.187	6.170	-0.017
CLBN_0000	Cairnlaw Burn. Downstream extent of model	2.550	2.543	-0.007
CLT1_0115d	Tributary 1. 115m upstream of Cairnlaw Burn confluence	16.573	16.574	0.001
CLT2_0136d	Tributary 2. 136m upstream of Cairnlaw Burn confluence	10.977	11.453	0.476
CLT2_0044	Tributary 2. 44m upstream of Cairnlaw Burn confluence	9.237	-	-
CLT3_0291	Kenneth's Black Well. 240m upstream of existing A96 crossing	14.077	14.083	0.006
CLT3_0135	Kenneth's Black Well. 88m upstream of existing A96 crossing	12.200	-	-
CLT3_0013	Kenneth's Black Well. Downstream of existing A96 crossing	7.681	7.856	0.175

Blockage of the Proposed Scheme Culverts

10.15 In order to assess the impact of the proposed Scheme culverts becoming obstructed, blockage sensitivity scenarios were modelled for the 'with-mitigation' situation for the 0.5% AEP +CC event. The scenarios consisted of a 50% and 90% blockage. Only the new culverts, SWF03-4 (C04) and SWF06-1 (C05), were blocked in these scenarios (Diagram 5). No blockage was applied to SWF03-1 (C03) as this is an extension of an existing culvert.

10.16 Scenarios where run with alternate culverts blocked:

- SWF03-4 (C04) blocked at 50% and 90% with SWF06-1 (C05) not blocked
- SWF06-1 (C05) blocked at 50% and 90% with SWF03-4 (C04) not blocked

10.17 Blocking culvert SWF03-4 (C04) by 50% causes an increase in water level of 1.036m upstream of the culvert. The increase extends to 440m upstream of the culvert on Cairnalw Burn and 98m upstream on Tributary 2. There is no increase on Kenneth's Black Well.

10.18 Blocking culvert SWF03-4 (C04) by 90% causes an increase in water level of 1.426m upstream of the culvert. The increase extends to 520m upstream of the culvert on Cairnalw Burn and 117m upstream on Tributary 2. There is also an increase in water level of 0.982m on Kenneth's Black Well as the water backing up from SWF03-4 (C04) bypasses the blockage. This increase extends 99m upstream on Kenneth's Black Well.

10.19 Blocking culvert SWF06-1 (C05) by 50% causes an increase in water level of 0.097m upstream of the culvert. The increase extends to 99m upstream of the culvert on Kenneth's Black Well. There is no increase on Cairnlaw Burn.

10.20 Blocking culvert SWF06-1 (C05) by 90% causes an increase in water level of 0.798m upstream of the culvert. The increase extends to 129m upstream of the culvert on Kenneth's Black Well. There is also an increase in water level of 0.983m on Cairnlaw Burn as the water backing up from SWF06-1 (C05) bypasses the blockage. This increase extends 520m upstream on Cairnlaw Burn. There is an increase in water level up to 88m from the confluence on Tributary 2 as a result of blocking culvert SWF06-1 (C05).

11 Model Assumptions and Limitations

Introduction

11.1 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.

11.2 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 and are therefore appropriate for the flood risk assessment.

11.3 The following sections summarise the key sources of uncertainty in addition to the limitations associated with the modelling undertaken for Cairnlaw Burn and its tributaries.

1D Domain

Cross sections

11.4 Three surveyed cross sections, in the 1D part of the model, have been extended using photogrammetry data.

11.5 For the realignment channels and the bypass channel, a basic cross section form has been used as per the supplied design drawing. Bed levels are based on a linear drop in gradient between the existing channel sections. Bank levels for the realignment are based on the MXROAD ASCII and the 2014 photogrammetry data.

11.6 For the flow onto Milton Road, cross sections have been extracted from the 2014 photogrammetry data and the Aberdeen to Inverness Railway Line crossing bridge dimensions have been estimated using Google Street View, for the baseline model. As the 'with-mitigation' model removes any overtopping into this area, the level of detail in the baseline model is considered appropriate and more detail is not required.

Channel Roughness

11.7 Channel roughness has been assigned using the best available information (site visit, survey data and aerial photographs). The roughness values used are based on available guidance (Chow 1959).

11.8 The realignment channels are assumed to be less heavily vegetated than the existing reaches, the adopted channel roughness is subsequently lower than the existing channels.

Representation of Structures

11.9 Hydraulic coefficients for structures have been applied using available guidance within the Flood Modeller software. The dimensions for structures have been based on detailed survey measurements.

11.10 The dimensions and roughness values for the culvert extensions match the existing situation. The new culverts are rectangular culverts with square headwalls. Roughness values for the culvert invert match the channel bed roughness. Where culverts are used to create a throttle there is no allowance for freeboard or mammal crossing within the culvert.

Downstream Boundary Conditions

11.11 A mean spring tide curve from Inverness has been used for all model runs, with an uplift applied in the climate change simulation using the appropriate guidance. The sensitivity analysis has shown that changes to the downstream boundary only impact on water levels up to 140m upstream of the downstream model extent. Therefore it was deemed appropriate to use the same downstream boundary for each modelled event.

2D Domain

Flood Plain Topography

11.12 The photogrammetry data is considered to appropriately represent the flood plain. A good match has been seen between banktop levels in the surveyed cross sections and photogrammetry.

11.13 For the 'with-scheme' and 'with-mitigation situation drainage ponds are assumed to be full at the start of the simulation.

Flood Plain Structures

11.14 A review of the flood plain using available aerial and road level photography, OS mapping and site inspection has shown that there are no flood plain structures that require representation in the model.

Grid Size

11.15 A 5m grid has been used. This is deemed suitable to represent flood plain features to an appropriate level of detail.

DTM Modifications

11.16 No modifications were made to the DTM in the baseline model. Site inspection and a check of aerial photographs established that no other breaklines were required.

11.17 For the 'with-scheme' and 'with-mitigation situation, the existing ground levels were modified within the proposed Scheme footprint from the MXROAD software.

Model calibration

11.18 No calibration was carried out as the Cairnlaw catchment is ungauged

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12 Conclusion

12.1 This report has detailed the modelling carried out to assess the baseline flood risk for Cairnlaw Burn and its tributaries with reference to the DMRB Stage 3 design of the proposed Scheme.

12.2 The results of the baseline modelling have shown that for Cairnlaw Burn, Tributary 1 and Tributary 2 there are no properties at risk of flooding. There is a risk of flooding to some properties on the left bank of Kenneth's Black Well. Flooding from Kenneth's Black Well also causes a risk of flooding to properties on the downstream side of the existing A96.

12.3 The 'with-scheme' situation was modelled by adding two sections of realignment, extending an existing culvert and adding two new culverts. Results of the 'with-scheme' model showed an increased flood risk to the existing A96 and Milton Road. In addition a shared use underpass which forms part of the proposed Scheme was at risk of flooding from Kenneth's Black Well. Therefore a 'with-mitigation' scenario was modelled.

12.4 The 'with-mitigation' scenario reduced the size of the proposed Scheme culvert on Cairnlaw Burn and added a bypass channel on Kenneth's Black Well. The 'with-mitigation' model reduces the risk of flooding to the existing A96, compared to the baseline, and removes the flood risk to Milton Road. The bypass channel on Kenneth's Black Well prevents any out of bank flooding in this area for events up to an including the 0.5% AEP +CC. This removes the pre-existing flood risk for properties adjacent to Kenneth's Black Well and on the downstream side of the existing A96.

13 References

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A.1 Maximum Water Level Tables and Long Sections

	Baseline Maximum Water Levels (mAOD)															
Modelled Event	**Model Node**															
	CLBN_1353 (Cairnlaw Burn. 167m upstream of C1032 Barn Church Road)	CLBN_1223 (Cairnlaw Burn Immediately upstream of the proposed Scheme at C1032 Barn Church Road)	CLBN_1185 (Cairnlaw Burn. Upstream of C1032 Barn Church Road)	CLBN_1163 (Cairnlaw Burn. Downstream of C1032 Barn Church Road)	CLBN_1045 (Cairnlaw Burn. 118m Downstream of C1032 Barn Church Road)	CLBN_0705 (Cairnlaw Burn. 115m upstream of existing A96 twin culvert)	CLBN_0589 (Cairnlaw Burn. Upstream of existing A96 twin culvert)	CLBN_0528 (Cairnlaw Burn. Downstream of Aberdeen to Inverness Railway Line crossing)	CLBN_0332 (Cairnlaw Burn. Downstream of Kenneth's Black Well confluence)	CLBN_0000 (Cairnlaw Burn. Downstream extent of model)	CLT1_0115d (Tributary 1. 115m upstream of Cairnlaw Burn confluence)	CLT2_0136d (Tributary 2. 136m upstream of Cairnlaw Burn confluence)	CLT2_0044 (Tributary 2. 44m upstream of Cairnlaw Burn confluence)	CLT3_0291 (Kenneth's Black Well. 240m upstream of existing A96 crossing)	CLT3_0135 (Kenneth's Black Well. 88m upstream of existing A96 crossing)	CLT3_0013 (Kenneth's Black Well. Downstream of existing A96 crossing)
50% AEP Event	14.974	14.199	13.655	13.508	11.909	8.047	7.246	6.919	5.607	2.356	16.217	10.839	8.248	13.499	11.741	6.755
20% AEP Event	15.041	14.268	13.762	13.582	11.987	8.162	7.461	7.029	5.726	2.361	16.281	10.858	8.271	13.620	11.878	6.923
10% AEP Event	15.089	14.306	13.843	13.633	12.039	8.210	7.667	7.100	5.806	2.366	16.321	10.870	8.283	13.698	11.963	7.038
3.33% AEP Event	15.120	14.368	13.923	13.705	12.126	8.303	8.106	7.211	5.922	2.377	16.389	10.897	8.306	13.817	12.076	7.224
2% AEP Event	15.140	14.397	13.979	13.741	12.169	8.433	8.353	7.255	5.965	2.383	16.421	10.909	8.374	13.871	12.115	7.311
1% AEP Event	15.170	14.445	14.061	13.788	12.235	8.752	8.732	7.308	6.025	2.393	16.467	10.931	8.740	13.947	12.144	7.441
0.5% AEP Event	15.194	14.499	14.153	13.840	12.305	9.121	9.112	7.378	6.087	2.404	16.518	10.956	9.117	14.019	12.174	7.572
0.5% AEP +CC Event	15.221	14.572	14.280	13.901	12.384	9.241	9.232	7.471	6.187	2.550	16.573	10.977	9.237	14.077	12.200	7.681
0.1% AEP Event	15.259	14.683	14.457	13.975	12.481	9.303	9.291	7.503	6.236	2.453	16.625	11.002	9.298	14.132	12.228	7.800

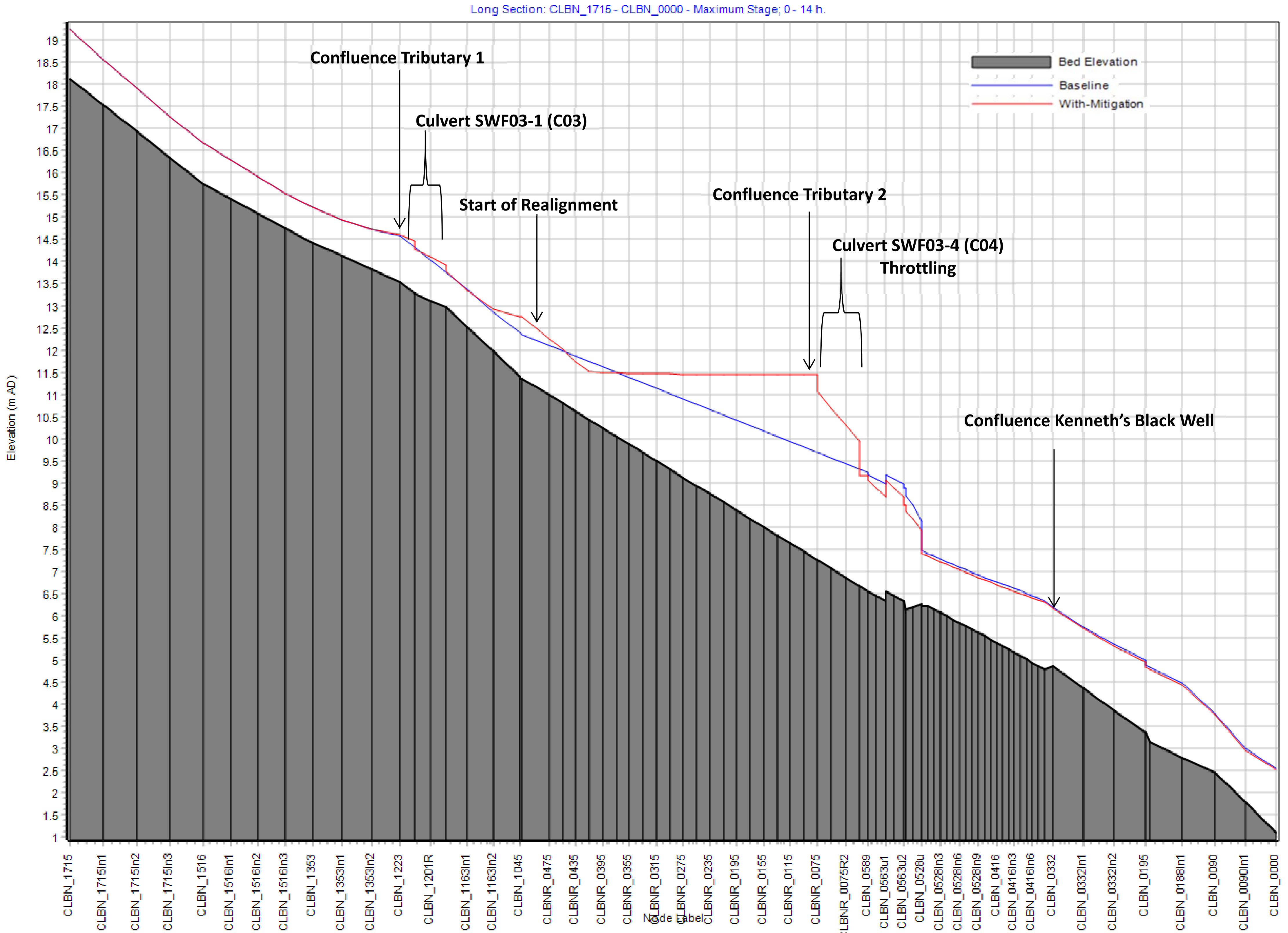
*at CLBN_0000 the climate change tidal peak is greater than the 0.1%AEP level.

	With-Mitigation Maximum Water Levels (mAOD))															
Modelled Event	**Model Node**															
	CLBN_1353 (Cairnlaw Burn. 167m upstream of C1032 Barn Church Road)	CLBN_1223 (Cairnlaw Burn Immediately upstream of the proposed Scheme at C1032 Barn Church Road)	CLBN_1185 (Cairnlaw Burn. Upstream of C1032 Barn Church Road)	CLBN_1163 (Cairnlaw Burn. Downstream of C1032 Barn Church Road)	CLBN_1045 (Cairnlaw Burn. 118m Downstream of C1032 Barn Church Road)	CLBN_0705 (Cairnlaw Burn. 115m upstream of existing A96 twin culvert)	CLBN_0589 (Cairnlaw Burn. Upstream of existing A96 twin culvert)	CLBN_0528 (Cairnlaw Burn. Downstream of Aberdeen to Inverness Railway Line crossing)	CLBN_0332 (Cairnlaw Burn. Downstream of Kenneth's Black Well confluence)	CLBN_0000 (Cairnlaw Burn. Downstream extent of model)	CLT1_0115d (Tributary 1. 115m upstream of Cairnlaw Burn confluence)	CLT2_0136d (Tributary 2. 136m upstream of Cairnlaw Burn confluence)	CLT2_0044 (Tributary 2. 44m upstream of Cairnlaw Burn confluence)	CLT3_0291 (Kenneth's Black Well. 240m upstream of existing A96 crossing)	CLT3_0135 (Kenneth's Black Well. 88m upstream of existing A96 crossing)	CLT3_0013 (Kenneth's Black Well. Downstream of existing A96 crossing)
3.33% AEP Event	15.120	14.374			12.339		8.118	7.213	5.935	2.379	16.390	10.874		13.775		7.268
0.5% AEP Event	15.195	14.521			12.641		9.088	7.364	6.104	2.409	16.519	11.041		13.987		7.667
0.5% AEP +CC Event	15.221	14.616			12.752		9.157	7.412	6.170	2.543	16.574	11.453		14.083		7.856
0.1% AEP Event	15.259	14.758			12.883		9.209	7.456	6.254	2.446	16.626	12.039		14.200		8.089

*at CLBN_0000 the climate change tidal peak is greater than the 0.1%AEP level

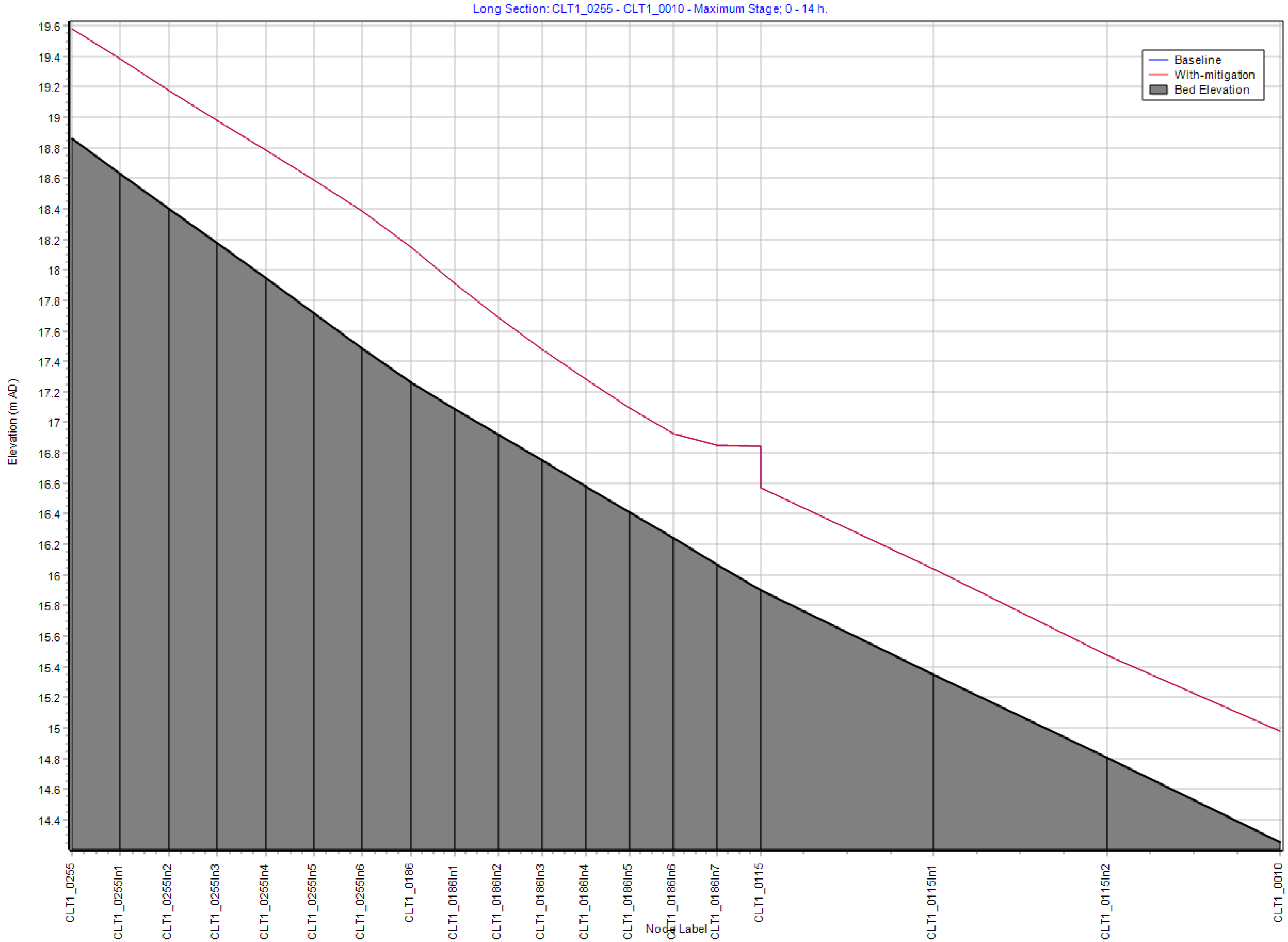
	Change in Water Level (m)															
Modelled Event	**Model Node**															
	CLBN_1353 (Cairnlaw Burn. 167m upstream of C1032 Barn Church Road)	CLBN_1223 (Cairnlaw Burn Immediately upstream of the proposed Scheme at C1032 Barn Church Road)	CLBN_1185 (Cairnlaw Burn. Upstream of C1032 Barn Church Road)	CLBN_1163 (Cairnlaw Burn. Downstream of C1032 Barn Church Road)	CLBN_1045 (Cairnlaw Burn. 118m Downstream of C1032 Barn Church Road)	CLBN_0705 (Cairnlaw Burn. 115m upstream of existing A96 twin culvert)	CLBN_0589 (Cairnlaw Burn. Upstream of existing A96 twin culvert)	CLBN_0528 (Cairnlaw Burn. Downstream of Aberdeen to Inverness Railway Line crossing)	CLBN_0332 (Cairnlaw Burn. Downstream of Kenneth's Black Well confluence)	CLBN_0000 (Cairnlaw Burn. Downstream extent of model)	CLT1_0115d (Tributary 1. 115m upstream of Cairnlaw Burn confluence)	CLT2_0136d (Tributary 2. 136m upstream of Cairnlaw Burn confluence)	CLT2_0044 (Tributary 2. 44m upstream of Cairnlaw Burn confluence)	CLT3_0291 (Kenneth's Black Well. 240m upstream of existing A96 crossing)	CLT3_0135 (Kenneth's Black Well. 88m upstream of existing A96 crossing)	CLT3_0013 (Kenneth's Black Well. Downstream of existing A96 crossing)
3.33% AEP Event	0.000	0.006			0.213		0.012	0.002	0.013	0.002	0.001	-0.023		-0.042		0.044
0.5% AEP Event	0.001	0.022			0.336		-0.024	-0.014	0.017	0.005	0.001	0.085		-0.032		0.095
0.5% AEP +CC Event	0.000	0.044			0.368		-0.075	-0.059	-0.017	-0.007	0.001	0.476		0.006		0.175
0.1% AEP Event	0.000	0.075			0.402		-0.082	-0.047	0.018	-0.007	0.001	1.037		0.068		0.289

Diagram A1: Cairnlaw Burn Long Section, 0.5%AEP +CC, In-Channel Peak Water Levels



NOTE: There are no baseline model nodes within the realignment section. The baseline water level shown for the realignment section is an interpolation between the upstream and downstream of the section and comparison to the 'with-mitigation' water level is not relevant at these sections.

Diagram A2: Tributary 1 Long Section, 0.5%AEP +CC, In-Channel Peak Water Levels



NOTE: The proposed Scheme does not change water levels on Tributary 1, therefore no differences are seen on the plot above

Diagram A3: Tributary 2 Long Section, 0.5%AEP +CC, In-Channel Peak Water Levels

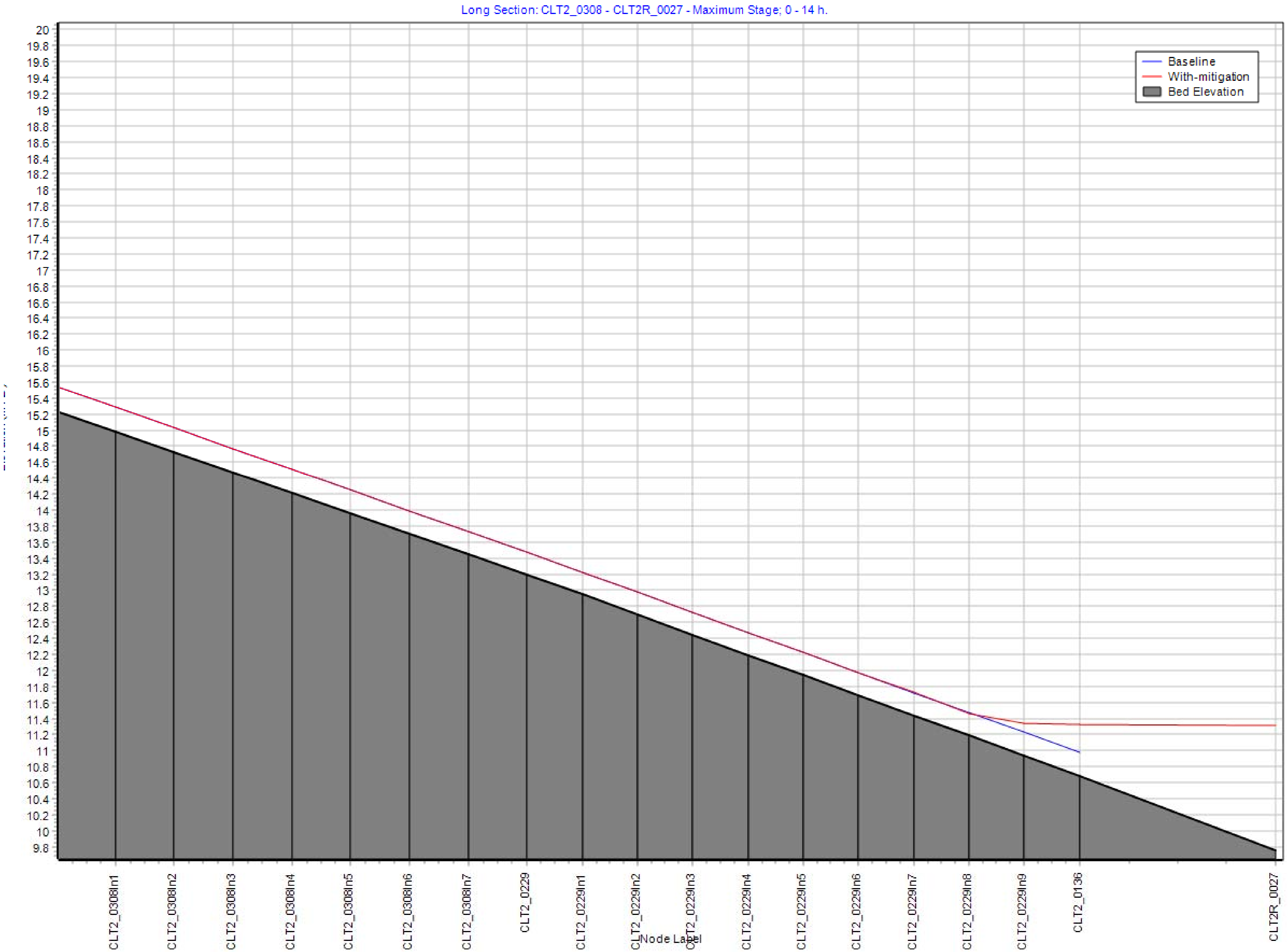
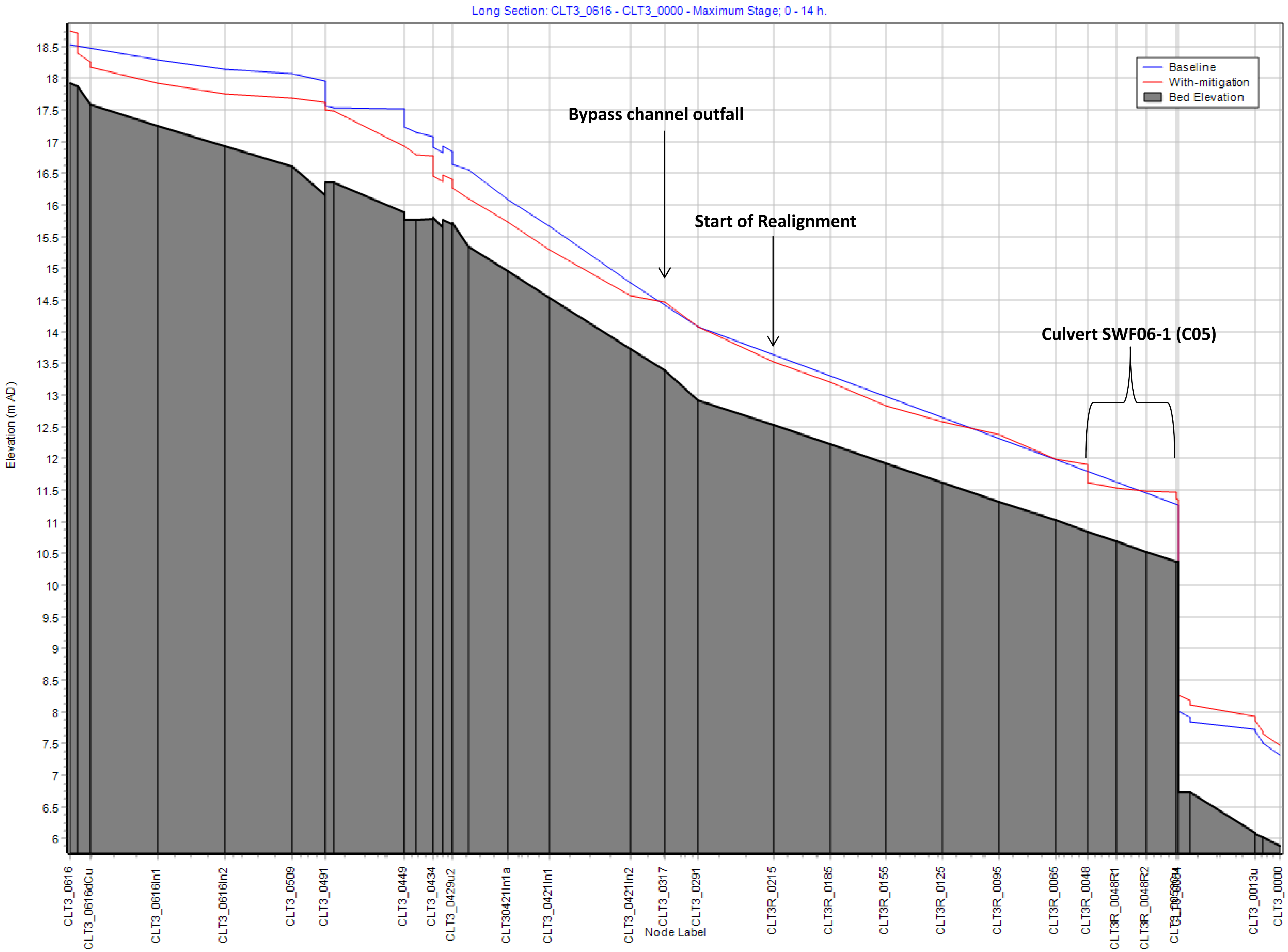


Diagram A4: Kenneth's Black Well Long Section, 0.5%AEP +CC, In-Channel Peak Water Levels



NOTE: There are no baseline model nodes within the realignment section. The baseline water level shown for the realignment section is an interpolation between the upstream and downstream of the section and comparison to the 'with-mitigation' water level is not relevant at these sections.

A.2 Flood Extent Maps (2D domain only)

Diagram A5: Baseline 2D Flood Extent. 3.33%, 2% and 1% AEP Events

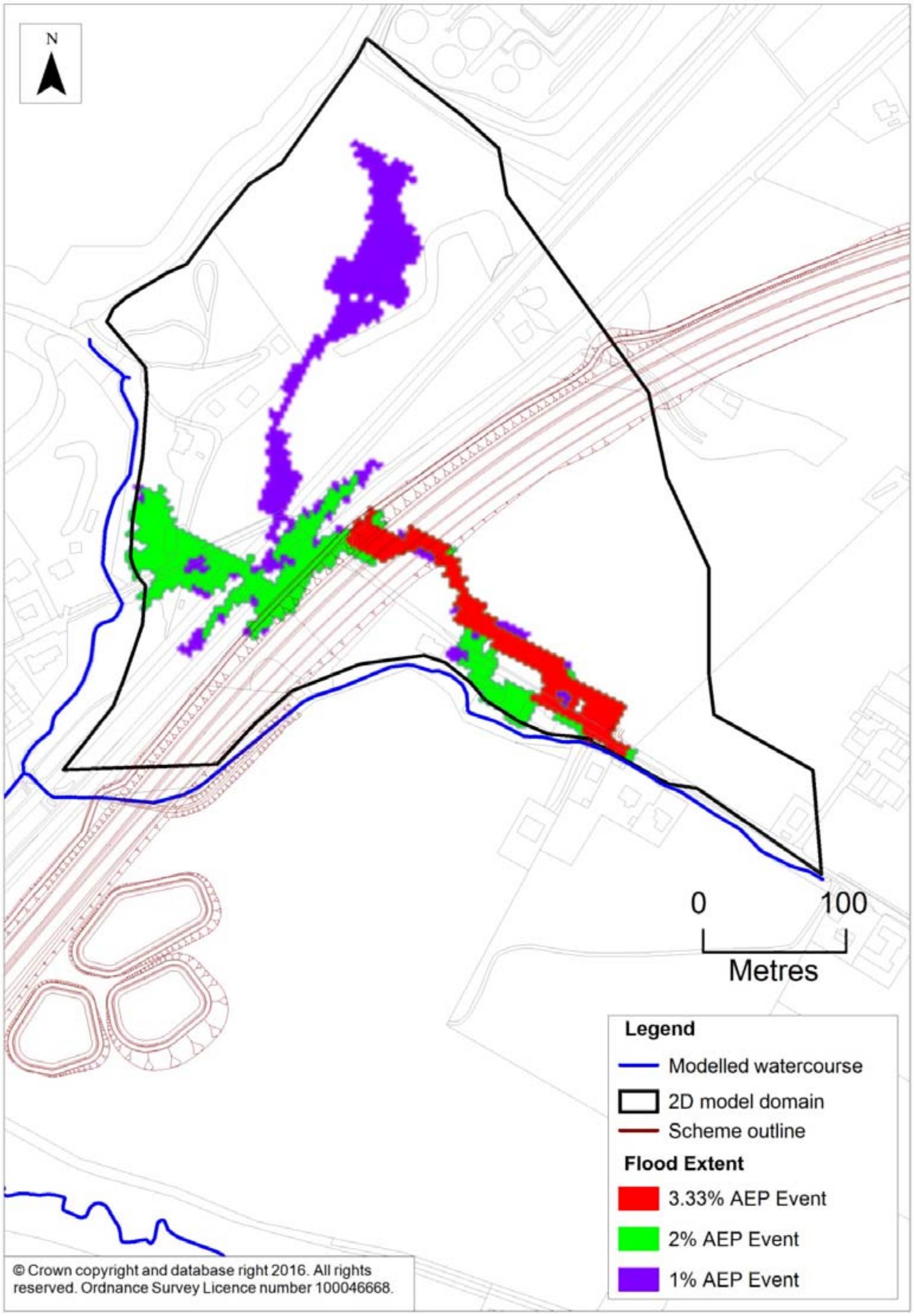
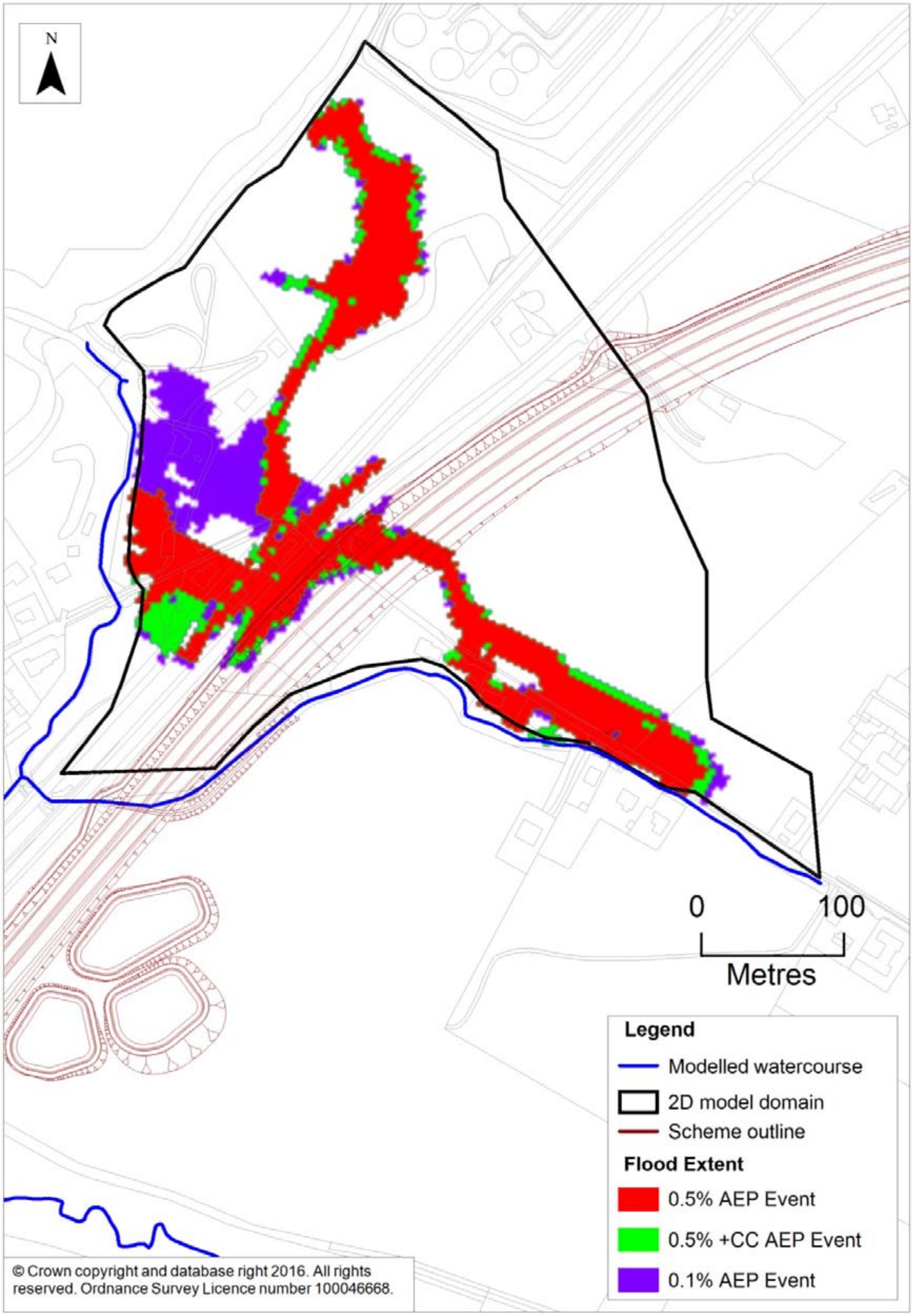


Diagram A6: Baseline 2D Flood Extent. 0.5%, 0.5% +CC and 0.1% AEP Events



A13.2.C Rough Burn Hydraulic Modelling Report

1 Introduction

Purpose

1.1 This annex provides detailed information on the hydraulic modelling relevant to Appendix 13.2 (Flood Risk Assessment).

1.2 The A96 Dualling Inverness to Nairn (including Nairn Bypass) scheme comprises the provision of approximately 31km of new dual carriageway, achieved through offline construction (hereafter referred to as the proposed Scheme). The existing A96 single carriageway would be de-trunked and reclassified as a local road to maintain local access. Due to the size and layout of the proposed Scheme, there are a number of flood risks, which may place the road and its users at risk of flooding. The proposed Scheme also has the potential to impact the level of flood risk elsewhere.

1.3 The proposed Scheme starts east of the roundabout for Inverness Retail Park, approximately 850m east of Raigmore Interchange, and continues approximately 30km east and ends at Hardmuir, 3.5km to the east of Auldearn. The proposed Scheme would incorporate:

- 22 watercourse crossings;
- provision of shared use paths suitable for Non-Motorised Users (NMU), approximately 30km in length;
- six grade separated junctions;
- 24 principal structures including a crossing of the River Nairn and three structures over the Aberdeen to Inverness Railway Line;
- local road diversions and provision of new private means of access; and
- utility diversions including major diversions for Scottish Gas Networks (SGN) and CLH Pipeline Systems (CLH-PS).

1.4 For key watercourse crossings a Flood Risk Assessment (FRA) was required to meet relevant local and national planning legislation and inform the design and planning process. Hydraulic modelling was required to support the FRA. This took the form of computational hydraulic models with associated catchment hydrology. The impact of the proposed Scheme on water level both upstream and downstream and the associated flood envelope was determined for a range of storm flood events at each watercourse crossing.

1.5 The key watercourse crossings for which a hydraulic modelling was carried out to support the FRA are:

- Cairnlaw Burn crossing (Annex 13.2.B Cairnlaw Burn Hydraulic Modelling Report);
- Rough Burn crossing (this report);
- Tributary of Ardersier Burn crossing (Annex D Tributary Of Ardersier Burn Hydraulic Modelling Report);
- River Nairn crossing (Annex 13.2.E River Nairn Hydraulic Modelling Report); and
- Auldearn Burn crossing (Annex 13.2.F Auldearn Burn Hydraulic Modelling Report).

1.6 This report details the methodology and the results of the hydraulic modelling carried out for the Rough Burn crossing, for the baseline and 'with-scheme' situation. This is a technical report, focused on the hydraulic modelling, and therefore the intended audience is those with a reasonable understanding and knowledge of hydraulic modelling principles, although no specific knowledge of particular software is needed.

Methodology

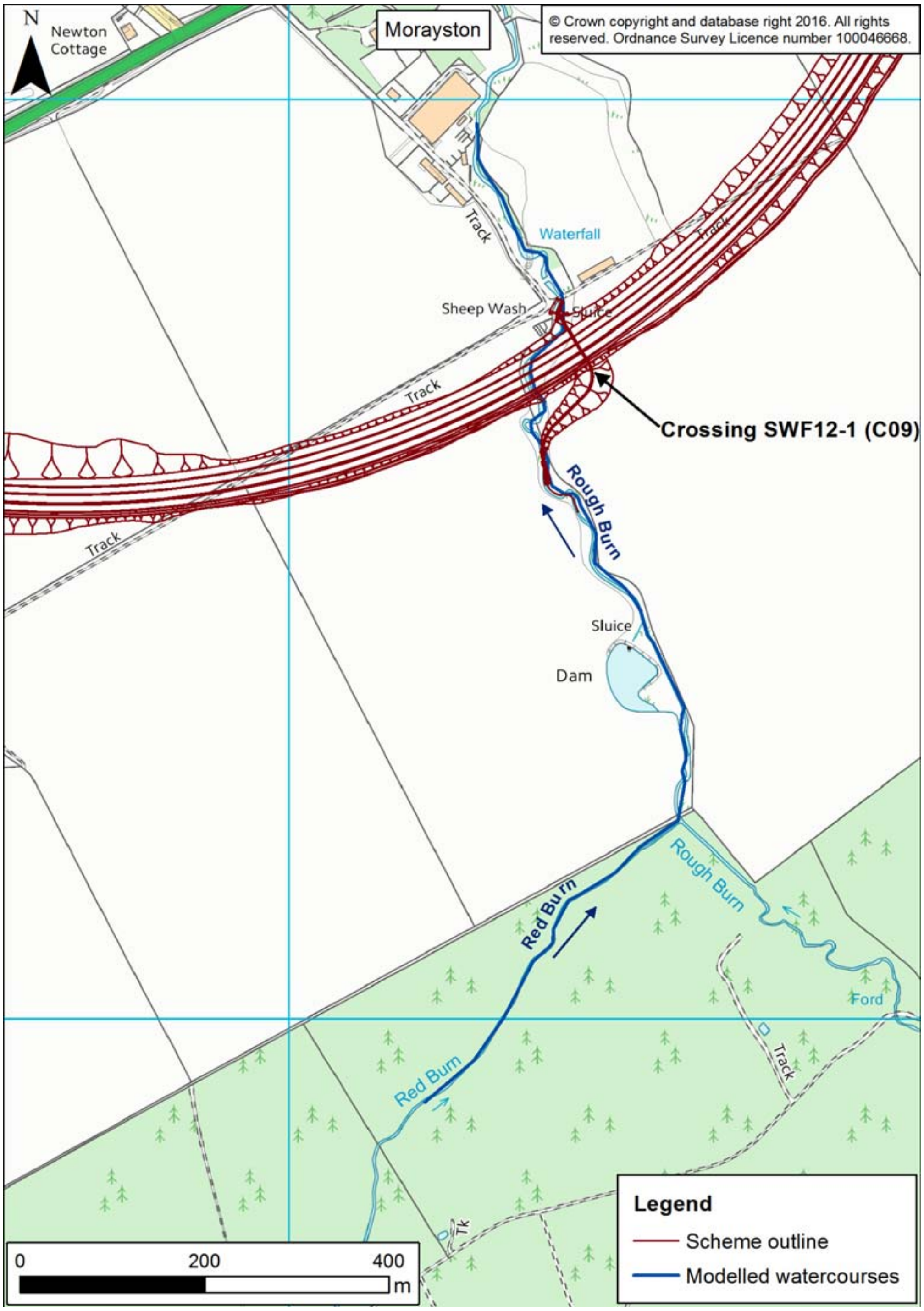
1.7 The hydraulic model was built using a linked One-dimensional/Two-dimensional (1D/2D) schematisation, where the river channel is represented as a 1D component and is linked to the flood plain, which is represented by a 2D domain. The 1D component was constructed using the river modelling package Flood Modeller Pro (version 4.1), and the 2D component was constructed using TUFLOW (version 2013-12-AE-iSP-w64).

Study Area

1.8 The proposed Scheme crosses the Rough Burn watercourse about 3km south of Inverness Airport. The new crossing for the proposed Scheme within the Rough Burn study has been named SWF12-1 (C09).

1.9 The 1D model covers a 514m reach of Red Burn and 842m reach of Rough Burn (see Diagram 1). The 2D model extends from High Wood area to the hamlet of Morayston and covers an area of approximately 0.5km^2 (see Diagram 1).

Diagram 1: Rough Burn Study Area



2 Input Data

2.1 The data used to construct the hydraulic model for Rough Burn are summarised in Table 1.

Table 1: Data Used to Build the Hydraulic Model

Data	Description	Source
Photogrammetry/ LiDAR	2014 composite DTM: Car-based LiDAR data for existing A96 carriageway 10m horizontal resolution photogrammetry data See A96 Geodetic Survey Report_v1_0.pdf Used to represent the topography for the downstream model extent. See Section 4 (Flood Plain Schematisation - 2D domain)	Blom Aerofilms
Photogrammetry	2009 2m horizontal resolution photogrammetry data. Used to represent the topography for the upstream model extent. See Section 4 (Flood Plain Schematisation - 2D domain)	Getmapping
Proposed Scheme topography	MXROAD ASCII grids	Jacobs 2016
OS maps	Mastermap data 1 to 10,000 Scale Raster	Transport Scotland
Channel survey	In-channel cross sections and hydraulic structures See Sections 4 (Flood Plain Schematisation - 1D domain)	Jacobs Site survey 2015/2016
Watercourse photographs	Site visit – in-channel watercourse photographs	Jacobs Site survey 2015 Site inspection 2015
Hydrological analysis	Hydrological analysis carried out for Rough Burn See Section 3 (Hydrology).	Jacobs 2016

3 Hydrology

3.1 The details of the analysis carried out to produce inflows for the hydraulic model are provided in a separate hydrology report (Annex 13.2.G (Surface Water Hydrology Report)), which was undertaken for the DMRB Stage 3 assessment.

3.2 Three inflows have been applied at the boundaries of the 1D domain (see locations in Diagram 2):

- at the upstream extent of Red Burn;
- at the upstream extent of Rough Burn; and
- a lateral inflow in Rough Burn from the confluence with Red Burn to upstream of the proposed Scheme location.

3.3 The peak inflows have been estimated for the 50%, 20%, 10%, 3.33%, 2%, 1%, 0.5% and 0.1% Annual Exceedance Probability (AEP) flood events.

3.4 The peak inflows were produced using the Flood Estimation Handbook (FEH) statistical method. The hydrograph shape was derived from the FEH rainfall-runoff model hydrograph shapes. These hydrographs used a theoretical critical storm duration of 7.4 hours calculated at the downstream extent of the hydrology model.

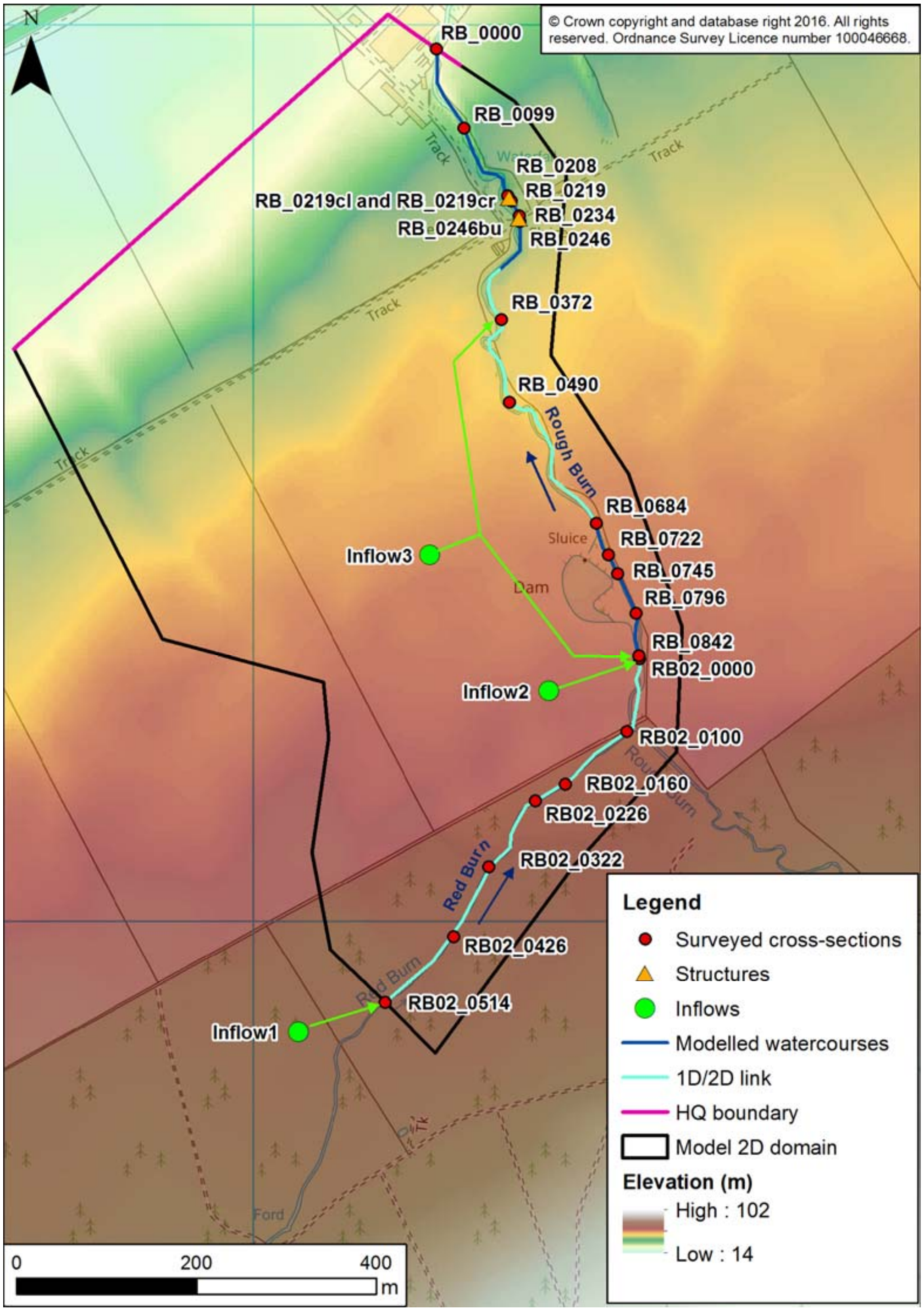
3.5 In order to assess the impact of Climate Change (CC), a 20% uplift of the hydrological inflows was applied on the 0.5% AEP event. This climate change uplift factor is based on current standard practice (SEPA 2015).

3.6 Peak inflows of the modelled watercourses are shown in Table 2 for all the events simulated.

Table 2: Hydrological Inflow Peak Values and Locations

Location	Peak Flow (m^3/s)								
	AEP 50%	AEP 20%	AEP 10%	AEP 3.33%	AEP 2%	AEP 1%	AEP 0.5%	AEP 0.5% + CC	AEP 0.1%
Red Burn upstream model extent (Inflow 1)	1.21	1.70	2.07	2.75	3.12	3.70	4.38	5.26	6.47
Rough Burn upstream model extent (Inflow 2)	0.71	0.99	1.21	1.61	1.83	2.16	2.56	3.07	3.79
Rough Burn lateral inflow (Inflow 3)	0.27	0.38	0.46	0.61	0.69	0.82	0.97	1.17	1.44

Diagram 2: Rough Burn Model Schematisation



4 Baseline Modelling

Watercourse Schematisation - 1D Domain

In-Channel Geometry

4.1 Surveyed cross section data has been used to inform the in-channel geometry of the modelled watercourses. The location of the surveyed cross sections is shown in Diagram 2. To aid model performance, interpolated cross sections were added between the surveyed cross sections as required, with spacing from 100m to 10m.

4.2 Table 3 shows the Flood Modeller nodes associated with the modelled watercourses, Red Burn and Rough Burn.

Table 3: Flood Modeller Nodes

Reach	Upstream Node	Downstream Node
Red Burn	RB02_0514	RB02_0000
Rough Burn	RB_0842	RB_0000

4.3 Upstream of its confluence with Red Burn, Rough Burn is represented only as an inflow. It is felt that an explicit representation of Rough Burn upstream of the confluence is not required in the model on the basis that:

- The Rough Burn channel upstream of the confluence is steep and deeply incised and all flows will reach the confluence location without any flow split or storage. Therefore there is no flood risk to the scheme from Rough Burn u/s of the confluence.
- The backwater effect of the scheme does not reach the confluence, which is 500m upstream and has a bed level more than 12m above the bed level at the scheme.

In-Channel Hydraulic Friction

4.4 Hydraulic roughness (Manning's 'n' coefficient) values were determined primarily using the photographs taken during the survey. Generally, pebbles can be seen in the bed of Red Burn and rocks or rough bed rock is seen in the bed of Rough Burn. Their banks are covered by high grass, bushes or trees. The Manning's 'n' coefficients used in the model are shown in Table 4.

Table 4: Manning's 'n' Coefficients – 1D Domain

Watercourse	Flood Modeller Nodes	Bed Manning's 'n'	Bed Material	Banks Manning's 'n'	Banks Material
Red Burn	RB02_0514 to RB02_0100	0.04	Pebbles	0.07	Medium vegetation
Red Burn	RB02_0000	0.05	Rough bed rock	0.07	Medium vegetation
Rough Burn	RB_0842 to RB_0000	0.05	Boulders	0.07	Medium vegetation

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In-Channel Hydraulic Structures

4.5 Two hydraulic structures on Rough Burn were included in the model. Table 5 provides details regarding these structures. Their locations are shown in Diagram 2.

Table 5: In-Channel Hydraulic Structures

Watercourse	Structure	Flood Modeller Node	Specification	
Rough Burn	Access track bridge	RB_0246bu	**Type:** **Bed level:** **Width:** **Springing height:** **Crown height:**	Arch Bridge 40.306mAOD 2.910m 1.344m 0.515m
Rough Burn	Twin culverts under an access track	RB_0219cl and RB_0219cr	**Type:** **Left upstream bed level:** **Left downstream bed level:** **Right upstream bed level:** **Right downstream bed level:** **Length:** **Diameter:**	Parallel circular conduits 39.525mAOD 39.302mAOD 39.423mAOD 39.320mAOD 11.450m 0.900m

4.6 An embankment retaining a small pond is located on the left bank, 750m upstream of Morayston hamlet. As no active connection was found between Rough Burn and the dam during the site survey it has not been included in the model. This location is not flooding for any of the modelled events; it therefore has no significant impact on the model results.

Boundary Conditions – 1D Domain

4.7 The upstream and downstream boundary conditions applied to the 1D domain are described in Table 6. Inflow locations are shown in Diagram 2.

Table 6: Boundary Conditions – 1D Domain

Type of Boundary	Flood Modeller Node	Description
FEH Boundary	Inflow1	Scaled FEH inflow boundary was applied at the upstream end of Red Burn at node RB02_0514 (see Section 3 (Hydrology)).
FEH Boundary	Inflow2	Scaled FEH inflow boundary was applied at the upstream end of Rough Burn at node RB_0842 (see Section 3 (Hydrology)).
FEH Boundary	Inflow3	Scaled FEH lateral inflow boundary was distributed along Rough Burn between the nodes RB_0842 and RB_0372 (see Section 3 (Hydrology)).
Normal Depth Boundary	RB_0000	Normal depth boundary condition applied to the downstream end of Rough Burn at node RB_0000

Flood Plain Schematisation - 2D domain

Flood Plain Topography

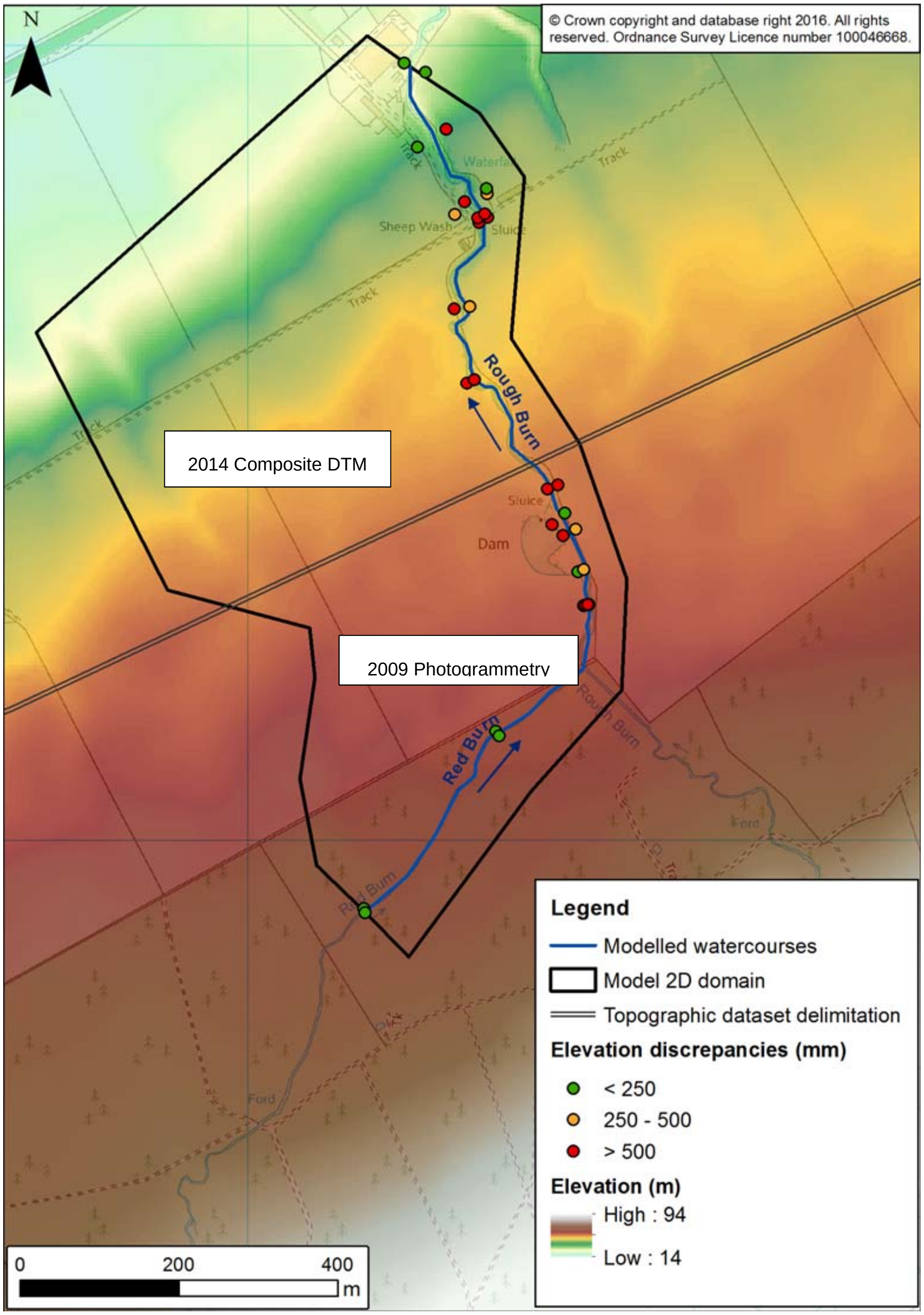
4.8 The 2D domain covers 0.5km^2 along Red Burn and Rough Burn. The topography is represented using a 5m resolution square grid. The levels for the grid cells are based on a Digital Terrain Model (DTM) derived from a composite of two datasets:

- 2014 composite DTM dataset (car-based LiDAR and photogrammetry data); and
- 2009 aerial photogrammetry dataset.

4.9 A review of the two datasets has indicated better vertical accuracy from the 2014 composite DTM for the Rough Burn model location. However this dataset does not cover the whole model extent. The 2009 photogrammetry dataset was therefore retained for the upper part of the model. Flood plain topography and the coverage of the two datasets are shown in Diagram 3 below.

4.10 Diagram 3 also shows the variance between the surveyed topographic data (used in the 1D domain) and the DTM (used in the 2D domain). A good match has been seen between banktop levels in the surveyed topographic data of Red Burn and 2009 photogrammetry dataset (green points on Diagram 3). Regarding Rough Burn, more significant discrepancies are observable, with DTM levels sitting above the surveyed grid. However it is thought that this is understandable as Rough Burn has irregular ground and runs on a steep slope. Also the Photogrammetry DTM is a smoothed grid based on source data of 10m resolution. For all the modelled events, channel overflow occurs from Red Burn where there is good confidence in the model arrangement, whilst all modelled water levels on Rough Burn remain in-channel and only receive return flows from flood plain. The compiled DTM is therefore deemed appropriate for the 2D model topography.

Diagram 3: Flood Plain Topography



Flood Plain Hydraulic Friction

4.11 Hydraulic roughness coefficients are applied over each grid cell of the 2D domain, as shown in Table 7, depending on land use taken from OS Mastermap data.

Table 7: Manning's 'n' Coefficients – 2D Domain

Land use	Manning's n
Roads, tracks and paths	0.025
Rail	0.050
Buildings, manmade structures	1.000
Land, trees, rough grassland	0.100
Land, cliff	0.050
Land, slope, manmade	0.050
Open land, general surface	0.050
Land, multi surface	0.055
Water, inland water	0.020

Boundary Conditions – 2D Domain

4.12 No inflow has been applied directly in the 2D domain. Table 8 describes the downstream boundary condition used in the 2D domain. Its location is shown in Diagram 2.

Table 8: Boundary Conditions - 2D Domain

Type of Boundary	TUFLOW Feature	Description
Stage-Discharge	HQ Boundary	Free flow boundary applied at the downstream extent of the model. This boundary assigns a water level to the 2D cells based on a stage–discharge curve generated using the ground slope.

1D/2D Linking

4.13 The link between the 1D and the 2D domains was defined along sections of Rough Burn and Red Burn using the combined DTM data. The location of the 1D/2D link is shown in Diagram 2.

5 'With-Scheme' Modelling

Scheme Arrangement

5.1 As shown on Diagram 4, from chainage 7500m to 7000m the proposed Scheme is crossing Rough Burn and its catchment approximately 300m upstream of Morayston Hamlet. It consists of a new offline dual carriageway with associated infrastructure. The Rough Burn crossing consists of a new culvert (SWF12-1 (C09)) and the realignment of a section of Rough Burn to create 230m of new channel.

Modelling Approach

<u>1D Model Updates</u>

5.2 The proposed realigned channel of Rough Burn has 230m chainage and includes:

- a new open channel section of 143m, upstream of a new culvert (from Flood Modeller node RB_0483 to RB_0340);
- a rectangular culvert SWF12-1 (C09) under the proposed Scheme of 65m long (Flood Modeller node RB_0340c); and
- a new open channel section of 22m, downstream of the new culvert (from Flood Modeller node RB_0275 to RB_0246).

5.3 The bed levels of the new cross sections were defined using a linear gradient between the existing cross sections at the upstream and downstream ends of the realignment. The old section of Rough Burn channel was removed from the model. A trapezoid channel shape was used in cross section with a 2m wide bed and linear, bankside slopes (a typical section is shown in (Diagram 5). Channel width at the bank tops was taken from the design drawings. The levels of the bank tops were taken from the MXROAD ASCII grids and the 2014 photogrammetry as required.

5.4 At the upstream end of the realignment the cross section is smaller than further downstream (Diagram 4), where the realignment cuts through high ground and a larger excavation is required to maintain the bed profile (Diagram 6).

5.5 The bed roughness for the realigned channel was set to a Manning's 'n' value of 0.05 and the bank roughness to a Manning's 'n' value of 0.07. This is in line with the channel bed materials across the model domain.

5.6 This new reach follows a less winding alignment and is therefore slightly shorter (7m) than the baseline scenario.

5.7 The culvert inlet and outlet are positioned at the toe of the proposed Scheme embankment. The culvert has been assumed rectangular and to have a square headwall. The roughness within the culvert was set to a Colebrook - White Friction value of 0.0014m (equivalent to a Manning's 'n' of 0.013) for the new concrete wall and soffit and to 0.300m for the culvert invert to match the bed roughness (equivalent to a Manning's 'n' of 0.032).

5.8 The dimensions of the culvert were determined with the following criteria:

- freeboard of 600mm within the culvert, above the 0.5% AEP +CC event maximum water level;
- mammal crossing to be included. It takes the form of a ledge on either side of the culvert. To model it, the culvert opening area was reduced by the mammal crossing area on each side of the culvert; and
- freeboard of 170mm between the 4% AEP event maximum water level and the mammal ledge soffit plus freeboard of 600mm above the mammal ledge soffit.

5.9 To achieve the criteria, the modelling results show that a culvert of 3m wide and 1.64m high would be required.

2D Model Updates

5.10 The DTM (Digital Terrain Model) was modified to represent the design features across Rough Burn flood plain in the 2D domain. The proposed Scheme road elevations were exported from the MXROAD software as an ASCII grid, for inclusion in the hydraulic model. Within the proposed Scheme footprint the ASCII grid replaced the existing ground elevation.

Diagram 4: Rough Burn Model Schematisation 'With-Scheme'

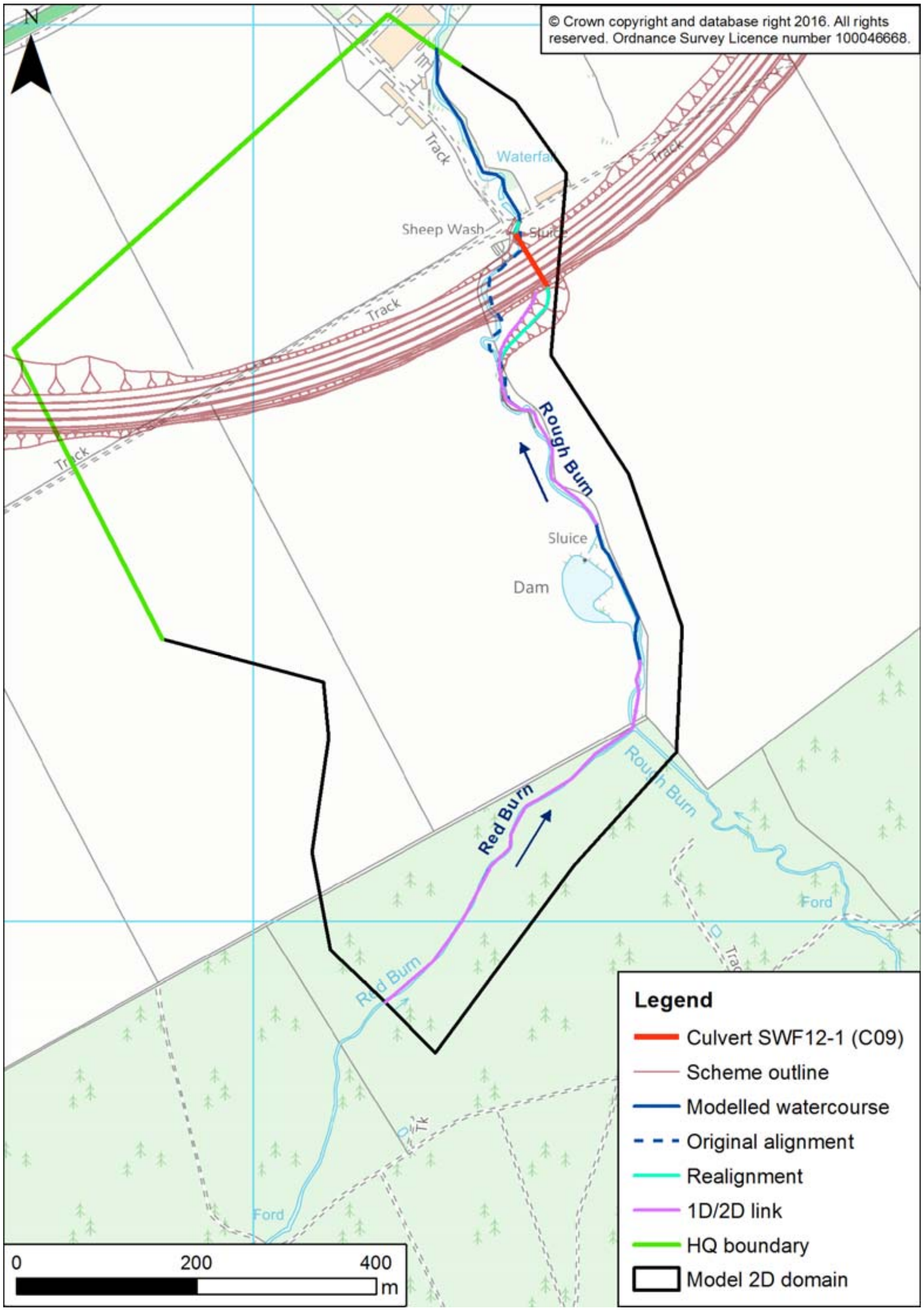


Diagram 5: Downstream Realignment Cross Section

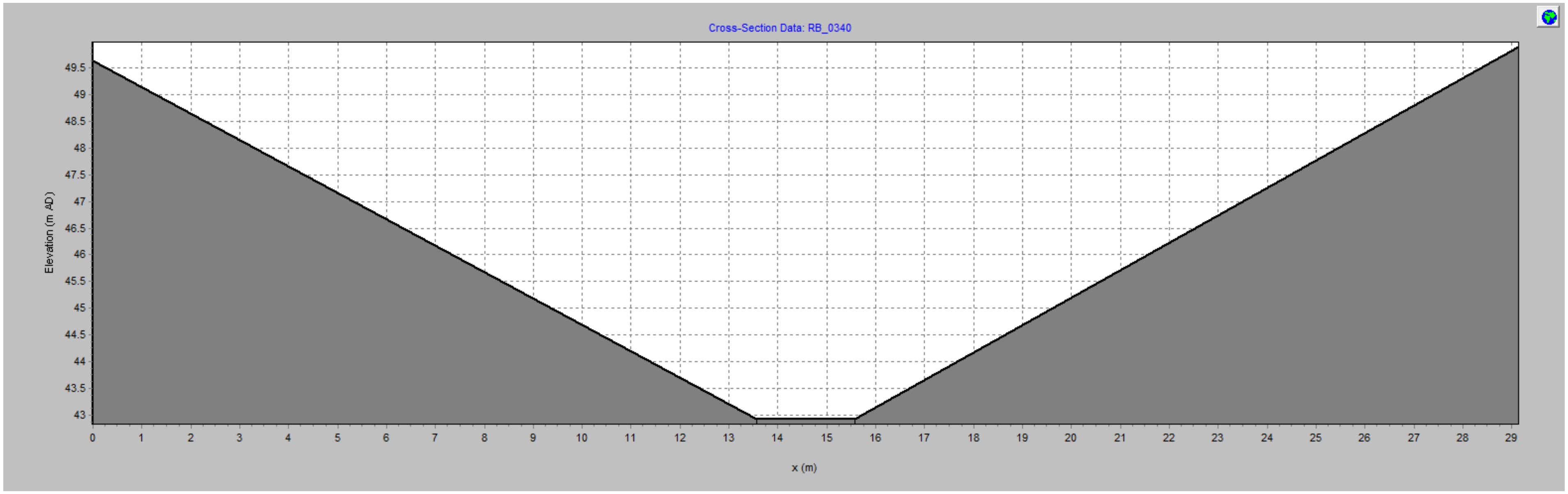
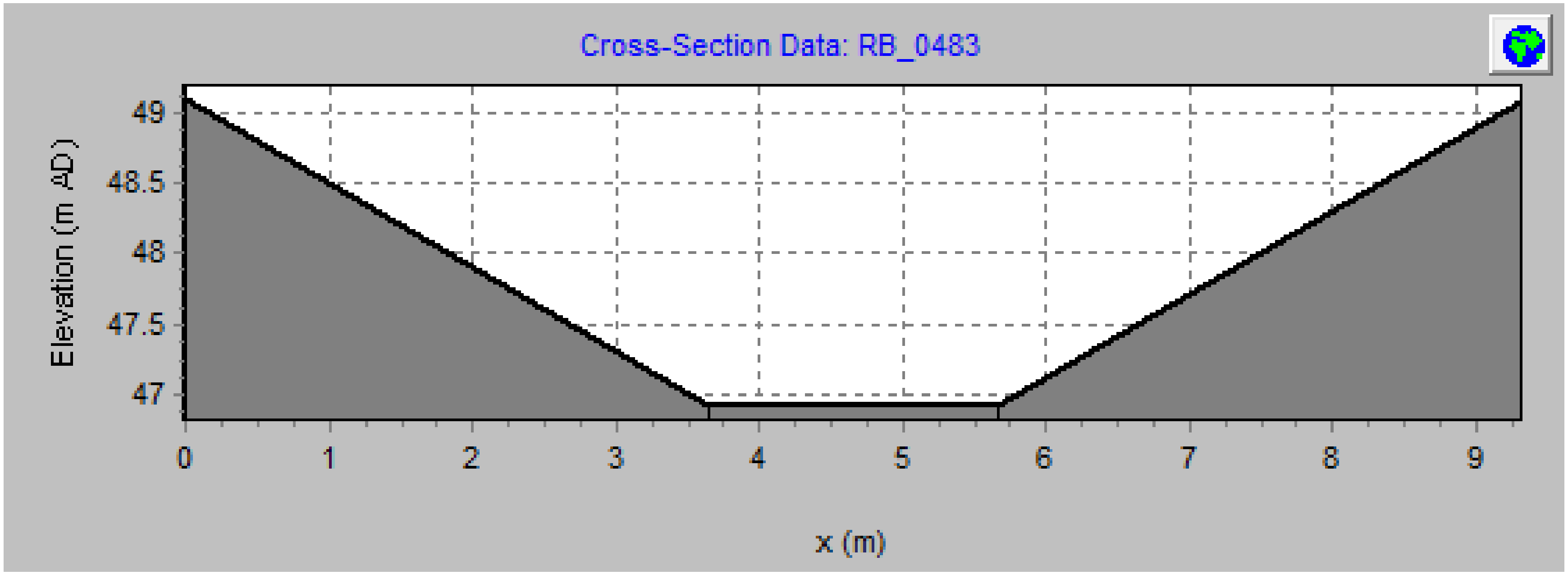


Diagram 6: Upstream Realignment Cross Section



6 Modelled events

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

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

Table 9: Modelled Events

Scenario	AEP Event								
	50%	20%	10%	3.33%	2%	1%	0.5%	0.5% + CC	0.1%
Baseline	✓	✓	✓	✓	✓	✓	✓	✓	✓
Roughness Sensitivity (1D and 2D)							✓		
Hydrological Inflow Sensitivity							✓		
Downstream Boundary Sensitivity (1D and 2D)							✓		
'With-Scheme'								✓	
'With-Mitigation' Measures				✓			✓	✓	✓
'With-Mitigation' Measures – 50% Blockage of the Mainline Culvert								✓	
'With-Mitigation' Measures – 90% Blockage of the Mainline Culvert								✓	

7 Model Proving

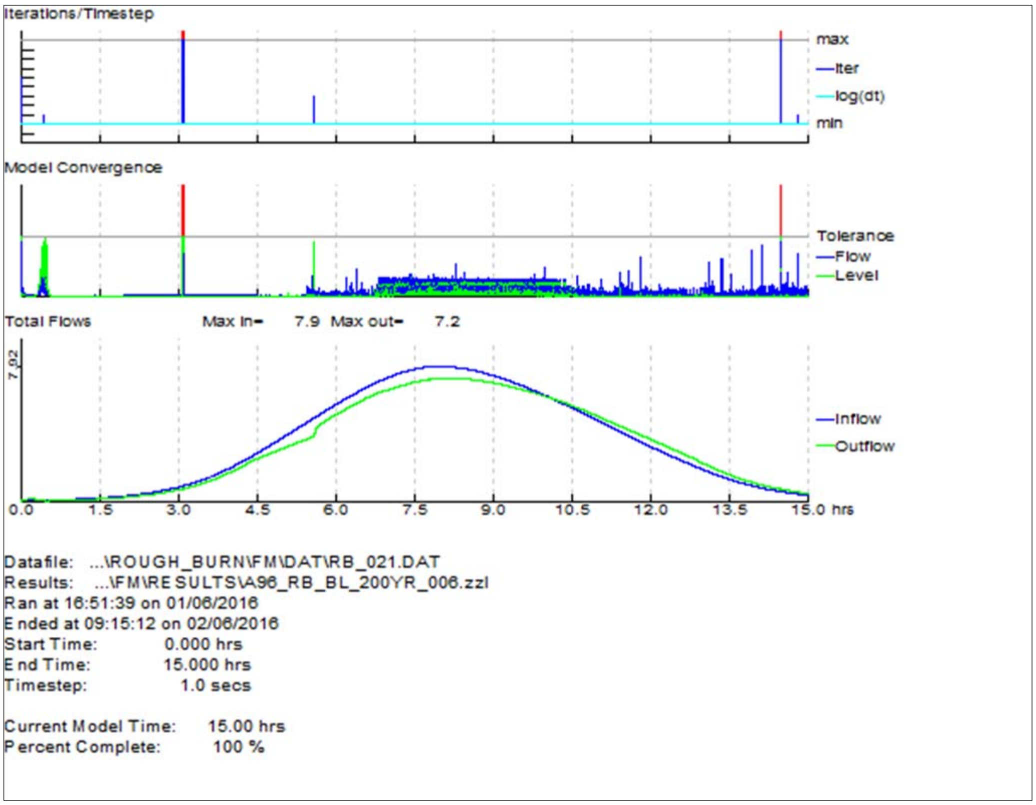
Introduction

7.1 The following sections discuss the model performance and the verification process. In addition, details relating to the additional runs carried out to test the sensitivity of the model to key variables are also discussed.

Model Performance

7.2 Run performance has been monitored throughout the model build process and then during each simulation carried out, to ensure a suitable model convergence was achieved. Convergence refers to the ability of the modelling software to arrive at a solution that is close to the exact solution within a pre-specified error tolerance. The convergence of the 1D model was checked as shown in Diagram 7 below. Some non-convergence occurs during a small number of isolated time steps; this does not affect peak flows and is deemed acceptable. This convergence plot is generally typical for the events modelled.

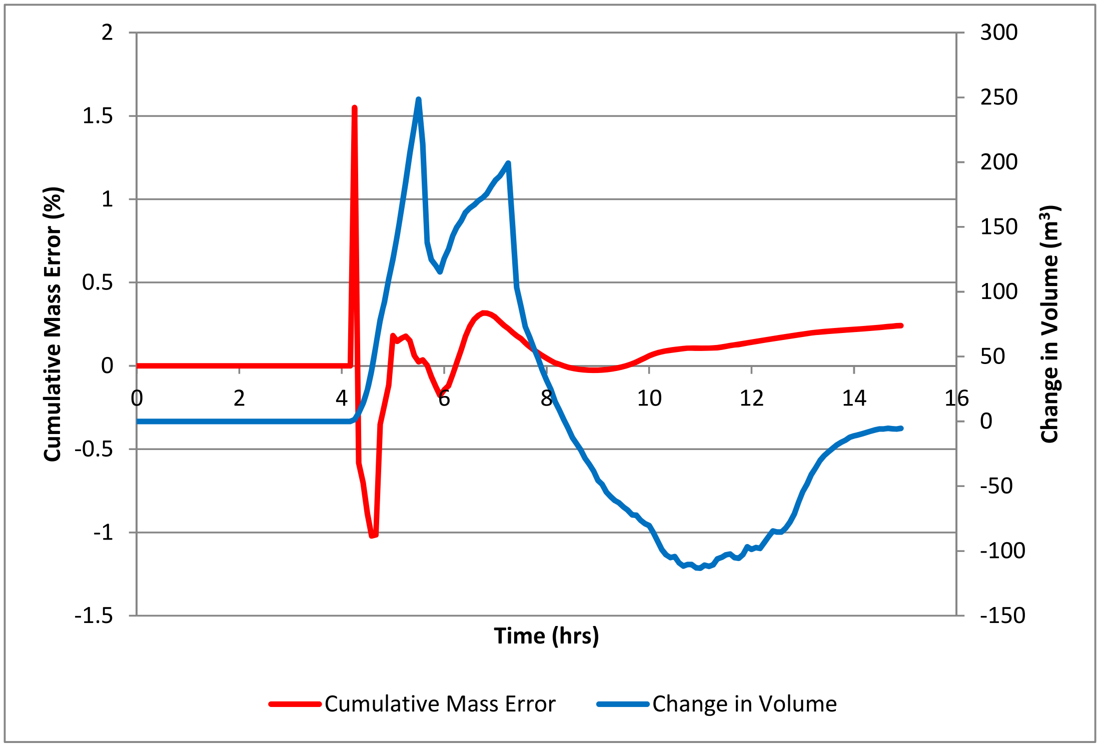
Diagram 7: 1D Model Convergence – 0.5 % AEP Event



7.3 The cumulative mass error reports output from the TUFLOW 2D model have been checked. The recommended tolerance range is +/- 1% Mass Balance error. The change in volume through the model simulation has also been checked and has been found to vary smoothly which is an indicator of good convergence of the 2D model.

7.4 Diagram 8 shows that for the 0.5% AEP event, the cumulative mass error is all less than 0.5%. There is a spike in the cumulative mass error which is outside of tolerance i.e. greater than 1% in absolute value. However, this spike occurs before there is significant volume of water in the model and is therefore deemed acceptable. This Mass Error diagnostic is typical for all the events modelled in which significant flooding occurs.

Diagram 8: 2D Cumulative Mass Error and Change in Volume – 0.5 % AEP Event



Calibration and Verification

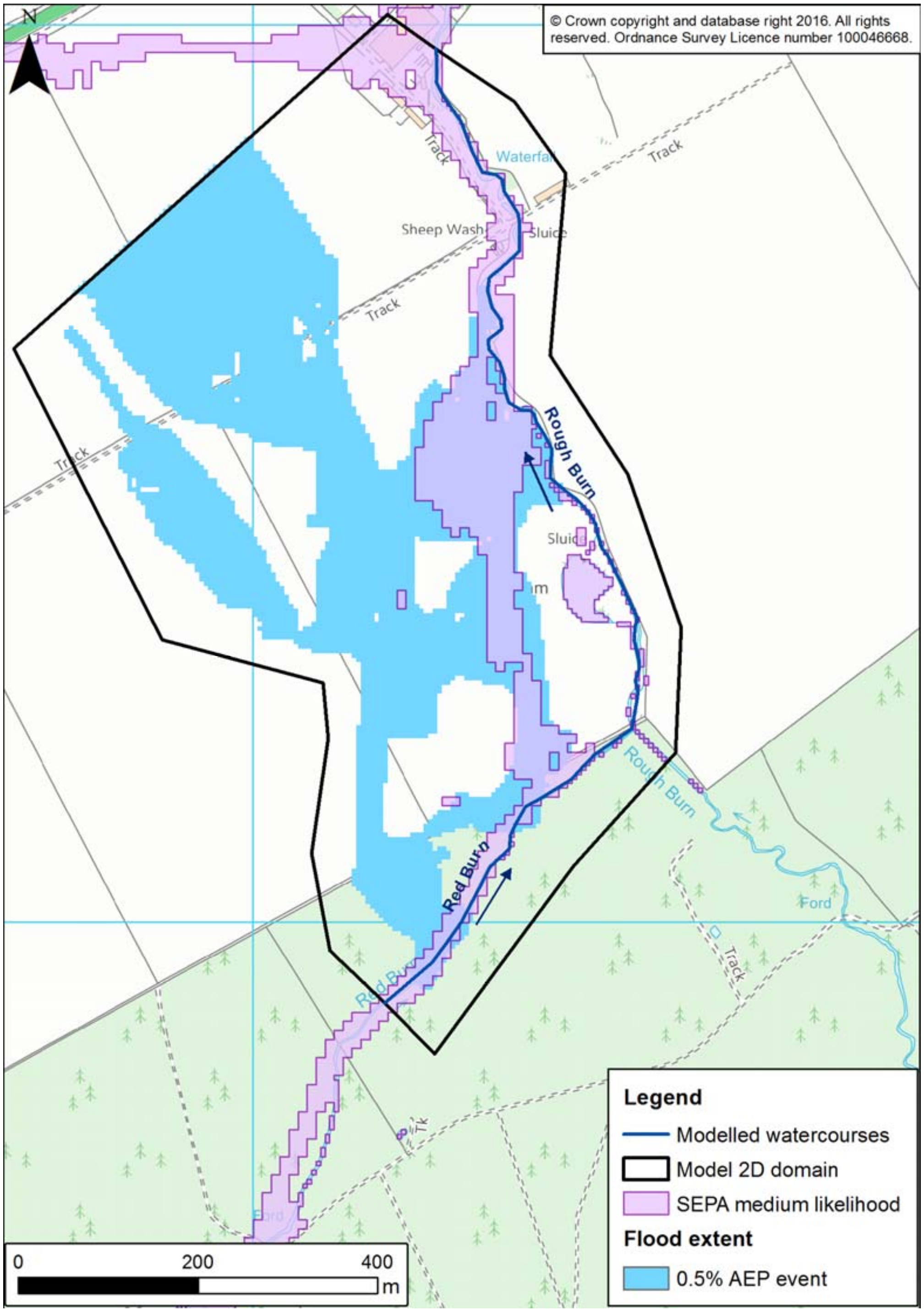
7.5 No suitable historic flood record is available for a hydraulic model calibration. However, a high level verification was undertaken.

Verification Using SEPA Flood Maps

7.6 Flood extent maps are available from the Scottish Environment Protection Agency (SEPA). These maps show the fluvial flood extent for different likelihoods of flooding (high, medium and low). The SEPA medium likelihood of flooding is equivalent to a 0.5% AEP event. Therefore a comparison has been made with the modelled baseline 0.5% AEP event flood extent (Diagram 9).

7.7 As shown in Diagram 9, the results for the 0.5% AEP event simulation show a significantly larger flood extent than the SEPA maps, with a significant flow path established from the left bank of Red Burn, progressing due north and diverging from the Rough Burn valley. Such differences with the SEPA flood mapping are expected as the FRA modelling presented in this report is based on a finer level of detail along with refined catchment hydrology analysis.

Diagram 9: Modelled 0.5 % AEP Event Flood Extent vs. SEPA Medium Likelihood Fluvial Extent



Sensitivity Analysis

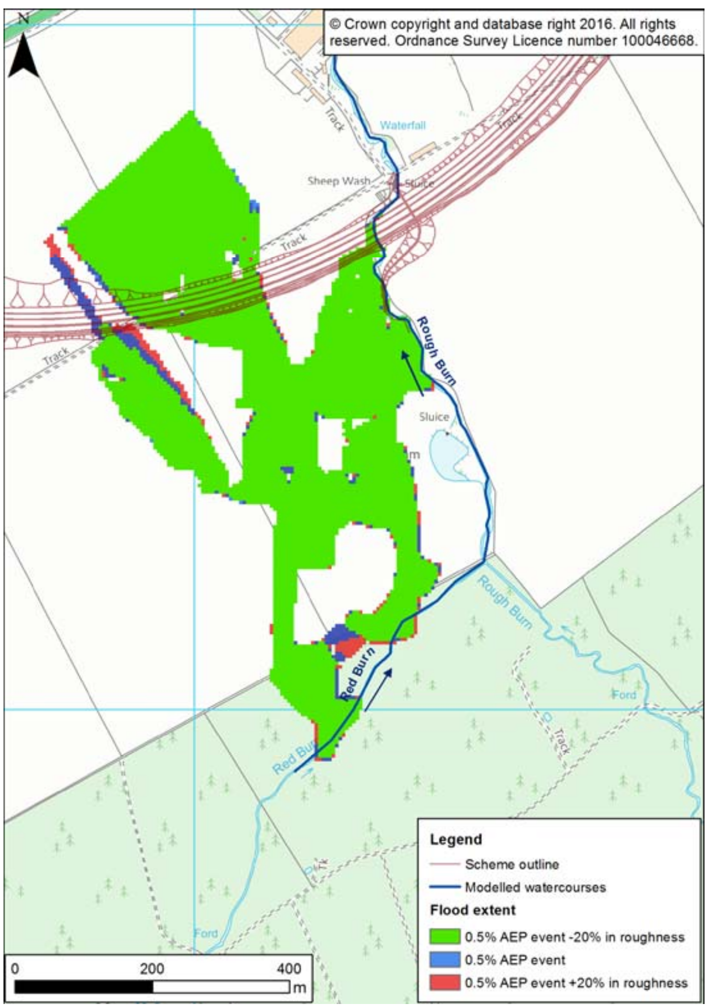
Roughness Sensitivity

7.8 In-channel and flood plain roughness coefficients (Manning's 'n') were changed by +20% and -20%. Table 10 shows the impact of changing the model roughness on in-channel water levels. The results show that the in-channel water levels are relatively insensitive to changes in roughness. Diagram 10 shows that changes in flood extent as a result of changing the model roughness are also minimal.

Table 10: Roughness Sensitivity Results

Sensitivity	Water Level Difference (m)			Water Level Difference Immediately Upstream of the Scheme (m)
	Max	Min	Average	RB_0490
+20% Roughness	0.070	-0.001	0.045	0.048
-20% Roughness	-0.076	0.006	-0.045	-0.067

Diagram 10: Change in the 0.5% AEP Event Flood Extent - Roughness Sensitivity



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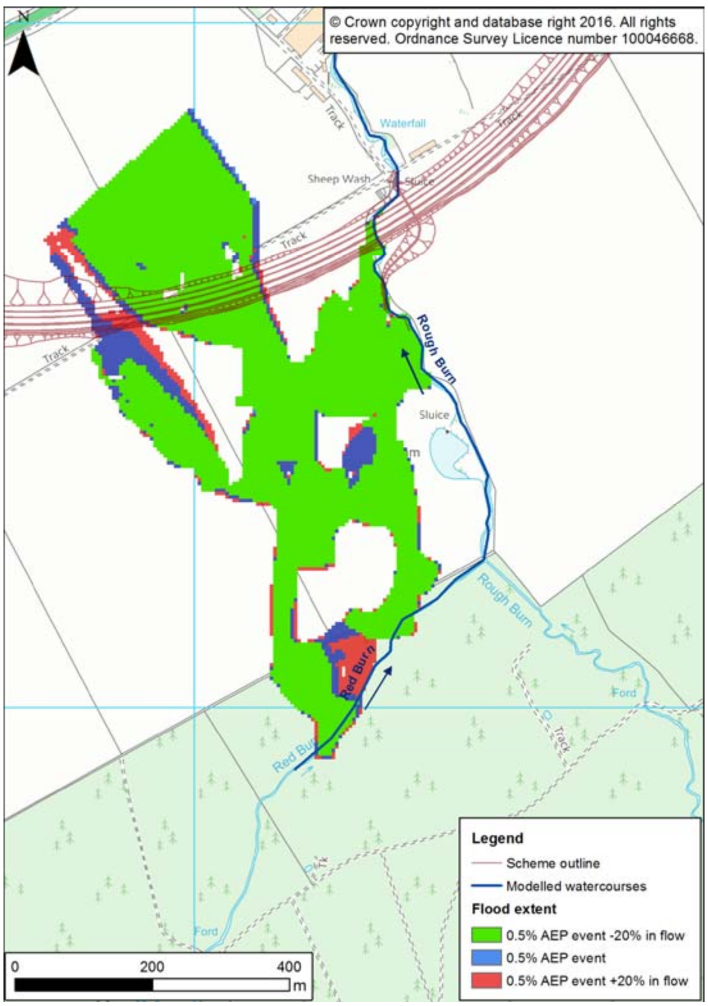
Hydrological Inflow Sensitivity

7.9 The flows into the model were adjusted by +20% and -20%. Table 11 shows the impact of changing the model inflows on in-channel water levels. The results show that the model is sensitive to changes in flow. Diagram 11 shows how the flood extent changes as a result of changing the model inflows. The results show that the flood extent is affected at the location of the proposed Scheme.

Table 11: Flow Sensitivity Results

Sensitivity	Water Level Difference (m)			Water Level Difference Immediately Upstream of the Scheme (m)
	Max	Min	Average	RB_0490
+20% Flow	0.128	0.011	0.052	0.067
-20% Flow	-0.143	-0.016	-0.060	-0.072

Diagram 11: Change in the 0.5% AEP Event Flood Extent - Inflow Sensitivity



Downstream Boundary Condition Sensitivity

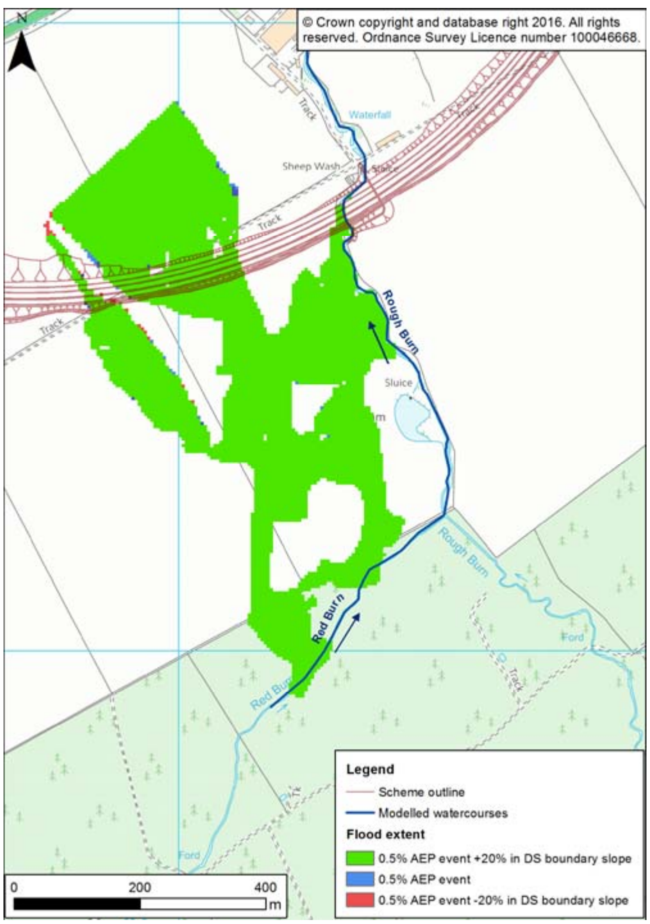
7.10 The slope of the downstream boundaries in the 1D and 2D models were adjusted by +20% and -20%. The results show that the changes to the downstream boundary only affect the downstream end of the model. Table 12 shows the response at the downstream end of the model (Flood Modeller Node RB_0000). The location at which there is no change in water level as a result of changing the downstream boundary has been identified. Distances from this location, in relation to the downstream end of the model (tailwater distance) and in relation to the proposed Scheme, are shown in Table 12. This indicates that the proposed Scheme is at least 147m upstream of the influence of the downstream boundary.

7.11 Diagram 12 shows how the flood extent changes as a result of changing the slope of the downstream boundaries. The results show only minimal response in flood extent and that the flood extent is not affected at the location of the proposed Scheme.

Table 12: Downstream Boundary Sensitivity Results

Sensitivity	Water Level Difference (m)		
	Water Level Difference (m) at RB_0000	Tailwater Distance (m)	Distance to Scheme (m)
+20% Downstream boundary slope	-0.027	99	147
-20% Downstream boundary slope	0.035	99	147

Diagram 12: Change in the 0.5% AEP Event Flood Extent – Downstream Boundary Slope Sensitivity



8 Model Results – Baseline and 'With-Scheme'

Baseline Scenario

8.1 Maps have been produced to show the baseline scenario flood extent for each modelled event in Section A.2 (Flood Extent Maps). For the 50% AEP event no out of bank flooding occurred, therefore no flood extent map was produced. The in-channel water levels at key locations for all modelled events are shown in Section A.1 (Water Level Tables and Long Section).

8.2 Diagram 13 shows the main flood mechanisms for the 0.5% AEP +CC event and has been analysed in conjunction with the extent maps (see Section A.2 (Flood Extent Maps)) to assess the baseline flooding.

8.3 Two main flow routes are predicted:

- flow path 1: Out of bank flooding on left bank of Red Burn, for events larger than the 20% AEP event. Flows re-enter in Rough Burn immediately upstream of the proposed Scheme; and
- flow path 2: For events larger than the 20% AEP event, out of bank flooding from the left bank of Red Burn flows parallel to the main channel, spreading out over the hillside and crossing the proposed Scheme alignment.

8.4 As shown in Diagram 14, for a 0.5% AEP + CC event maximum flood depths are generally small (below 50mm) over the flood extent. At the upstream part of the model some higher flood depths between 500 and 750mm occur where there are depressions in the topography. At the proposed Scheme footprint, flood depths are between 50mm and 100mm in the centre of flow path 2, but are generally lower than 50mm.

Diagram 13: 0.5 % AEP +CC Event Flood Mechanisms – Baseline Scenario

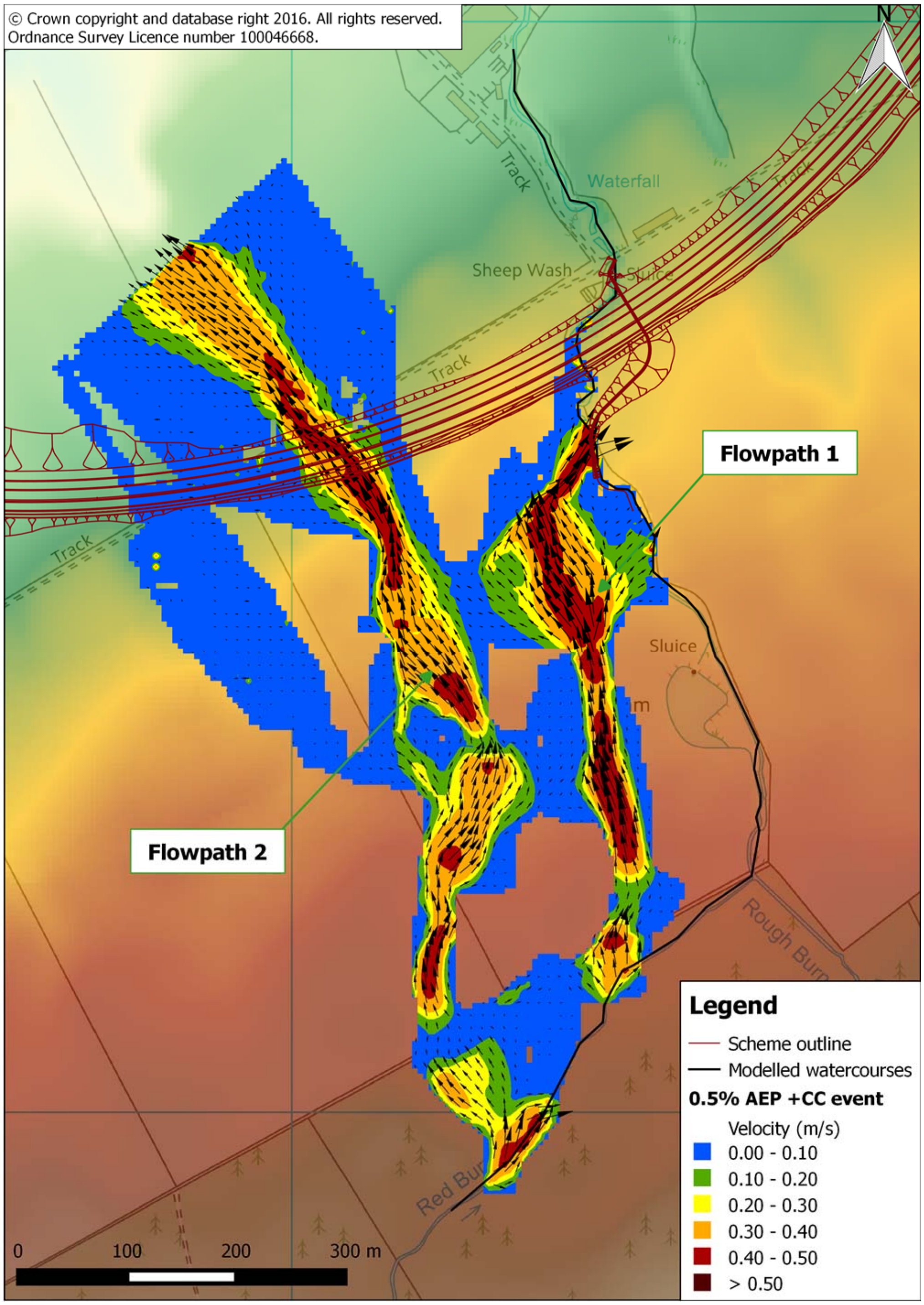
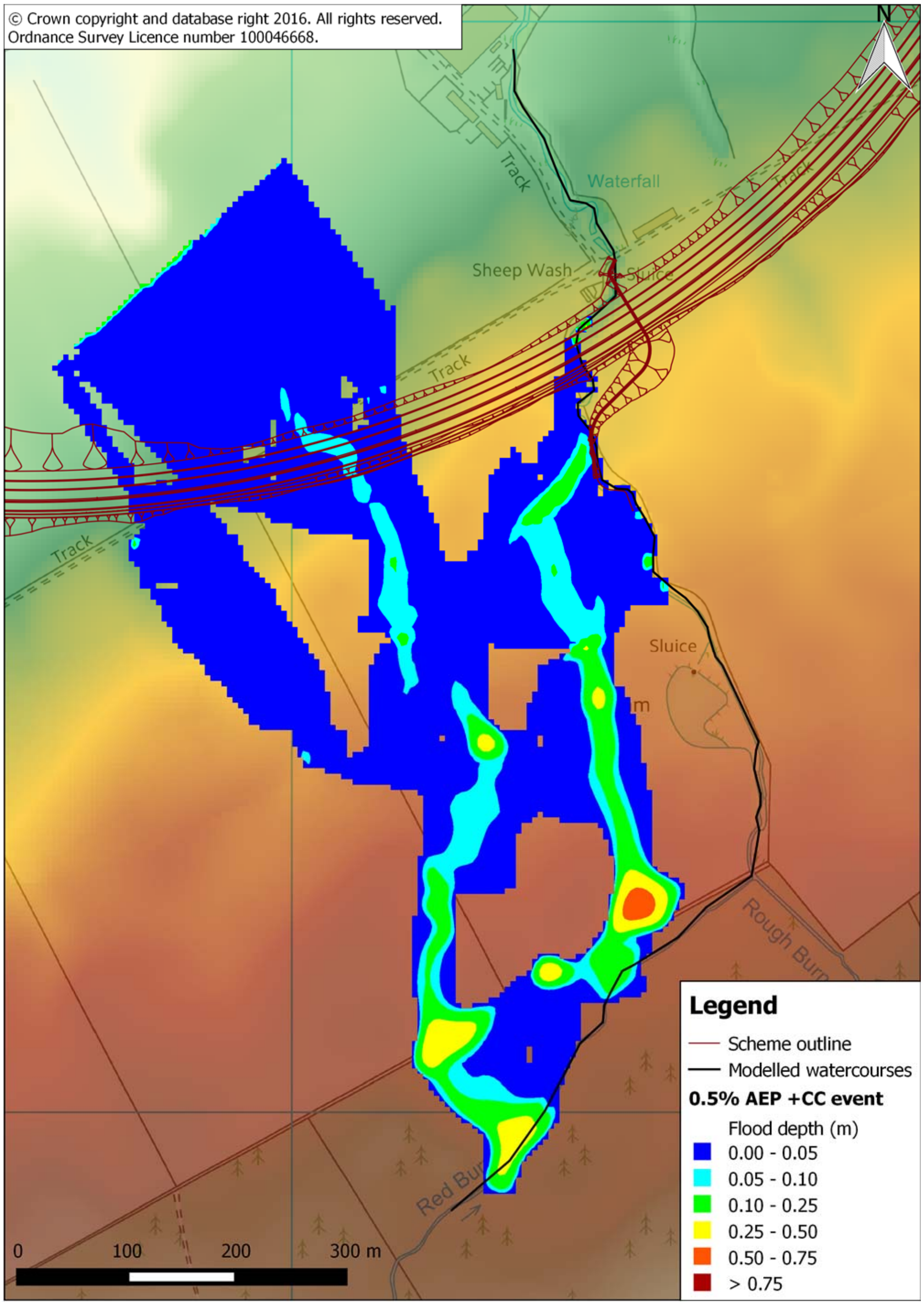


Diagram 14: 0.5 % AEP +CC Event Maximum Flood Depths – Baseline Scenario



'With-Scheme' Scenario

8.5 Diagram 15 and Diagram 16 show respectively the main flood mechanisms and maximum flood depths for the 0.5% AEP +CC event for the 'with-scheme' scenario.

8.6 Out of bank flooding from the left bank of Red Burn flows downhill following the two main flow paths described in the analysis of the baseline model results (section 8 (Baseline Scenario)):

- flows along Flow Path 1 re-enter into Rough Burn upstream of the proposed Scheme and pass under the proposed Scheme through the new culvert SWF12-1 (C09); and
- flows along Flow Path 2 hit the proposed Scheme and turn through 90 degrees flowing west along the toe of the embankment.

Diagram 15: 0.5 % AEP +CC Event Flood Mechanisms - ‘With-Scheme’ Scenario

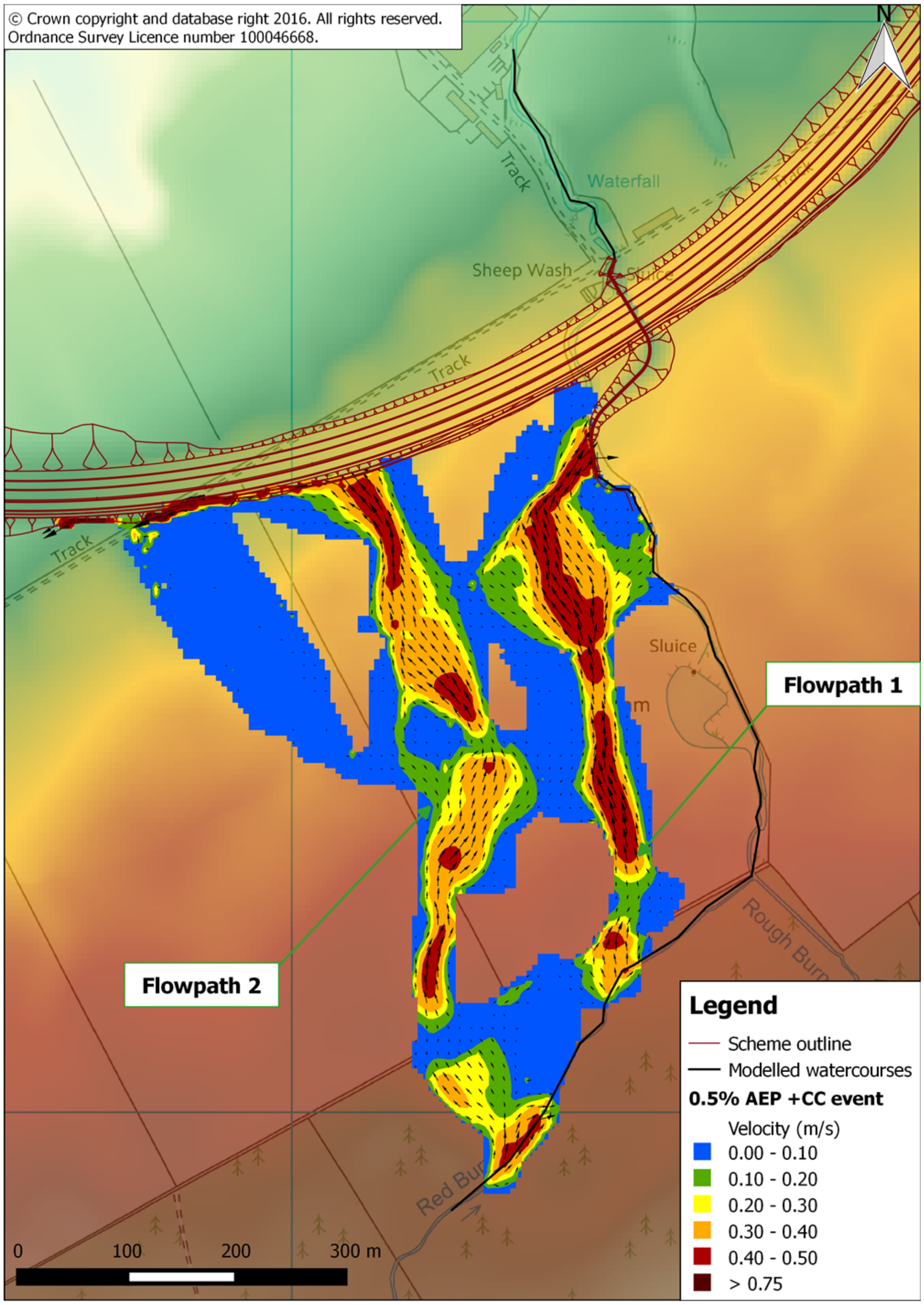
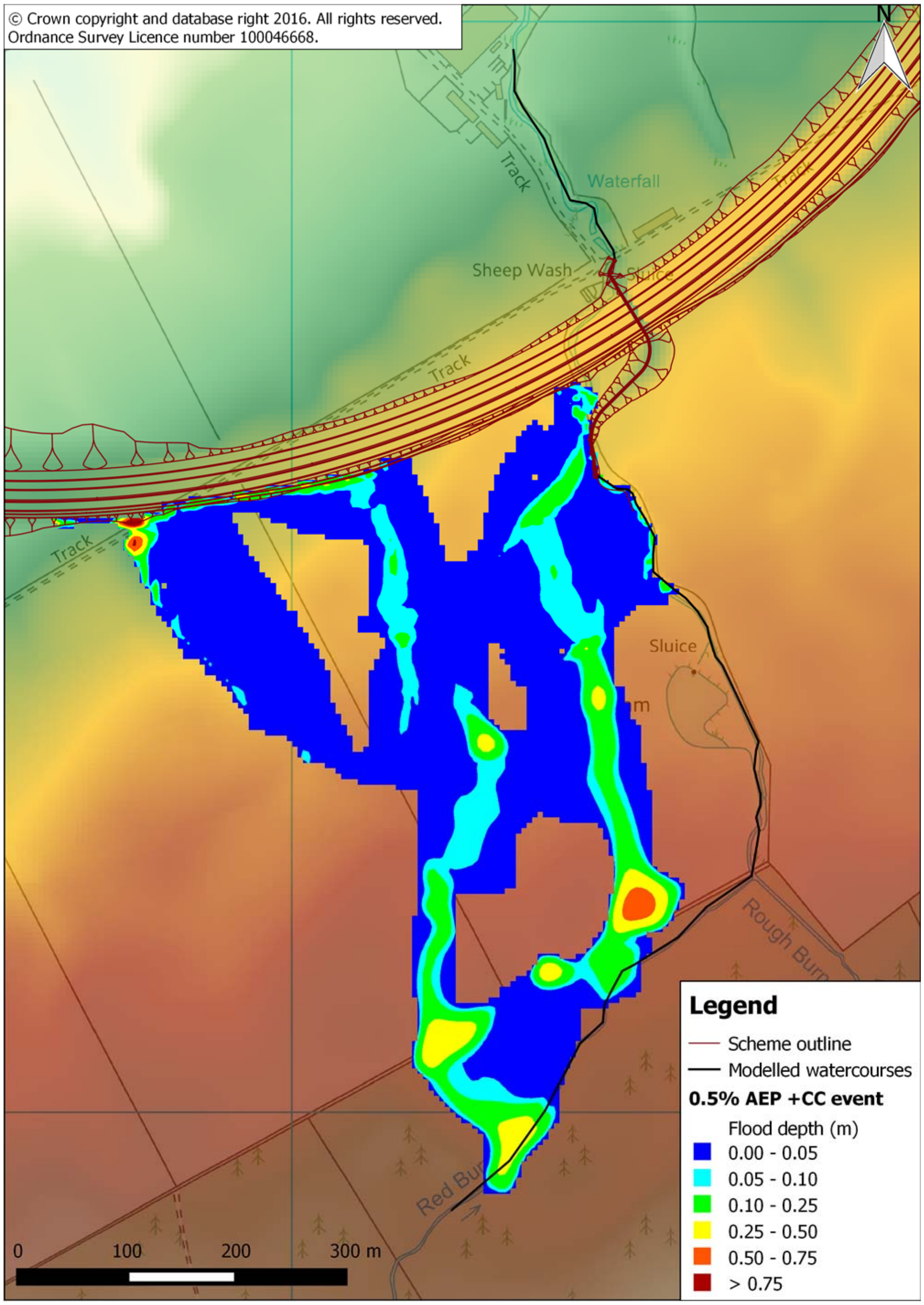


Diagram 16: 0.5 % AEP +CC Event Maximum Flood Depths – 'With-Scheme' Scenario



9 'With-Mitigation' Measures Modelling

9.1 As described in the baseline results section (section 8 (Baseline Scenario)), for events larger than the 20% AEP event, out of bank flooding from the left bank of Red Burn flows parallel to the main channel, spreading out over the hillside and crossing the proposed Scheme alignment. 'With-scheme' results show that the flow path from Red Burn is interrupted by the proposed Scheme embankment.

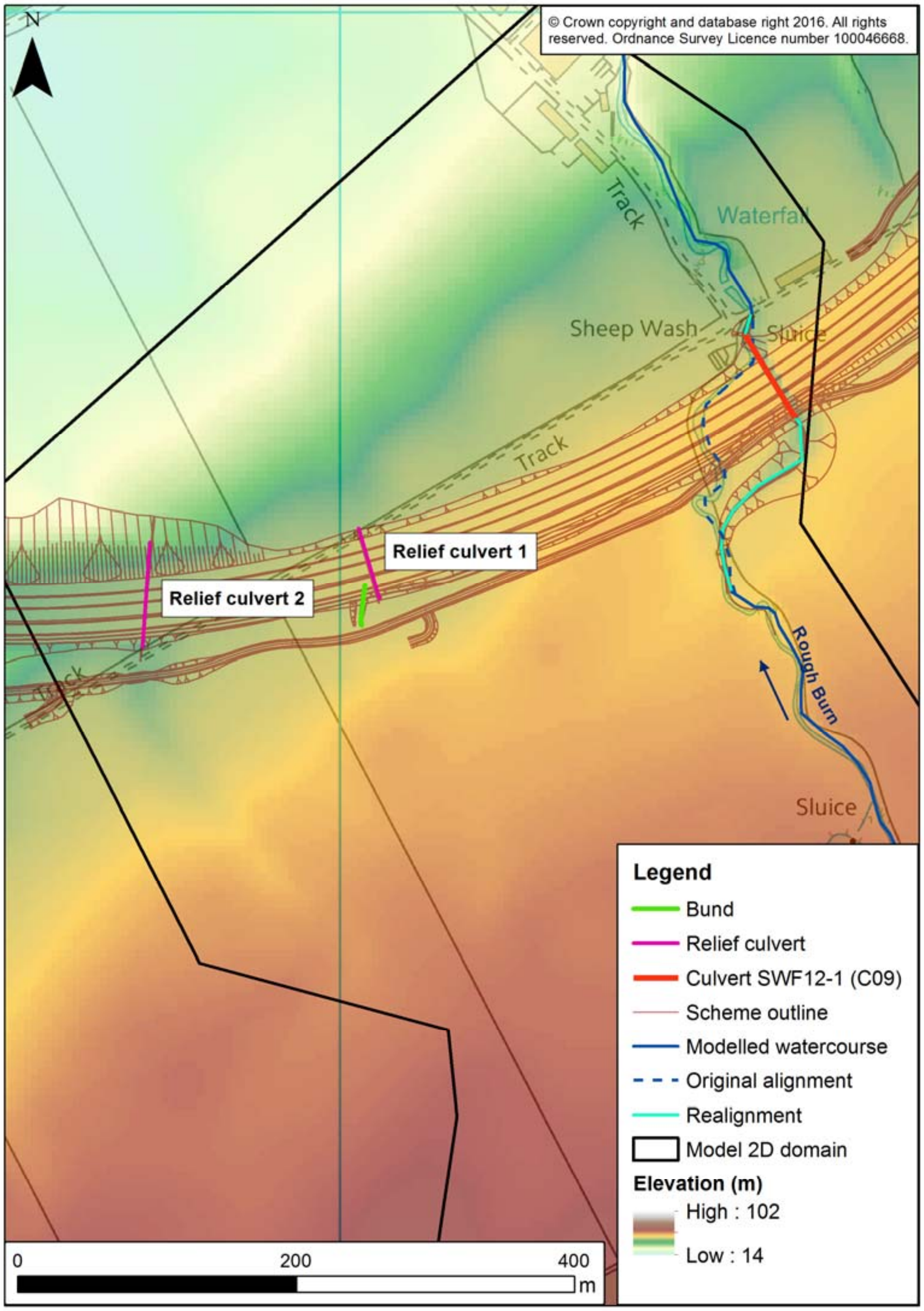
9.2 In order not to increase flood risk at the proposed Scheme and to match the baseline flood mechanisms, mitigation measures are proposed. Two culverts under the proposed Scheme embankments of 1m diameter are placed at the location of the main baseline flow paths as shown on Diagram 17 (relief culverts 1 and 2).

9.3 To match with the baseline flood mechanisms, a bund is placed at the east of the inlet of the relief culvert 1 in order to encourage the main flow to go through this culvert.

9.4 The results show that this bund should be at least 0.80m high.

9.5 During the development of the 'with-mitigation' scenario, an access track has been added to the scheme as shown on Diagram 17. This update was included in the with-mitigation model. As a consequence the scheme culvert was lengthened by 5m for a total length of 70m. A minor change was also made to the realignment due to the change in length of the culvert.

Diagram 17: Rough Burn Model Schematisation 'With-Mitigation' Measures.



10 Model Results – 'With-Mitigation' Measures

'With-Mitigation' Measures Scenario

10.1 Diagram 18 and Diagram 19 show respectively the main flood mechanisms and maximum flood depths for the 0.5% AEP +CC event for the 'With-Mitigation' measures scenario.

10.2 With this arrangement, flood mechanisms match well with the baseline scenario, with a main flow path going downhill and crossing the proposed Scheme through Relief Culvert 1 and a secondary flow path passing through Relief Culvert 2.

10.3 The maximum peak flow through Relief Culvert 1 is 1.7m^3/s for the 0.1% AEP and 1.07 for the 0.5%AEP +CC event. Peak flow is less than 0.02m^3/s through Relief Culvert 2.

Diagram 18: 0.5 % AEP +CC Event Flood Mechanisms - 'With-Mitigation' Measures

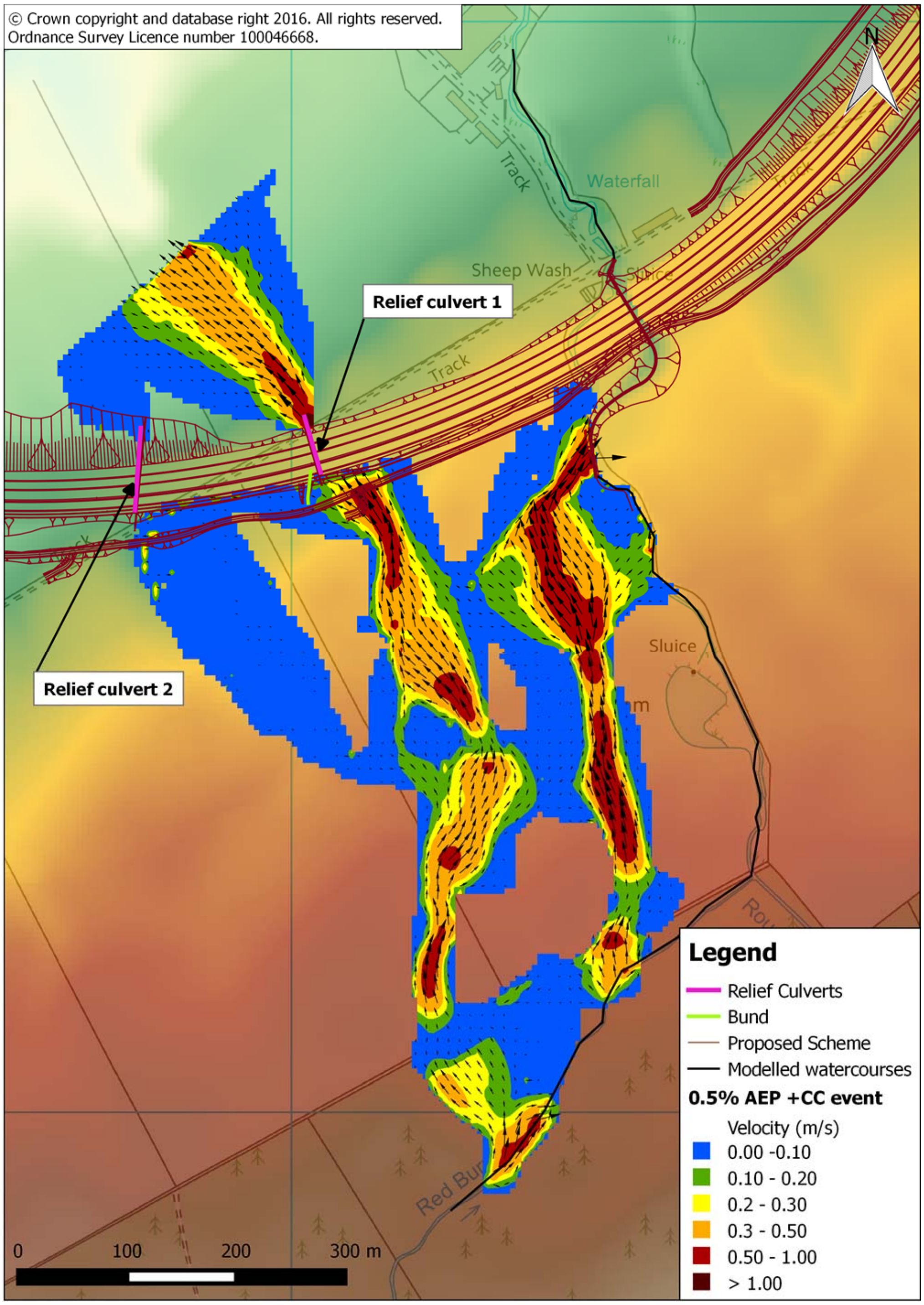
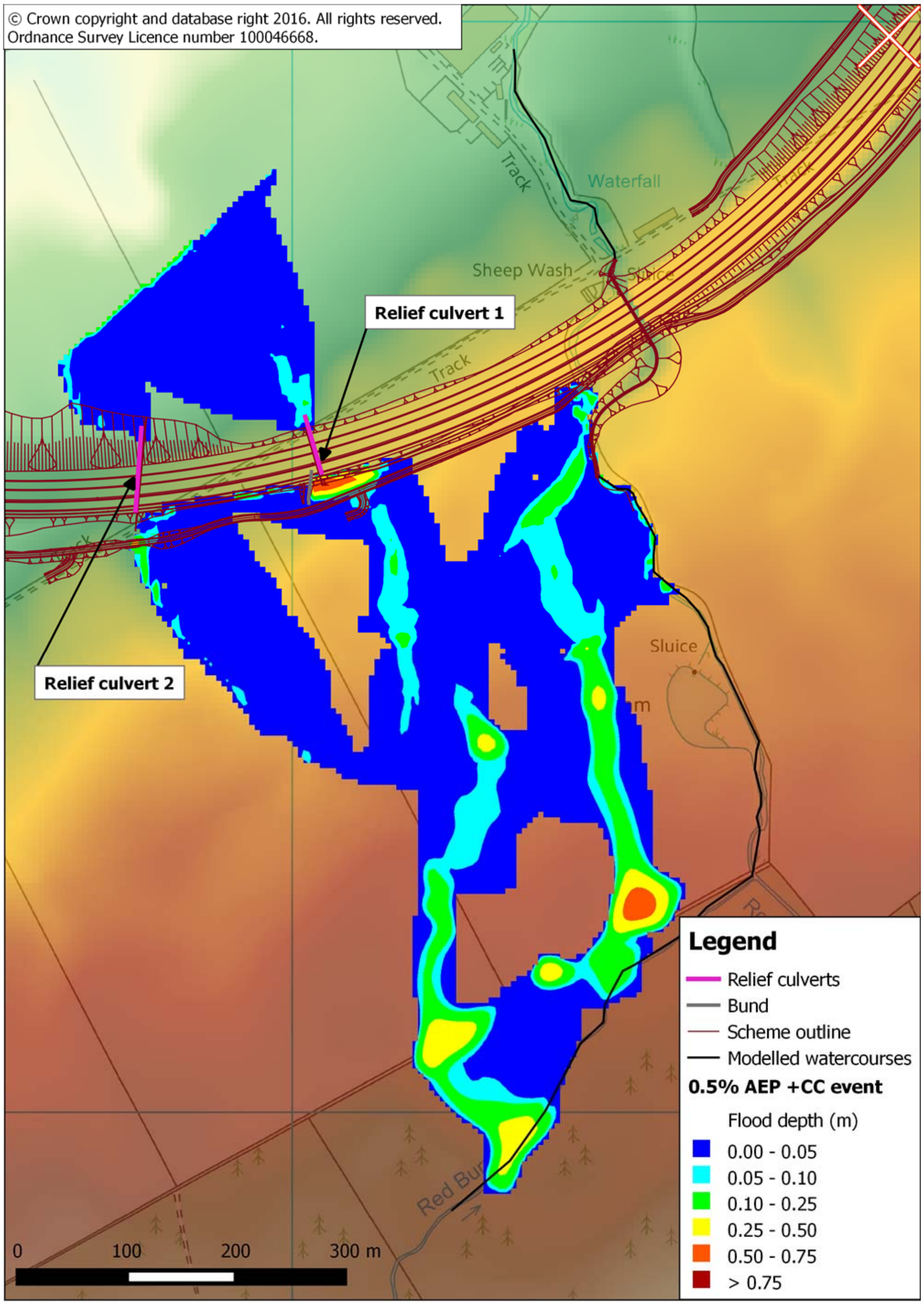


Diagram 19: 0.5 % AEP +CC Event Maximum Flood Depths – 'With-Mitigation' Measures



Comparison of Baseline and 'With-Mitigation' Scenarios

Differences in Maximum Flood Depths across the Flood Plain

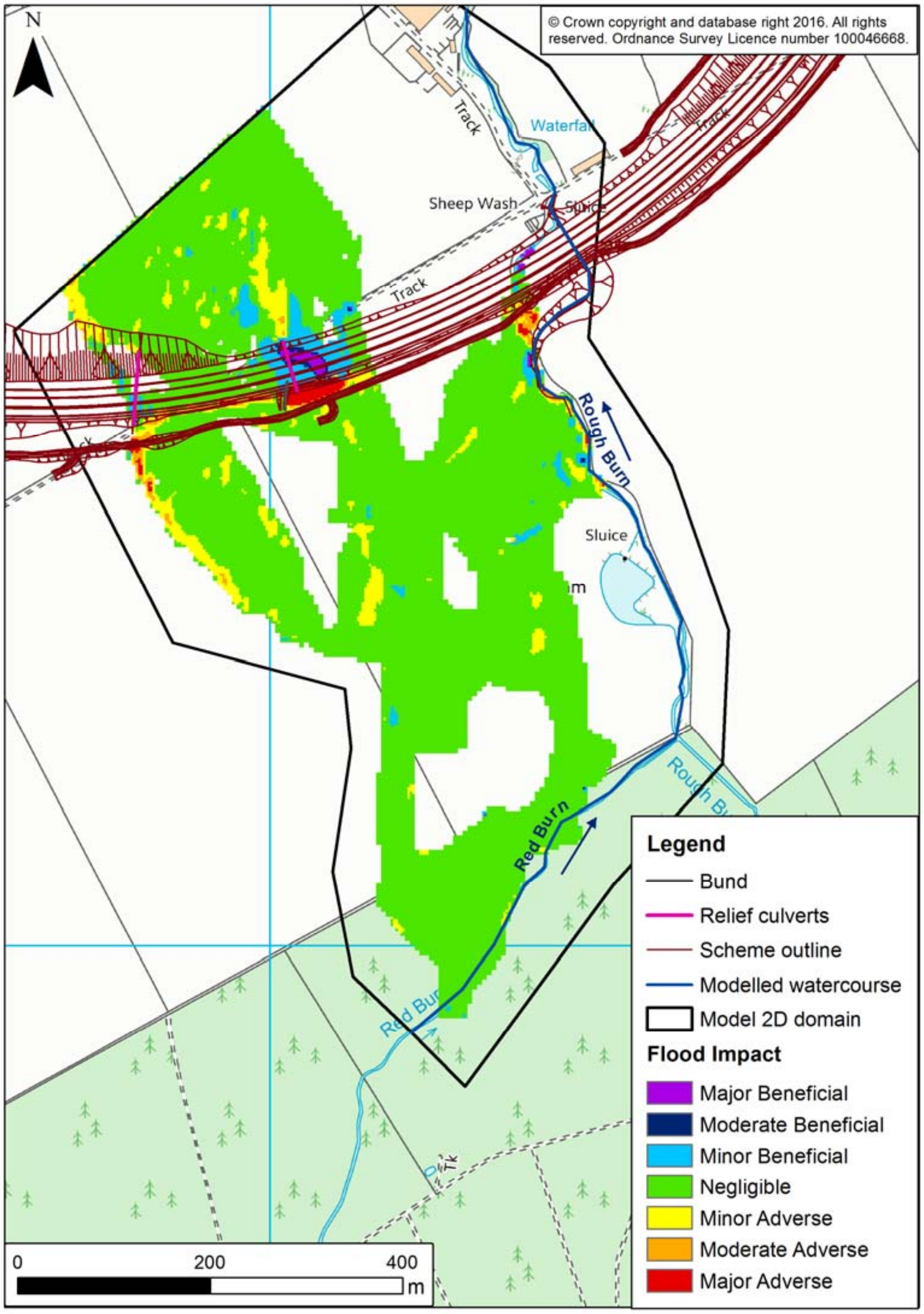
10.4 In order to assess the impact of the proposed Scheme on the existing flood risk, the differences in maximum flood depths were calculated for the 3.33%, 0.5%, 0.5% +CC and 0.1% AEP events between the baseline and the 'With-Mitigation' measures scenarios. All the change in depth maps are shown in Section A.3 (Depth Change Maps). The impact on flood risk, whether adverse or beneficial, have been categorised in Table 13.

10.5 Diagram 20 below shows the differences in maximum flood depths for the 0.5% AEP +CC event. Generally the difference in flood depth is negligible across the flood plain. Localised patches of minor beneficial and adverse variance can be seen. These are due to the limitations of model accuracy for shallow water flowing on a steep hillside. Immediately upstream of the inlets of the relief culverts flood depths are significantly increased, up to 0.78m at the inlet of relief Culvert 1 for the 0.5% AEP +CC event. In the vicinity of the old channel of Rough Burn flood depths cannot be compared with the baseline scenario as the channel is realigned here.

Table 13: Categorisation of Difference in Flood Depths

	Potential Flood Impact	Criteria	Flood Risk
	Major Adverse	Results in loss of attribute and/ or quality and integrity of the attribute	Increase in peak flood depth >100 mm
	Moderate Adverse	Results in effect on integrity of attribute, or loss of part of attribute	Increase in peak flood depth 50-100 mm
	Minor Adverse	Results in some measurable change in attributes quality or vulnerability	Increase in peak flood depth 10-50 mm
	Negligible	Results in effect on attribute, but of insufficient magnitude to affect the use or integrity	Negligible change in peak flood depth <+/- 10 mm
	Minor Beneficial	Results in some beneficial effect on attribute or a reduced risk of negative effect occurring	Reduction in peak flood depth 10-50 mm
	Moderate Beneficial	Results in moderate improvement of attribute quality	Reduction in peak flood depth 50-100 mm
	Major Beneficial	Results in major improvement of attribute quality	Reduction in peak flood depth >100mm

Diagram 20: 0.5% AEP +CC Event Maximum Flood Depth Difference Map



Differences in Maximum In-Channel Water Levels

10.6 Table 14 and Table 15 show the changes in in-channel water level between the baseline and the 'With-Mitigation' measures scenarios, for the 0.5% and the 0.5% AEP +CC events respectively. Where the proposed Scheme has removed the baseline nodes for the model, no comparison was made.

10.7 Generally, for the 3.33%, 0.5%, 0.5% +CC and 0.1% AEP events, changes in Rough Burn in-channel water levels are observed from 170m upstream of the proposed Scheme to 22m downstream of the proposed Scheme.

10.8 Table 14 and Table 15 below show that at 312m upstream of the proposed Scheme, the change in in-channel water level is negligible for the 0.5% and the 0.5% AEP +CC event (1mm and 2mm respectively). Just upstream of the realignment of Rough Burn, there is a decrease in in-channel water level of 69mm and 72mm for the 0.5% and the 0.5% AEP +CC events respectively. This is due to the changes in channel form within the realignment. Downstream of the proposed Scheme, the in-channel water level change is negligible for the 0.5% and the 0.5% AEP +CC events (1mm and 3mm respectively).

Table 14: In-Channel Water Level at Key Location for the 0.5% AEP Event

Model Node	Description	Baseline Water Level (mAOD)	'With-Mitigation' Water Level (mAOD)	Change in Water Level (m)
RB_0684	312m Upstream of Scheme crossing	53.114	53.113	-0.001
RB_0490	118m Upstream of Scheme crossing	48.065	47.996	-0.069
RB_0372	At Scheme crossing (Baseline)	44.925	-	-
RB_0340	At Scheme crossing (Design)	-	44.344	-
RB_0246	126m Downstream of Scheme crossing	41.667	41.668	0.001

Table 15: In-Channel Water Level at Key Location for the 0.5% AEP +CC Event

Model Node	Description	Baseline Water Level (mAOD)	'With-Mitigation' Water Level (mAOD)	Change in Water Level (m)
RB_0684	312m Upstream of Scheme crossing	53.174	53.172	-0.002
RB_0490	118m Upstream of Scheme crossing	48.132	48.060	-0.072
RB_0372	At Scheme crossing (Baseline)	44.978	-	-
RB_0340	At Scheme crossing (Design)	-	44.480	-
RB_0246	126m Downstream of Scheme crossing	41.795	41.798	0.003

Blockage of the Mainline Culvert Scenarios

10.9 The blockage of the mainline culvert SWF12-1 (C09) was considered for the 0.5% AEP +CC event, with 50% and 90% blockages to the culvert modelled.

10.10 Diagram 21 and Diagram 22 show the maximum flood depths for a 50% and a 90% blockage of the mainline culvert respectively.

10.11 The model results show that a 50% blockage of the mainline culvert results in no changes in flood depths across the flood plain. Immediately upstream of the culvert, in-channel water levels increase by 173mm.

10.12 The model results show that a 90% blockage of the mainline culvert results in significant flood water depth increase (> 1m) immediately upstream of the culvert at the foot of the proposed Scheme. In-channel water levels increase by more than 4m. Out of bank flows run to the north-east direction along the proposed Scheme, and flow out of the model. There is no effect on the wider hillside floodplain to the west of Rough Burn.

Diagram 21: 0.5% AEP +CC Event Maximum Flood Depths – 50% Blockage of the Mainline Culvert

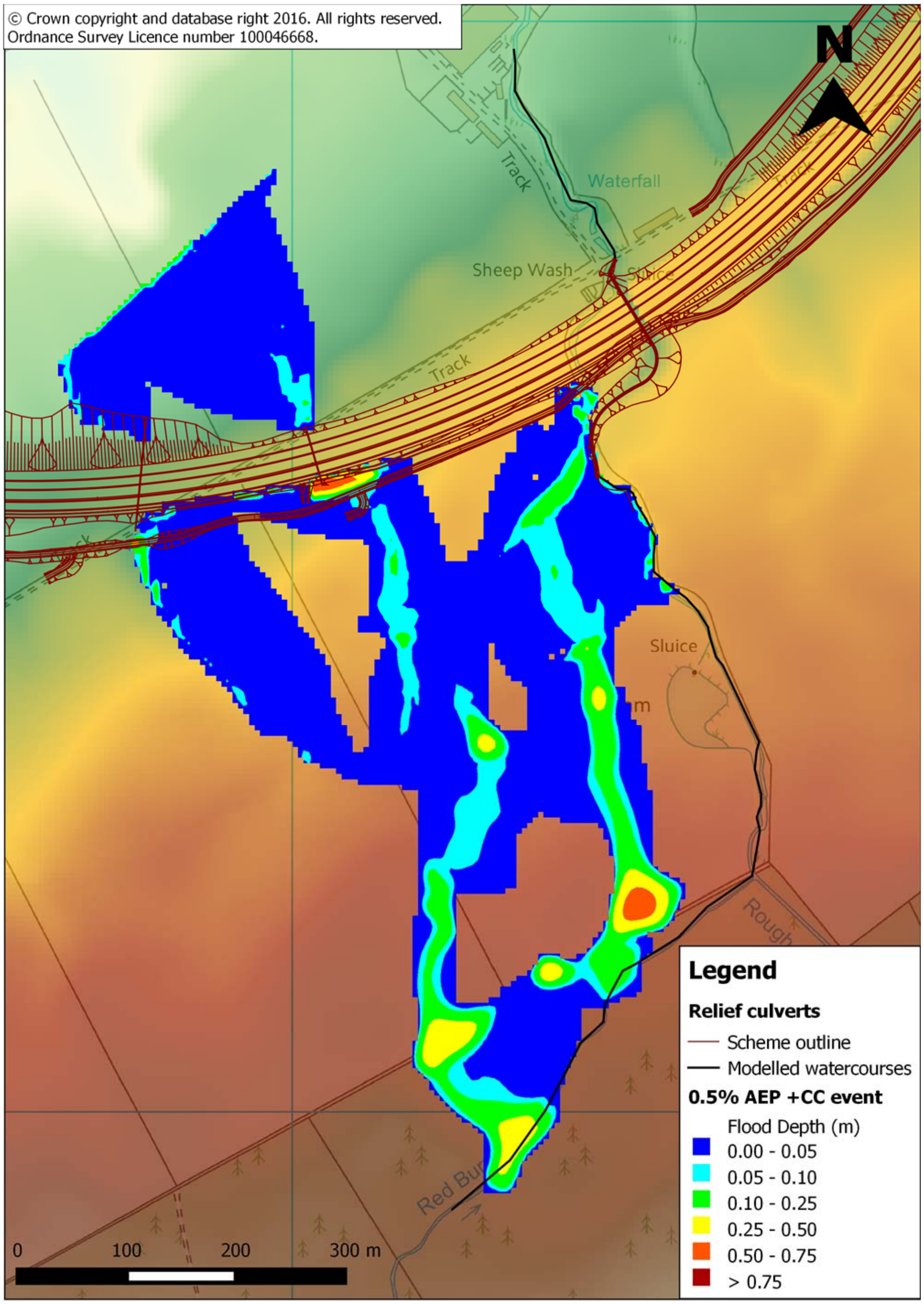
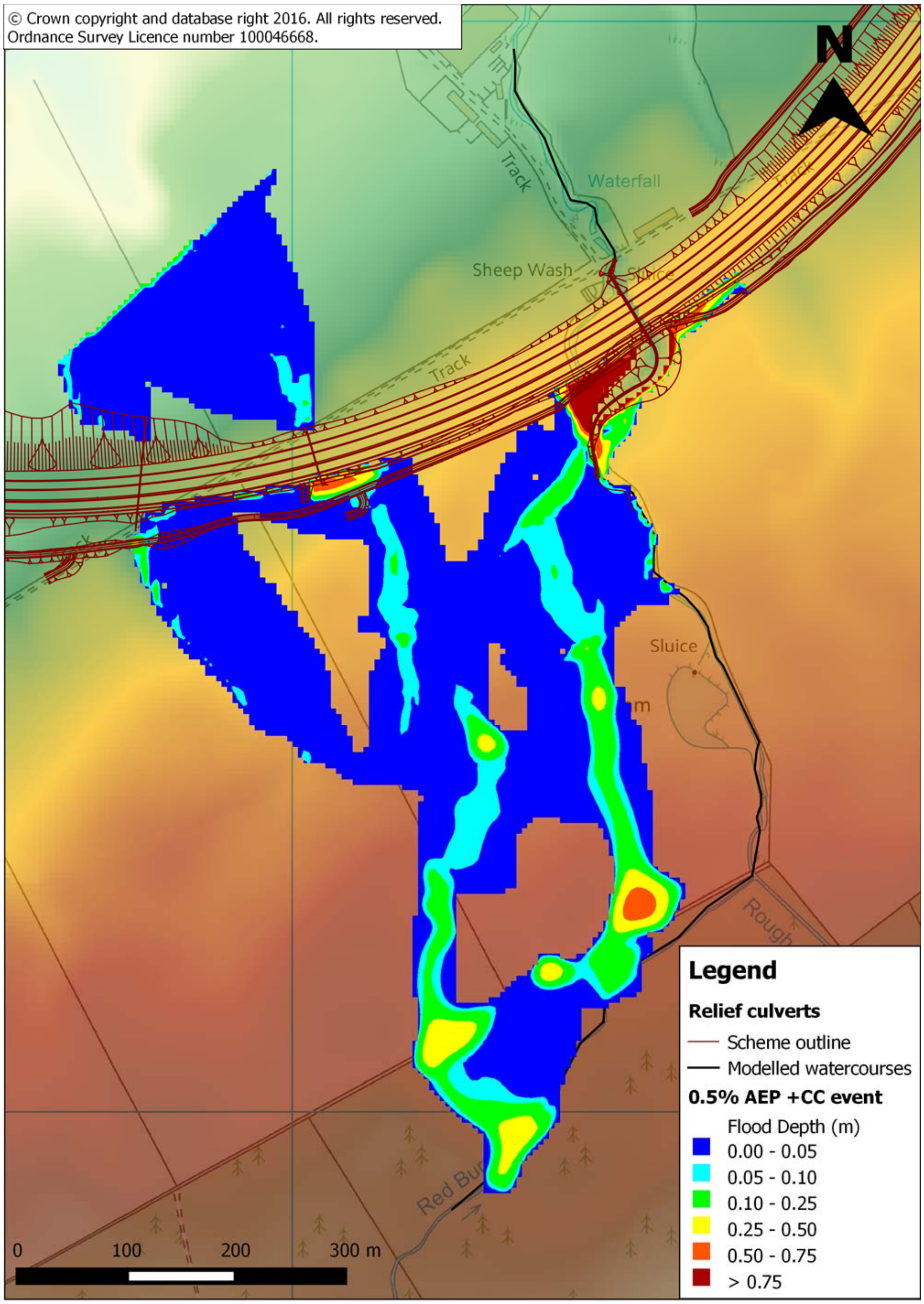


Diagram 22: 0.5 % AEP +CC Event Maximum Flood Depths – 90% Blockage of the Mainline Culvert



11 Model Assumptions and Limitations

Introduction

11.1 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.

11.2 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 and are therefore appropriate for the flood risk assessment.

11.3 The sections below summarise the key sources of uncertainty in addition to the limitations associated with the modelling undertaken for Rough Burn.

1D Domain

Channel Roughness

11.4 Channel roughness has been assigned using the best available information (site visit, survey data and aerial photographs). The roughness values used are based on available guidance (Chow 1959).

Representation of In-Channel Structures

11.5 Hydraulic coefficients for structures have been applied using available guidance within the Flood Modeller software. The dimensions for structures have been based on detailed survey measurements.

11.6 An embankment retaining a small pond is located on Rough Burn left bank, 750m upstream of Morayston hamlet. As no active connection was found between Rough Burn and the dam during the site visit, it has not been included in the model. This location is not flooding for any of the modelled events; this feature is therefore not significant for flood risk assessment.

Downstream Boundary Conditions

11.7 The downstream boundary is free discharge type without any downstream control; a normal depth boundary condition is applied. This is deemed appropriate as the downstream boundary is approximately 235m downstream of the proposed Scheme location. In addition the sensitivity analysis has shown that changes to the downstream boundary only impact on water levels up to 147m upstream of the downstream model extent.

2D Domain

Flood Plain Topography

11.8 The Digital Terrain Model (DTM) is a composite of two datasets, the 2009 photogrammetry dataset and the 2014 composite DTM dataset.

11.9 A review of the two datasets has indicated better vertical accuracy from the 2014 composite DTM dataset or the Rough Burn model extent. However this dataset does not cover the whole model extent, 2009 photogrammetry dataset was therefore retained for the upper part of the model. A good match has been seen between banktop levels in the surveyed topographic data of Red Burn and 2009 photogrammetry data.

11.10 For all the modelled AEP events, overflows occur from Red Burn while Rough Burn remains in-channel or receives return flows from flood plain. This composite DTM is therefore deemed acceptable.

Grid Size

11.11 A 5m grid has been used. This is suitable to represent flood plain features to an appropriate level of detail.

Flood Plain Structures

11.12 A review of the flood plain using available aerial photographs, OS mapping and site inspection has shown that there are no flood plain structures that require representation in the model.

DTM Modifications

11.13 No modifications were made to the DTM. Site inspection and a check of aerial photographs established that no breaklines were required.

Model Artefacts

11.14 The flood depth comparison between the 'With-Mitigation' scenario and the baseline scenario has shown locally minor beneficial and adverse impacts. These are model artefacts due to shallow water flowing on steep hill.

11.15 Immediately upstream of the proposed Scheme crossing, in the vicinity of the old channel of Rough Burn, the flood depth comparison shows a significant increase in depth. In reality, depths cannot be compared as in the baseline scenario this location is part of the channel and in the 'With-Mitigation' scenario, it is part of the flood plain.

Model Calibration

11.16 No calibration was carried out as the modelled catchment is ungauged.

12 Conclusion

12.1 This report has detailed the modelling carried out to assess flood risk for Rough Burn and Red Burn with reference to the location of the proposed Scheme. A 0.8km reach of Rough Burn and 0.5km of Red Burn were represented in the model. A range of flood events from 50% to 0.1% AEP events were simulated.

12.2 The results have shown that in the baseline scenario, there are no properties at risk of flooding from Rough Burn and Red Burn. However the proposed Scheme footprint does interrupt modelled overland flow paths.

12.3 Rough Burn crossing by the proposed Scheme consists of a new culvert (SWF12-1 (C09)) and a realignment of a section of Rough Burn over 230m immediately upstream and downstream of the culvert. The proposed Scheme arrangement has been incorporated into the design scenario to assess its impact on the baseline flood risk. Results have shown that out of bank flows hit the proposed Scheme and flow along it to the west direction creating new flood risk.

12.4 Therefore mitigation measures are proposed which consist of two relief culverts under the proposed Scheme at the location of the main flow paths present in the flood plain.

12.5 With the mitigation measures in place, there is a decrease in in-channel water levels of less than 100mm for the 0.5% + CC AEP event immediately upstream of the realignment of Rough Burn. In the flood plain, flood impacts are negligible to minor, except immediately upstream of the relief culverts where localised flood depth increases of up to 0.72m are shown in the 0.5% AEP +CC event. This is due to the training of overland flows into the flood relief culverts.

12.6 A 50% and 90% blockage of the mainline culvert during a 0.5% AEP +CC event were considered. A 50% blockage would result in increasing in-channel water level immediately upstream of the culvert. A 90% blockage would result in significant in-channel and flood water depths increases immediately upstream of the culvert and a new flow path from the channel to the north-east direction along the proposed Scheme.

13 References

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

Scottish Environment Protection Agency (V9.1, 2015). Technical Flood Risk Guidance for Stakeholders (Ref SS-NFR-P_002)

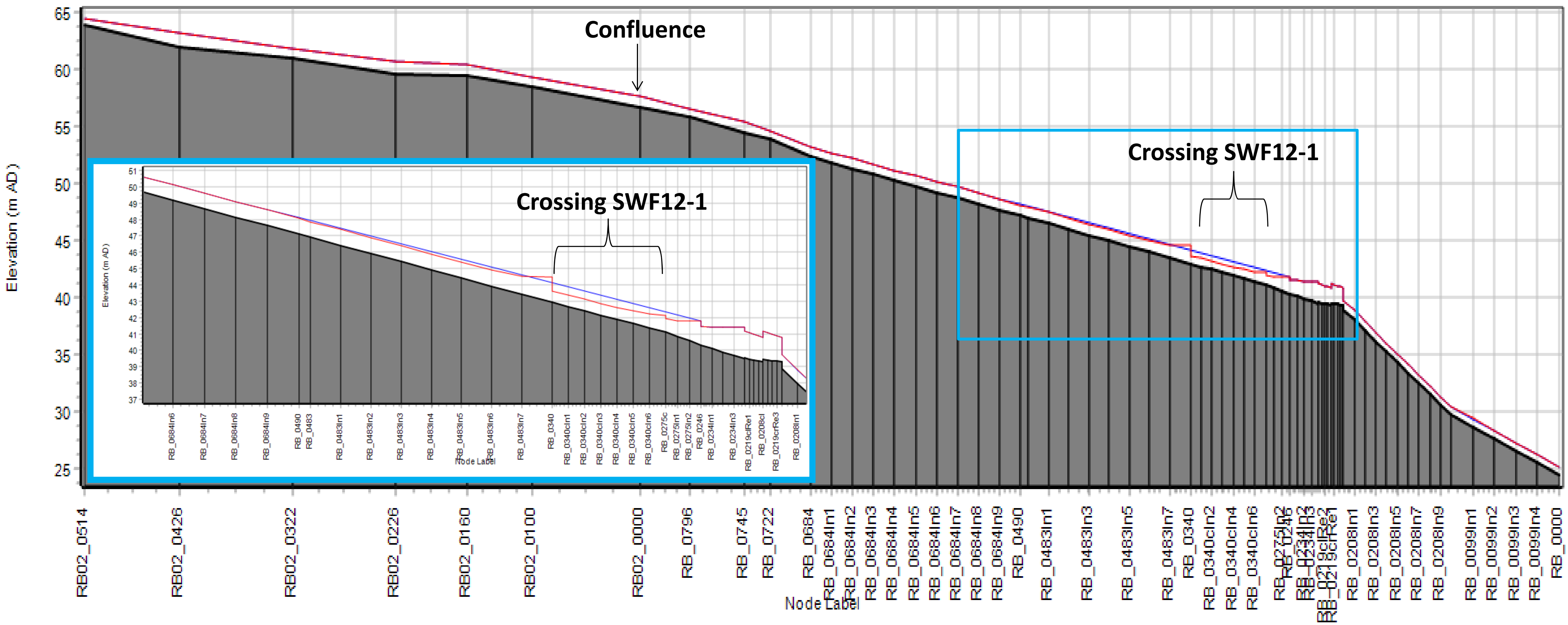
A.1 Water Level Tables and Long Sections

	Baseline Water Levels (mAOD)				
Modelled Event	**Model Node**				
	RB_0684 (312m Upstream of Scheme crossing)	RB_0490 (118m Upstream of Scheme crossing)	RB_0372 (At Scheme crossing)	RB_0340 (At Scheme crossing)	RB_0246 (126m Downstream of Scheme crossing)
50% AEP Event	52.805	47.717	44.588	-	40.955
20% AEP Event	52.878	47.799	44.658	-	41.085
10% AEP Event	52.920	47.845	44.707	-	41.200
3.33% AEP Event	52.983	47.915	44.787	-	41.374
2% AEP Event	53.015	47.952	44.823	-	41.451
1% AEP Event	53.064	48.008	44.873	-	41.557
0.5% AEP Event	53.114	48.065	44.925	-	41.667
0.5% AEP +CC Event	53.174	48.132	44.978	-	41.795
0.1% AEP Event	53.252	48.208	45.049	-	41.974

	'With-Mitigation' Water Levels (mAOD)				
Modelled Event	**Model Node**				
	RB_0684 (312m Upstream of Scheme crossing)	RB_0490 (118m Upstream of Scheme crossing)	RB_0372 (At Scheme crossing)	RB_0340 (At Scheme crossing)	RB_0246 (126m Downstream of Scheme crossing)
3.33% AEP Event	52.984	47.855	-	44.011	41.375
0.5% AEP Event	53.113	47.996	-	44.344	41.668
0.5% AEP +CC Event	53.172	48.060	-	44.480	41.798
0.1% AEP Event	53.252	48.145	-	44.669	41.983

	Change in Water Level (m)				
Modelled Event	**Model Node**				
	RB_0684 (312m Upstream of Scheme crossing)	RB_0490 (118m Upstream of Scheme crossing)	RB_0372 (At Scheme crossing)	RB_0340 (At Scheme crossing)	RB_0246 (126m Downstream of Scheme crossing)
3.33% AEP Event	0.001	-0.060	-	-	0.001
0.5% AEP Event	-0.001	-0.069	-	-	0.001
0.5% AEP +CC Event	-0.002	-0.072	-	-	0.003
0.1% AEP Event	0.000	-0.063	-	-	0.009

Diagram A1: Rough Burn Long Section – 0.5% AEP +CC Event - In-Channel Peak Water Levels



A.2 Flood Extent Maps

Diagram A2: Baseline Flood Extent for Entire Model Extent. 20%, 10%, 3.33% and 2% AEP Flood Events

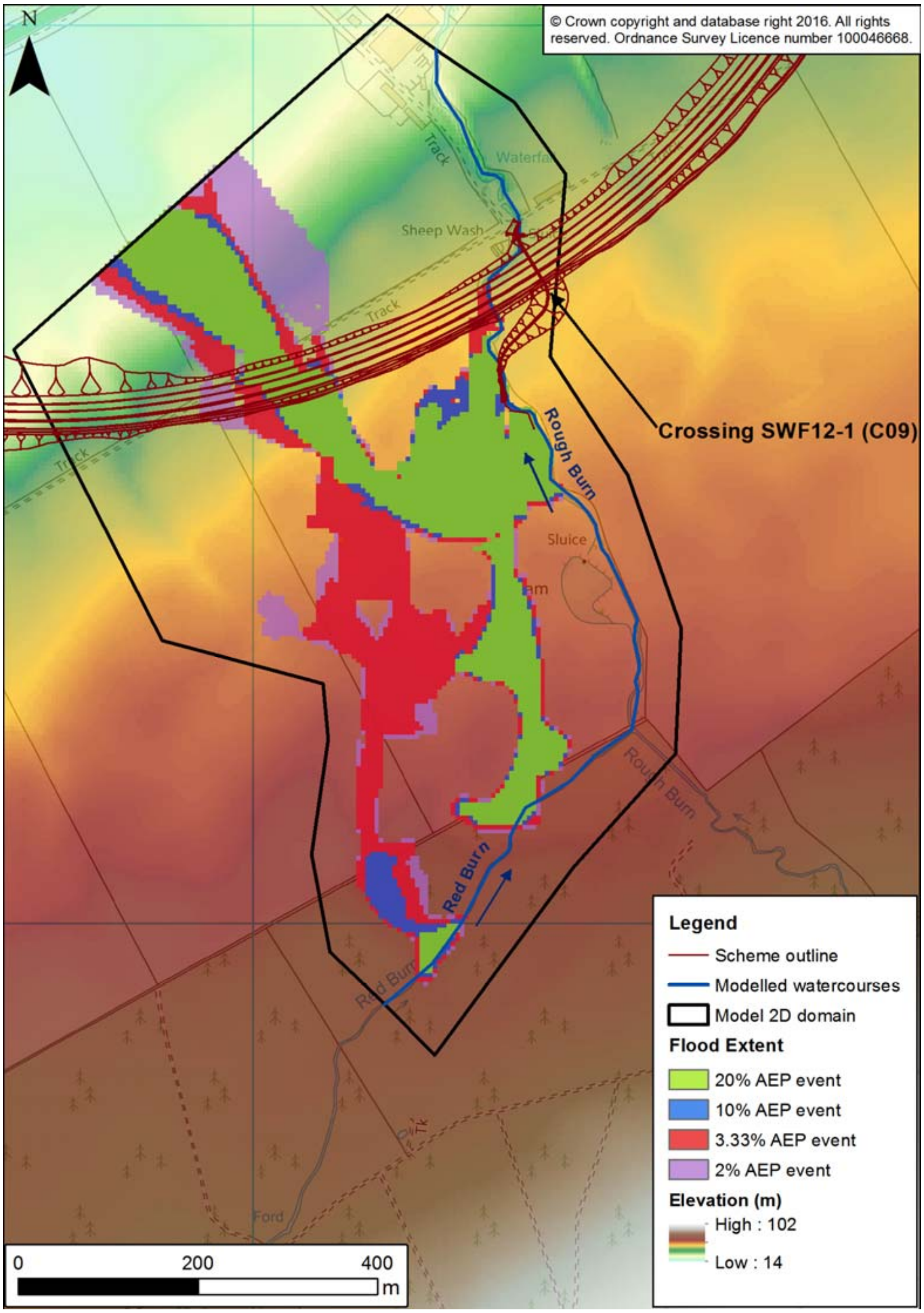
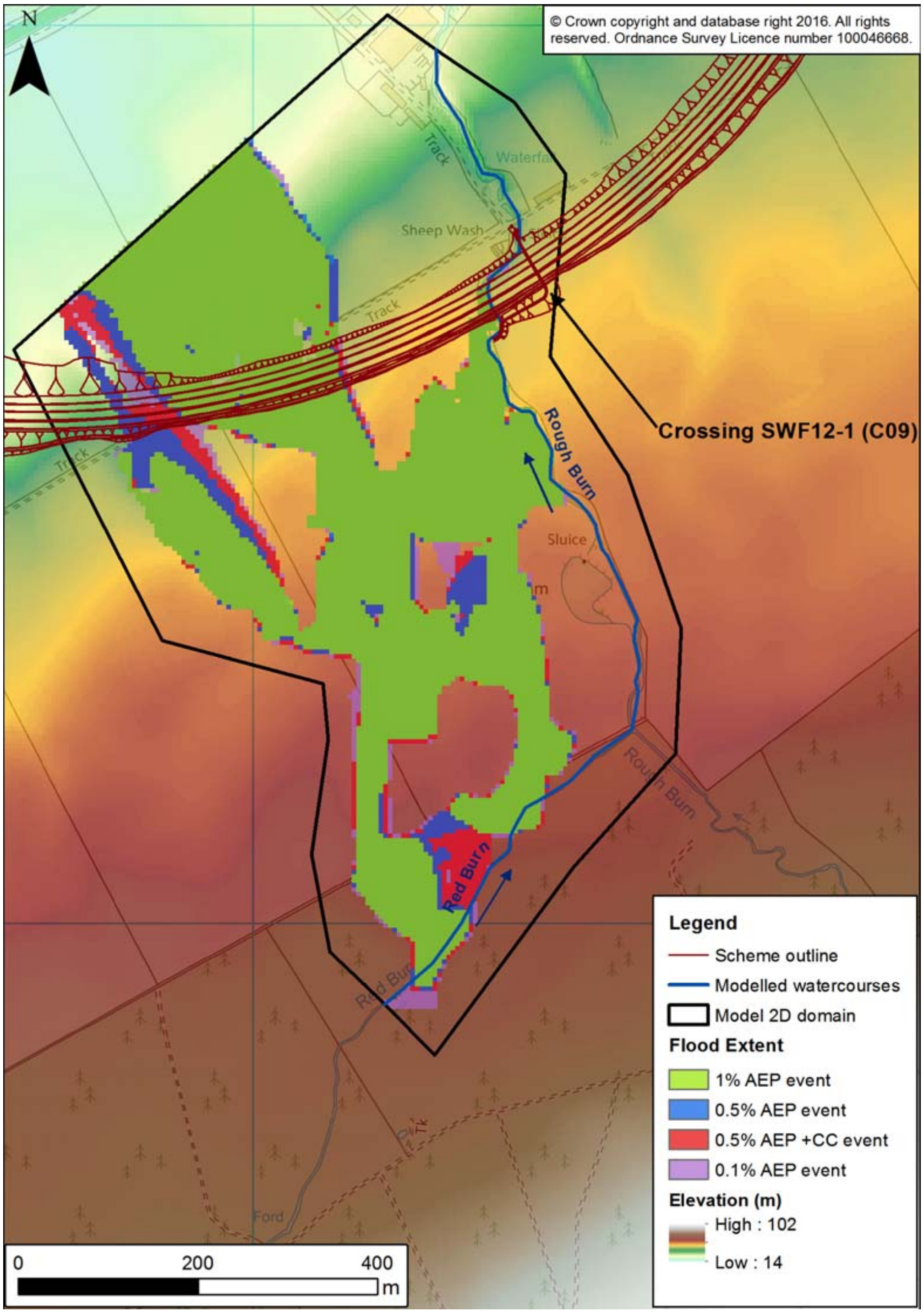


Diagram A3: Baseline Flood Extent for Entire Model Extent. 1%, 0.5%, 0.5% +CC and 0.1% AEP Flood Events



A.3 'With-Mitigation' Depth Change Maps

Diagram A4: 3.33% AEP Event Depth Difference Map

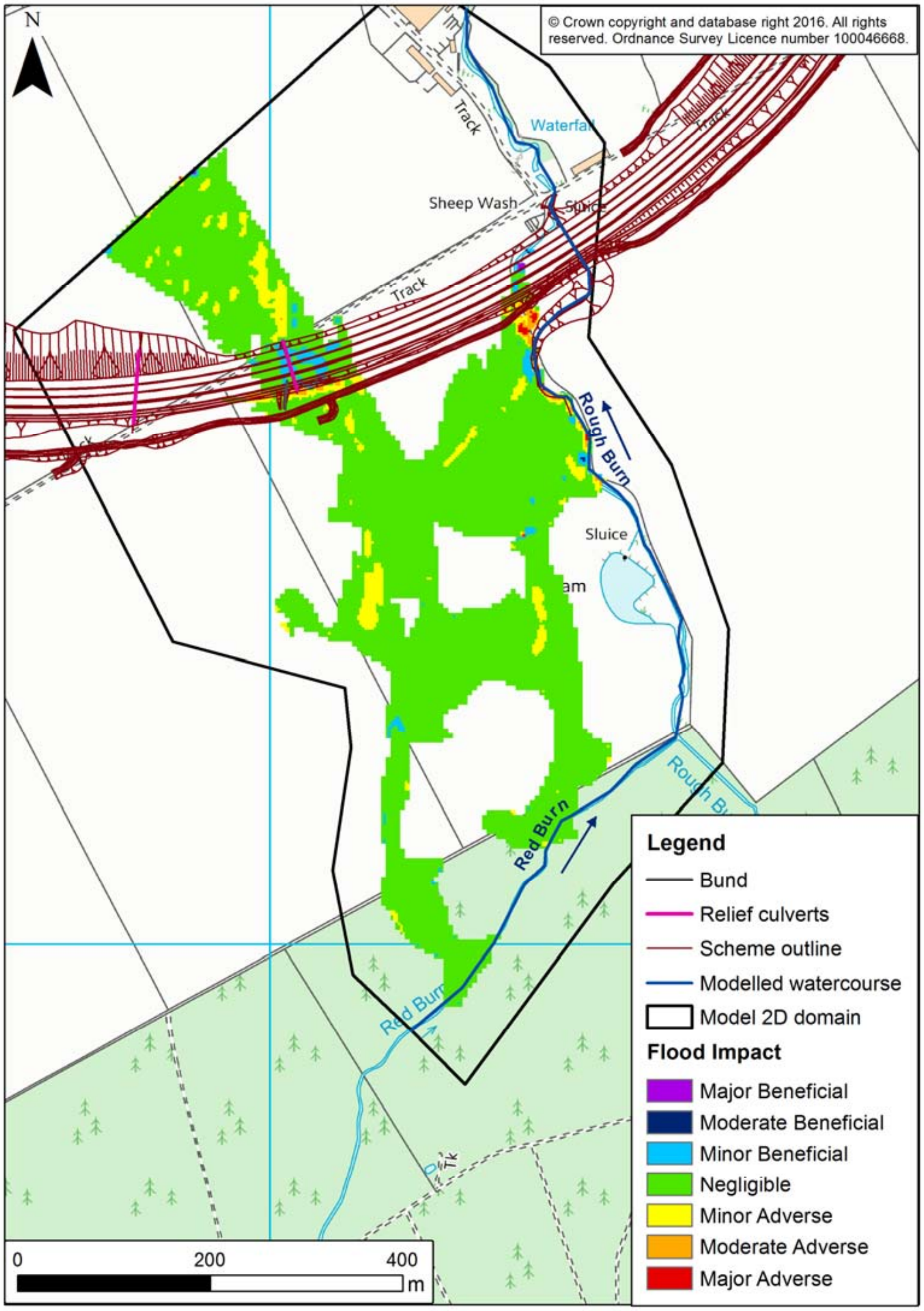


Diagram A5: 0.5% AEP Event Depth Difference Map

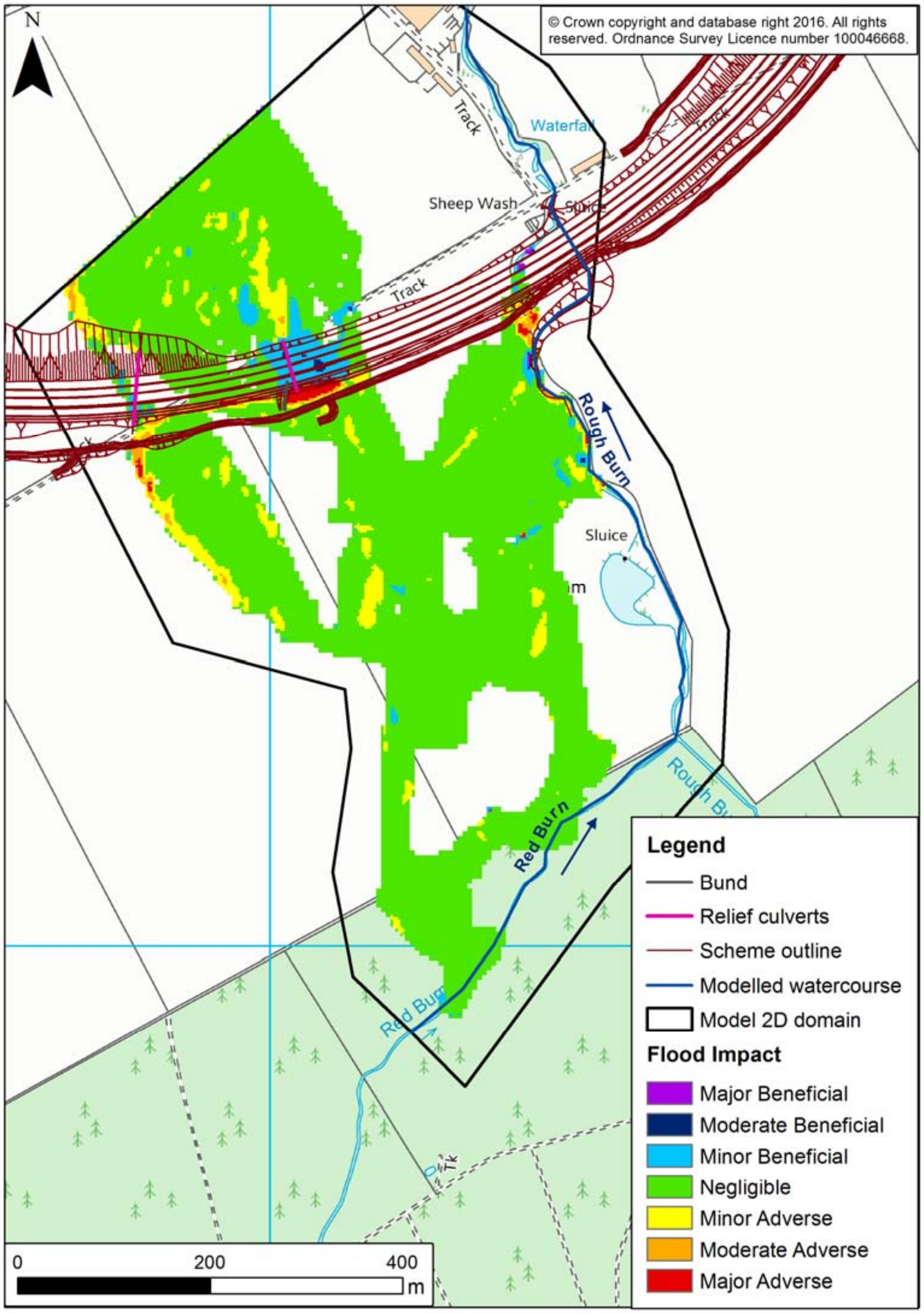


Diagram A6: 0.5% AEP +CC Event Depth Difference Map

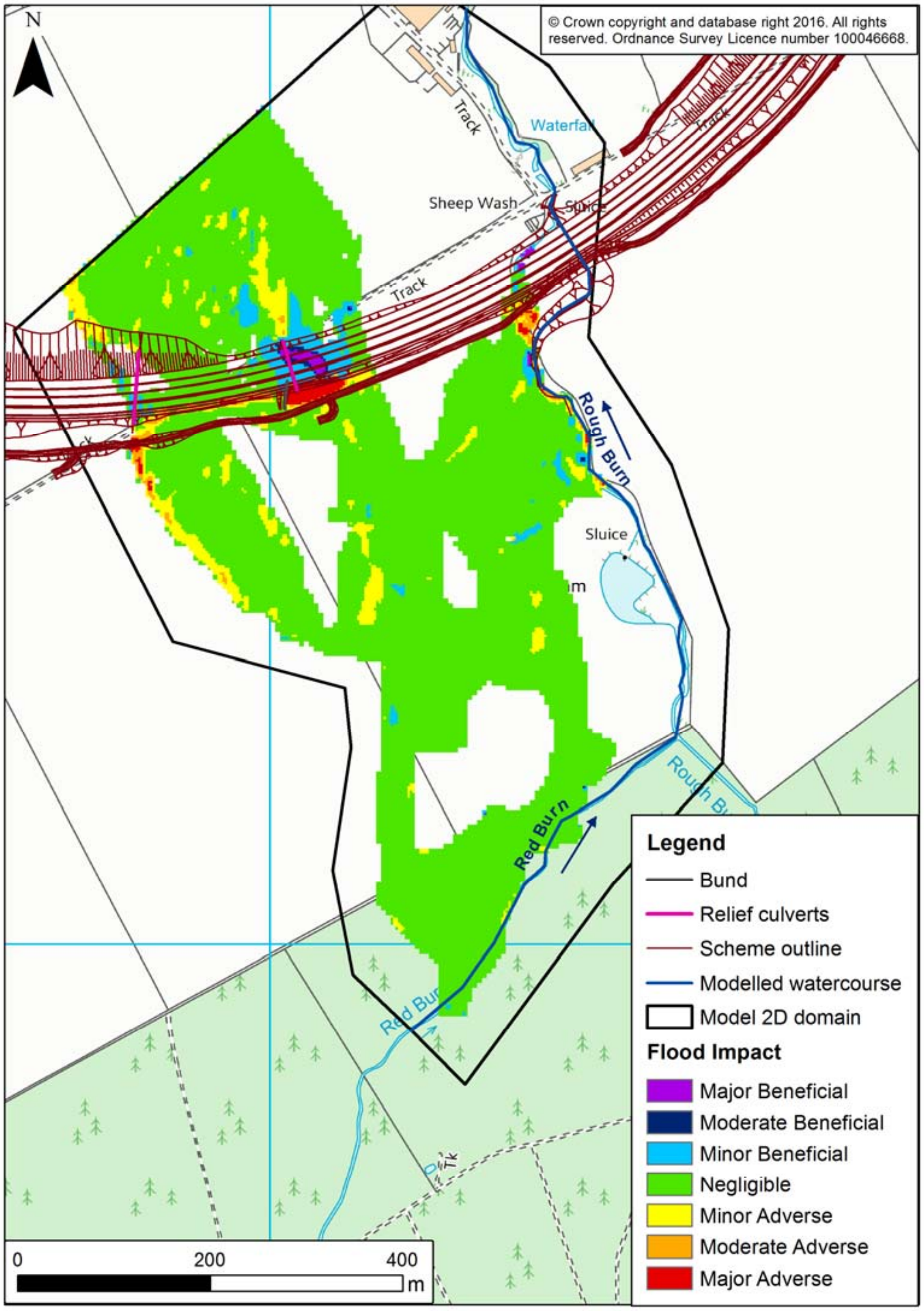
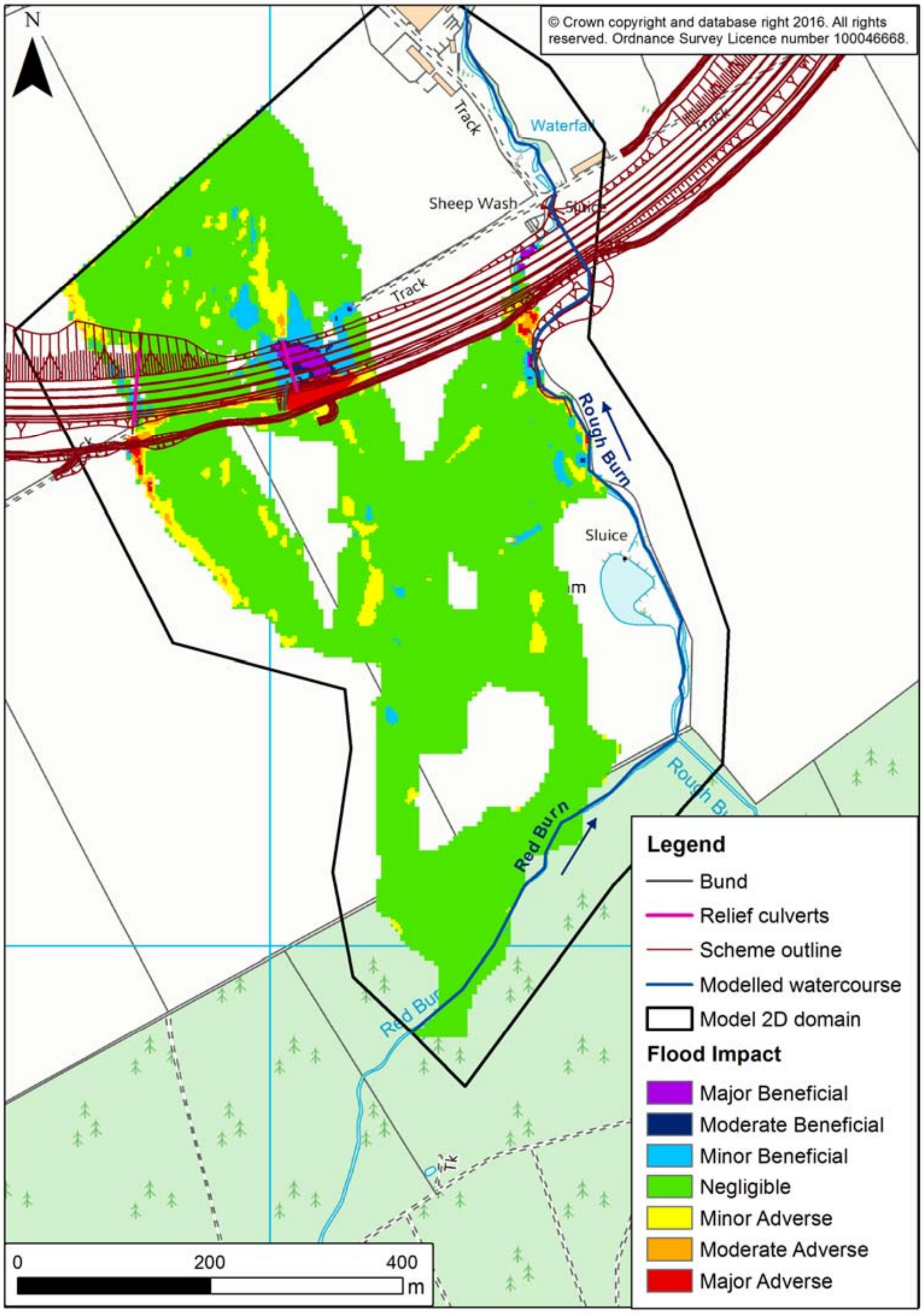


Diagram A7: 0.1% AEP Event Depth Difference Map



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A13.2.D Tributary of Ardersier Burn Hydraulic Modelling Report

1 Introduction

Purpose

1.1 This annex provides detailed information on the hydraulic modelling relevant to Appendix 13.2 (Flood Risk Assessment).

1.2 The A96 Dualling Inverness to Nairn (including Nairn Bypass) scheme comprises the provision of approximately 31km of new dual carriageway, achieved through offline construction (hereafter referred to as the proposed Scheme). The existing A96 single carriageway would be de-trunked and reclassified as a local road to maintain local access to the proposed Scheme. Due to the size and layout of the proposed Scheme, there are a number of flood risks, which may place the road and its users at risk of flooding. The proposed Scheme also has the potential to impact the level of flood risk elsewhere.

1.3 The proposed Scheme starts east of the roundabout for Inverness Retail Park, approximately 850m east of Raigmore Interchange, and continues approximately 30km east and ends at Hardmuir, 3.5km to the east of Auldearn. The proposed Scheme would incorporate:

- 22 watercourse crossings;
- provision of shared use paths suitable for Non-Motorised Users (NMU), approximately 30km in length;
- six grade separated junctions;
- 24 principal structures including a crossing of the River Nairn and three structures over the Aberdeen to Inverness Railway Line;
- local road diversions and provision of new private means of access; and
- utility diversions including major diversions for Scottish Gas Networks (SGN) and CLH Pipeline Systems (CLH-PS).

1.4 For key watercourse crossings a Flood Risk Assessment (FRA) was required to meet relevant local and national planning legislation and inform the design and planning process. Hydraulic modelling was required to support the FRA. This took the form of computational hydraulic models with associated catchment hydrology. The impact of the proposed Scheme on water level both upstream and downstream and the associated flood envelope was determined for a range of storm flood events at each watercourse crossing.

1.5 The key watercourse crossings for which a hydraulic modelling was carried out to support the FRA are:

- Cairnlaw Burn crossing (Annex 13.2.B Cairnlaw Burn Hydraulic Modelling Report);
- Rough Burn crossing (Annex 13.2.C Rough Burn Hydraulic Modelling Report);
- Tributary of Ardersier Burn crossing (this report);
- River Nairn crossing (Annex 13.2.E River Nairn Hydraulic Modelling Report); and
- Auldearn Burn crossing (Annex 13.2.F Auldearn Burn Hydraulic Modelling Report).

1.6 This report details the methodology and the results of the hydraulic modelling carried out for the Tributary of Ardersier Burn crossing, for the baseline and 'with-scheme' situation. This is a technical report, focused on the hydraulic modelling, and therefore the intended audience is those with a reasonable understanding and knowledge of hydraulic modelling principles, although no specific knowledge of particular software is needed.

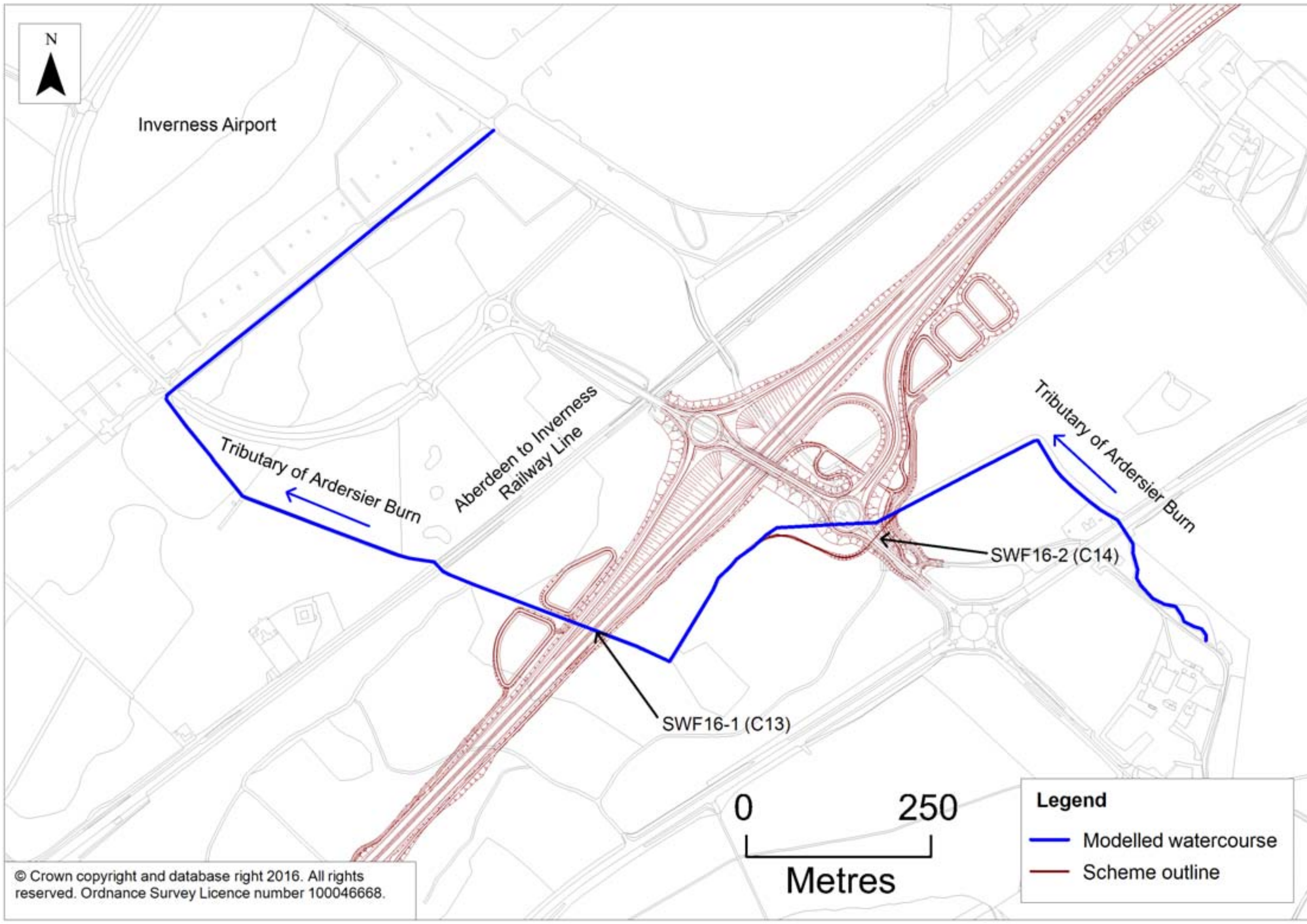
Methodology

1.7 The hydraulic model was built using a linked One-dimensional/Two-dimensional (1D/2D) schematisation, where the river channel is represented as a 1D component and is linked to the flood plain, which is represented by a 2D domain. The 1D component was constructed using the river modelling package Flood Modeller Pro (version 4.1), and the 2D component was constructed using TUFLOW (version 2013-12-AE-iSP-w64). 350m of watercourse at the downstream end of the model was represented in 2D only.

Study Area

1.8 Within the study area (Diagram 1) the Tributary of Ardersier Burn flows north-west before turning 90 degrees to flow south-west. After a second 90 degree bend the watercourse flows north-west and under the Aberdeen to Inverness Railway Line. At Inverness Airport the Tributary of Ardersier Burn turns 90 degrees and flows north-east to a culvert under the airport. The model includes approximately 2.4km of the Tributary of Ardersier Burn. There are two new crossings for the proposed Scheme within the Tributary of Ardersier Burn study area; these have been named SWF16-1 (C13) and SWF16-2 (C14).

Diagram 1: Tributary of Ardersier Burn Study Area



2 Input Data

2.1 The data used to construct the hydraulic model for the Tributary of Ardersier Burn are summarised in Table 1.

Table 1: Data Used to Build the Hydraulic Model

Data	Description	Source
Photogrammetry/ LiDAR	2014 composite DTM: Car-based LiDAR data for existing A96 carriageway 10m horizontal resolution photogrammetry data See A96 Geodetic Survey Report_v1_0.pdf Used to represent the topography for part of the 2D domain	Blom Aerofilms
A96 proposed Scheme topography	MXROAD ASCII grids	Jacobs 2016
OS maps	Mastermap data 1 to 10,000 Scale Raster	Transport Scotland
Channel survey	In-channel cross sections and hydraulic structures See Section 4 (Watercourse Schematisation - 1D Domain)	Jacobs Site survey 2015
Flood plain survey	Point survey of flood plain at approximately 10m spacing. Used to represent the topography for most of the 2D model extent. See Section 4 (Flood Plain Schematisation - 2D domain)	Jacobs Site survey 2016
Watercourse photographs	Site visit – in-channel watercourse photographs	Jacobs Site survey 2015 Site inspection 2015
Hydrological analysis	Hydrological analysis carried out for the Tributary of Ardersier Burn See Section 3 (Hydrology)	Jacobs 2016

3 Hydrology

3.1 The details of the analysis carried out to produce inflows for the hydraulic model are provided in a separate hydrology report (Annex 13.2.G (Surface Water Hydrology Report)), which was undertaken for the DMRB Stage 3 assessment.

3.2 Two inflows have been applied to the model. A point inflow at the upstream extent of the Tributary of Ardersier Burn and a lateral inflow applied over 270m of channel, upstream of the first crossing (see locations in Diagram 2).

3.3 The peak inflows have been estimated for the 50%, 20%, 10%, 3.33%, 2%, 1%, 0.5% and 0.1% Annual Exceedance Probability (AEP) flood events.

3.4 The peak inflows were produced using the Flood Estimation Handbook (FEH) statistical method. The hydrograph shape was derived from the FEH rainfall-runoff model hydrograph shapes. These hydrographs used a theoretical critical storm duration of 6.6 hours calculated at the downstream extent of the hydrology model. During the modelling, a critical storm duration analysis was carried out, which showed that a storm duration of 10.2 hours was critical at key proposed Scheme locations. Therefore, a critical storm duration of 10.2 hours was used in the modelling. The same hydrograph shape and critical storm duration was used for all inflows.

3.5 In order to assess the impact of Climate Change (CC), a 20% uplift of the hydrological inflows was applied on the 0.5% AEP event. This climate change uplift factor is based on current standard practice (SEPA 2015).

3.6 Peak inflows of the modelled watercourses are shown in Table 2 for all the events simulated.

Table 2: Hydrological Inflow Peak Values and Locations

Location	Peak Flow (m^3/s)								
	AEP 50%	AEP 20%	AEP 10%	AEP 3.33%	AEP 2%	AEP 1%	AEP 0.5%	AEP 0.5% + CC	AEP 0.1%
Tributary of Ardersier Burn upstream model extent	0.93	1.30	1.58	2.10	2.39	2.83	3.35	4.02	4.95
Upstream of first crossing (lateral inflow)	0.03	0.04	0.05	0.07	0.08	0.09	0.10	0.12	0.15

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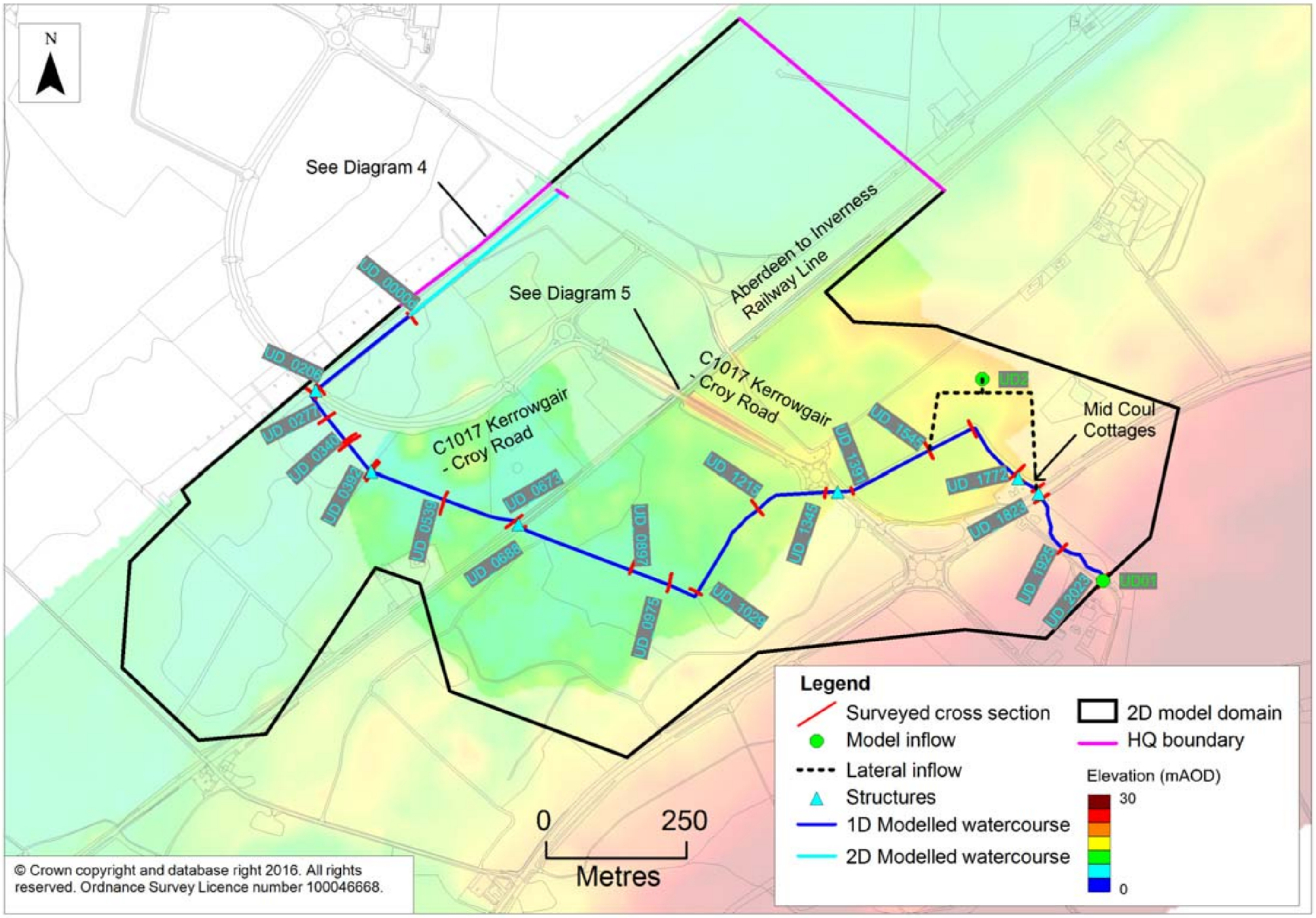
Diagram 2: Tributary of Ardersier Burn Model Schematisation



4 Baseline Modelling

Watercourse Schematisation - 1D Domain

In-Channel Geometry

4.1 Surveyed cross section data has been used to inform the in-channel geometry of the modelled watercourse. The location of the surveyed cross sections is shown in Diagram 2. To aid model performance, interpolated cross sections were added between the surveyed cross sections as required. The spacing of the interpolated cross was approximately 40m.

4.2 Table 3 shows the Flood Modeller nodes associated with the modelled watercourse.

Table 3: Flood Modeller Nodes

Reach	Upstream Node	Downstream Node
Tributary of Ardersier Burn	UD_2023	UD_0000

In-Channel Hydraulic Friction

4.3 Hydraulic roughness (Manning's 'n' coefficient) values were determined primarily using the photographs taken during the survey. Generally the watercourse is vegetated with some clearer sections at the upstream and downstream end. The banks of Tributary of Ardersier Burn are vegetated with rough grass. The Manning's 'n' coefficients used in the model are shown in Table 4. Roughness values adopted were taken from standard guidance (Chow 1959).

Table 4: Manning's 'n' Coefficients – 1D Domain

Flood Modeller Nodes	Bed Manning's 'n'	Bed Material	Banks Manning's 'n'	Banks Material
UD_2023 to UD_1823	0.04	Steep, stony channel	0.07	Rough grass
UD_1801 to UD_1391	0.06	Heavily vegetated channel	0.07	Rough grass
UD_1345 to UD_0688	0.04	Encroaching vegetation, clear bed material	0.07	Rough grass
UD_0673 to UD_0221	0.05	Heavily vegetated channel	0.07	Rough grass
UD_0206 to UD_0000	0.04	Wide and clear channel	0.07	Rough grass

In-Channel Hydraulic Structures

4.4 Six hydraulic structures were included in the model. Table 5 provides details regarding these structures. Their locations are shown in Diagram 2.

4.5 The culvert under C1017 Kerrowgair – Croy Road at model node UD_0221 had an irregular shape caused by infilling with bed material. To model this, a regular shaped sprung arch conduit was used with a blockage unit at the upstream and downstream end. The blockage unit reduces the functional bore area of the opening to match that seen in the survey. The upstream was blocked by 24% and the downstream blocked by 31%.

Table 5: In-Channel Hydraulic Structures

Structure	Flood Modeller Node	Specification	
Culvert under the existing A96	UD_1823	**Type:** **Upstream bed level:** **Downstream bed level:** **Length:** **Diameter:**	Circular conduit 15.253mAOD 15.112mAOD 21.330m 1.810m
Twin culvert under gardens at Mid Coul Cottages	UD_1772	**Type:** **Left upstream bed level:** **Left downstream bed level:** **Right upstream bed level:** **Right downstream bed level:** **Length:** **Left diameter:** **Right diameter:**	Twin circular conduits 14.060mAOD 13.750mAOD 14.029mAOD 13.800mAOD 18.130m 0.620m 0.360m
Twin culvert under C1017 Kerrowgair – Croy Road	UD_1391	**Type:** **Left upstream bed level:** **Left downstream bed level:** **Right upstream bed level:** **Right downstream bed level:** **Length:** **Diameter:**	Twin circular conduits 11.750mAOD 11.604mAOD 11.730mAOD 11.615mAOD 46.480m 0.900m
Culvert under Aberdeen to Inverness Railway Line	UD_0688	**Type:** **Upstream bed level:** **Downstream bed level:** **Length:** **Width:** **Springing height:** **Crown height:**	Sprung arch conduit 7.501mAOD 7.247mAOD 15.210m 1.630m 1.609m 0.810m
Culvert under access track	UD_0405	**Type:** **Upstream bed level:** **Downstream bed level:** **Length:** **Diameter:**	Circular conduit 6.897mAOD 6.802mAOD 12.710m 0.700m
Culvert under C1017 Kerrowgair – Croy Road	UD_0221	**Type:** **Upstream bed level:** **Downstream bed level:** **Length:** **Width:** **Springing height:** **Crown height:**	Sprung arch conduit with blockage units at inlet and outlet (see description in text) 6.550mAOD 6.550mAOD 15.150m 2.240m 0.470m 0.660m

Boundary Conditions – 1D Domain

4.6 The upstream and downstream boundary conditions applied to the 1D domain are described in Table 6. Inflow locations are shown in Diagram 2.

Table 6: Boundary Conditions – 1D Domain

Type of Boundary	Flood Modeller Node	Description
FEH Boundary	UD01	Scaled FEH boundary. Applied at the upstream end of the Tributary of Ardersier Burn.
FEH Boundary	UD02	Scaled FEH boundary. Applied as a lateral inflow upstream of first the proposed Scheme crossing.
Head-Time	UD_0000d	Dummy Head-Time boundary condition applied to the downstream end of Tributary of Ardersier Burn (see paragraph 4.8), required to facilitate transfer of flows to the 2D domain.

Flood Plain Schematisation - 2D domain

Flood Plain Topography

4.7 Diagram 2 shows the 2D model domain of Tributary of Ardersier Burn, which covers an area of approximately 1.3km². The topography is represented using a 4m resolution square grid. The levels for the grid cells are based on a Digital Terrain Model (DTM) derived from two datasets. The DTM for the wider flood plain and the flood plain close to the channel at the upstream and downstream model extents is based on 2014 photogrammetry data. Due to the coarse nature of the photogrammetry data there was a discrepancy with the channel survey data. This was an issue as it affects the level used for the link between the 1D and 2D model domains. Therefore, for the flood plain close to the channel in the vicinity of the proposed Scheme a spot level survey was carried out in 2016 and used to replace the photogrammetry data within this area. Diagram 3 shows the extent of the two topographic surveys within the study area.

2D Schematisation

4.8 At the downstream extent of the river survey data the Tributary of Ardersier Burn continues towards Inverness Airport. Initial model results showed that this section of watercourse needed to be included in the model. This section of the model was schematised as shown in Diagram 4. A dummy HT boundary in the 1D model was joined to an SX connection in the 2D model, allowing flow to leave the 1D model and enter the 2D domain. The watercourse was carved into the 2D domain using a breakline. The carved channel is approximately 350m long. The levels in the channel gradually transition from the bed level of the downstream Flood Modeller cross section to the levels in the 2014 photogrammetry data. This coarse approach was adopted to represent the channel due to the lack of survey data here. In addition it has been shown that the downstream extent of the model does not affect water levels at the proposed Scheme (see Section 7 (Sensitivity Analysis)).

4.9 A Stage-Discharge (HQ) boundary, Normal Depth type was added at the downstream of the carved channel, at the airport boundary, where the watercourse enters a culvert. It was appropriate to use a free discharge boundary, ignoring the effect of the culvert, as this area of the model does not impact on water levels at the proposed Scheme (see Section 7 (Sensitivity Analysis)). An additional HQ boundary of Normal Depth type was added to the north-west of the carved channel along the 2D model extent to allow any water here to flow out of the model. The 2D downstream boundaries are described further in paragraph 4.12.

Flood Plain Hydraulic Friction

4.10 Hydraulic roughness coefficients are applied over each grid cell of the 2D domain, as shown in Table 7, depending on land use taken from OS Mastermap data. Roughness values adopted were taken from standard guidance (Chow 1959).

Table 7: Manning's 'n' Coefficients – 2D Domain

Land Use	Manning's n
Roads, tracks and paths	0.025
Rail	0.050
Buildings, manmade structures	1.000
Trees, rough grassland	0.100
Embankments, cliff	0.050
Land, general surface	0.055
Water, inland water	0.020
Property gardens	0.050
Unclassified land/open ground	0.035

Diagram 3: Topographic Data Extent

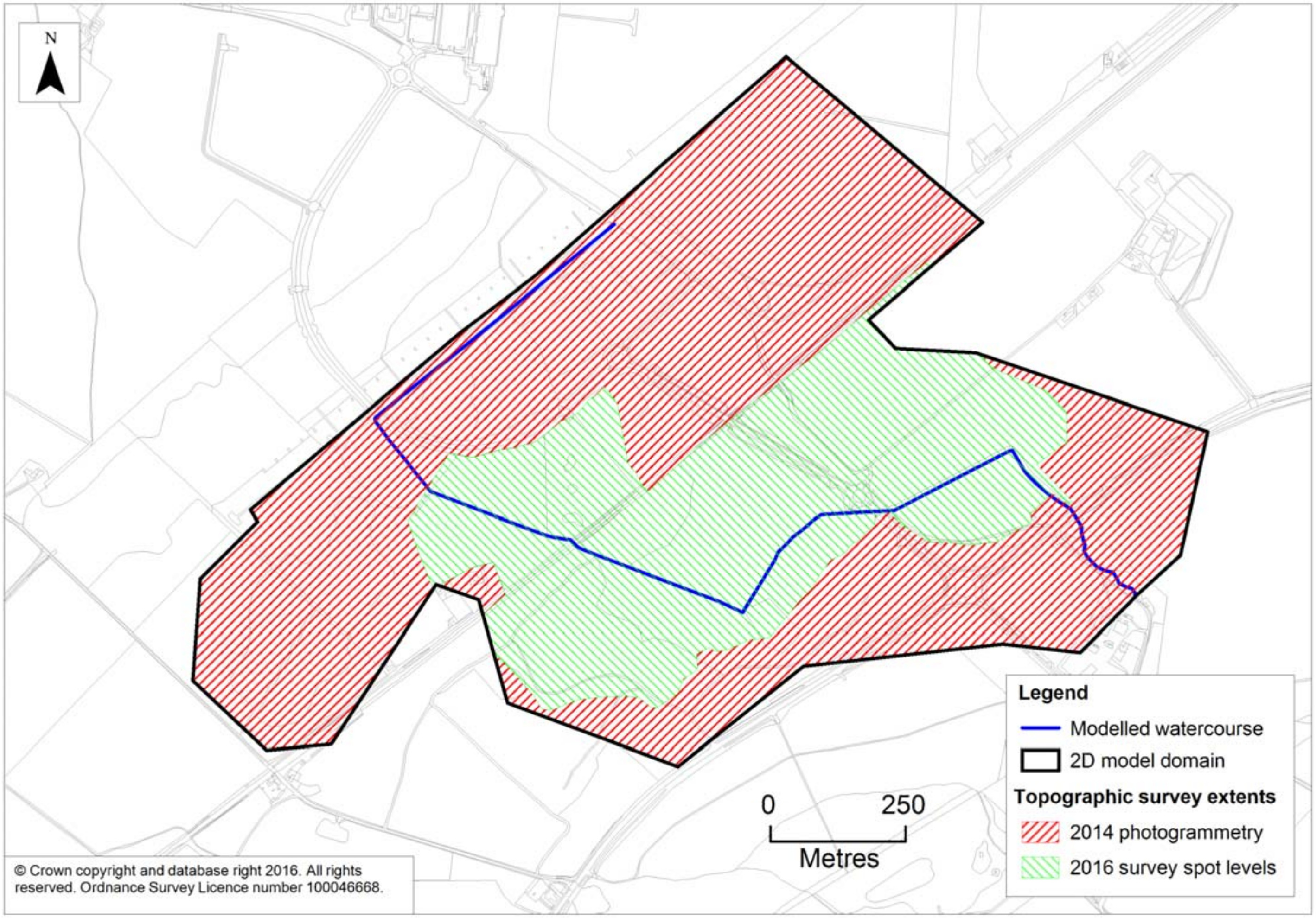
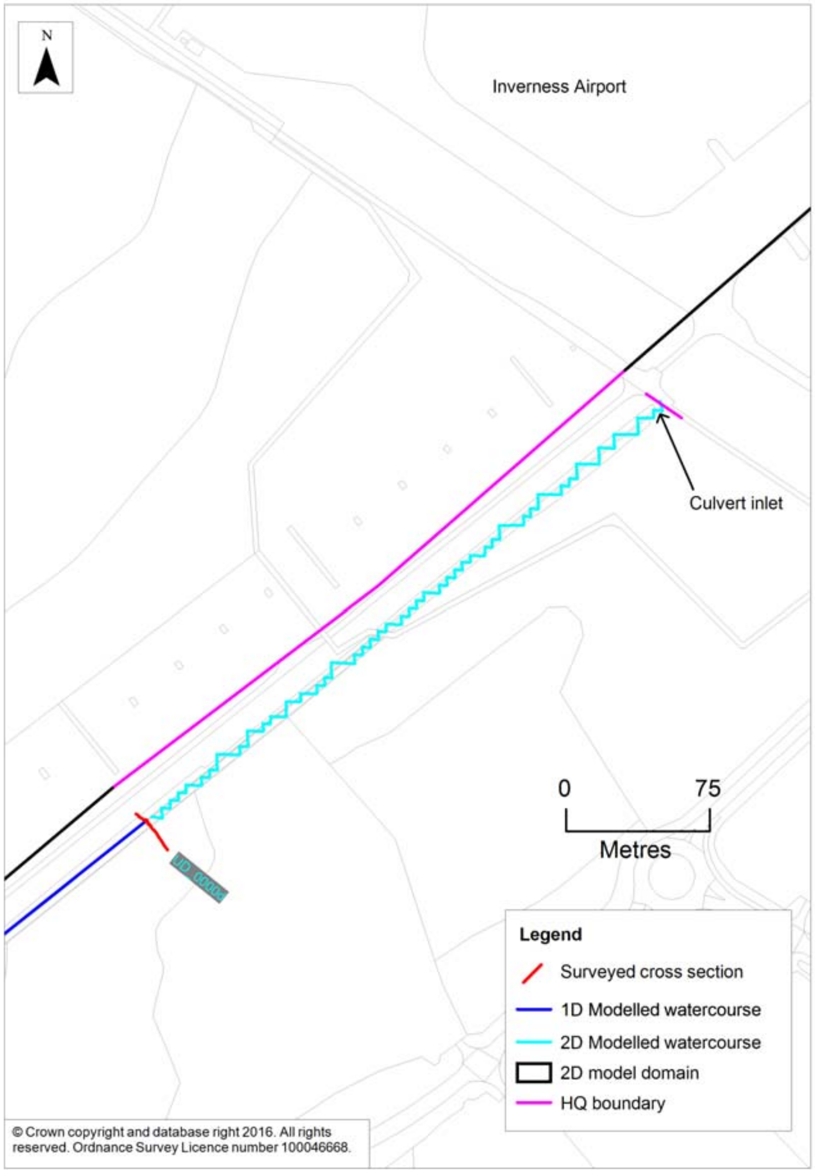


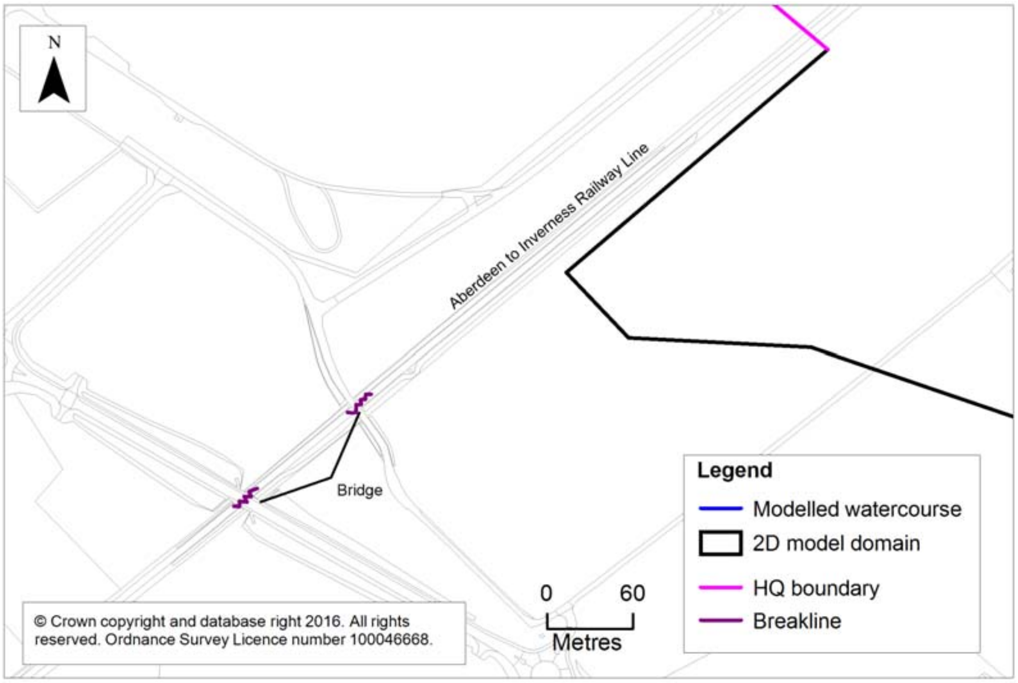
Diagram 4: Model Downstream Schematisation



<u>Flood Plain Structures</u>

4.11 To the north-west of the model extent is the Aberdeen to Inverness Railway Line (Diagram 5). Initial model results showed that flood water will flow along the Aberdeen to Inverness Railway Line, which is in a cutting. There are two road bridges crossing the Aberdeen to Inverness Railway Line. The topography only contains the road deck level, which creates a barrier to flow along the Aberdeen to Inverness Railway Line. Therefore breaklines were added at each of these bridges to allow the modelled flows to propagate correctly.

Diagram 5: Flood Plain Modification at Aberdeen to Inverness Railway Line Road Crossings



Boundary Conditions – 2D Domain

4.12 No inflow has been applied directly in the 2D domain. Table 8 describes the downstream boundary conditions used in the 2D domain. The locations are shown in Diagram 2.

Table 8: Boundary Conditions - 2D Domain

Type of Boundary	TUFLOW Feature	Description
Stage-Discharge	HQ Boundary	Free flow boundaries to allow water to flow out of the model at three locations: • At the downstream end of the carved channel to represent flow out of the model at the location of the culvert under the airport. • To the north-west of the carved channel to allow water overtopping from the carved channel to flow out of the model. • On the north-east model extent to allow flow in larger events to leave the model. These boundaries assigns a water level to the 2D cells based on a stage–discharge curve generated using the ground slope.

1D/2D Linking

4.13 The 1D and 2D domains were linked along the Tributary of Ardersier Burn. The link was defined preferentially using the 2016 spot survey data, and using the 2014 photogrammetry outside of the topographic survey extent (see Diagram 3).

5 'With-Scheme' Modelling

Proposed Scheme Arrangement

5.1 As shown in Diagram 7, the proposed Scheme, within the Tributary of Ardersier Burn study area, consists of a new offline dual carriageway with associated infrastructure. There are two new culverts (SWF16-1 (C13) and SWF16-1 (C14)). In addition there is one area of watercourse realignment and a number of highway drainage ponds incorporated within the proposed Scheme.

Modelling Approach

<u>1D Model Updates</u>

SWF16-1 (C13)

5.2 Structure SWF16-1 (C13) is a new culvert under the proposed Scheme. The culvert inlet and outlet tie into the toe of the proposed Scheme embankments. The invert levels for the inlet and outlet were matched to the bed levels of the channel from the baseline model. The culvert has been modelled as a box culvert and is assumed to have a square headwall. The dimensions of the culvert were determined by calculating the channel capacity in this area in the baseline model. This gave a culvert of 2m wide by 1.5m high.

5.3 The Roughness within the culvert was set at a Colebrook-White Friction value of 0.001m (Manning's 'n' equivalent N=0.012) for new concrete walls and soffit and 1.36m (Manning's 'n' equivalent N=0.04) for the culvert invert, to match the upstream bed roughness.

SWF16-1 (C14)

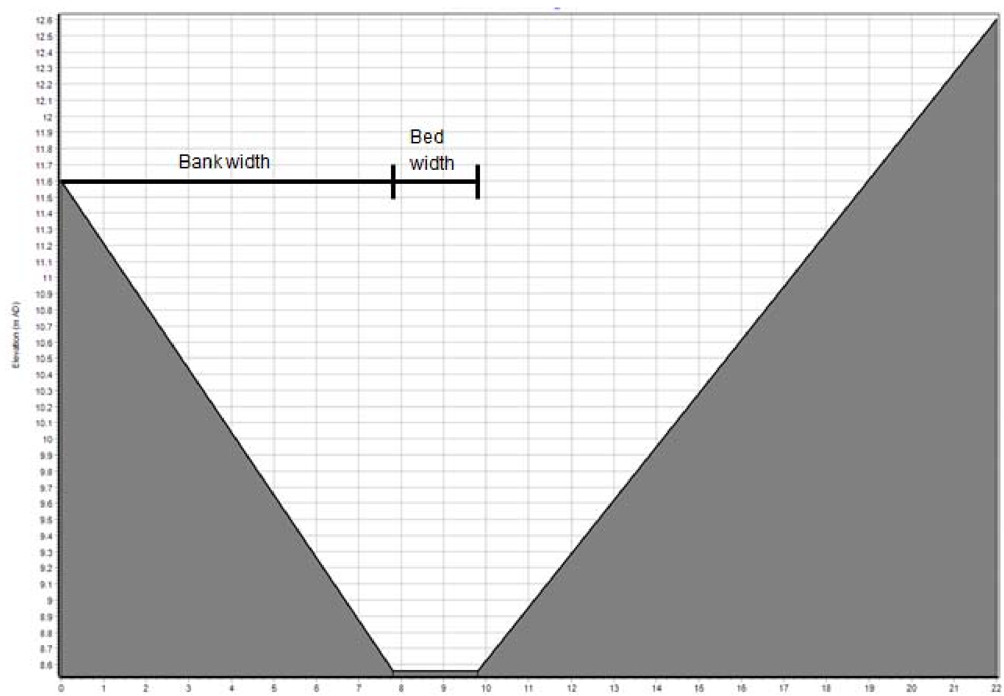
5.4 Structure SWF16-1 (C14) is a new culvert under C1017 Kerrowgair – Croy Road. The culvert inlet and outlet tie into the toe of the proposed Scheme embankments. The invert levels for the inlet and outlet were matched to the bed levels of the channel, defined by the realignment of the Tributary of Ardersier Burn (see paragraph 5.6). The culvert has been modelled as a box culvert and is assumed to have a square headwall. The dimensions of the culvert were determined by calculating the capacity of culvert UD_1391 in the baseline model. This gave a culvert of 1m wide by 1m high.

5.5 The Roughness within the culvert was set at a Colebrook-White Friction value of 0.001m (Manning's 'n' equivalent N=0.012) for new concrete walls and soffit and 1.36m (Manning's 'n' equivalent N=0.04) for the culvert invert, to match the upstream bed roughness.

Realignment

5.6 The proposed Scheme requires a realignment of the Tributary of Ardersier Burn onto a 259m reach of new channel (Diagram 7). New cross sections were added to the model along this reach. The bed levels of the new cross sections were defined using a linear gradient between cross sections from the baseline model, at the upstream and downstream end of the realignment. The old section of channel, between model node UD_1391 and UD_1215 was removed from the model. A typical channel shape was used for the section with a 2m wide bed and sloping banks (Diagram 6). The width of the banks was measured from the design drawings. The existing ground levels from the 2016 survey and 2014 photogrammetry were used for the bank tops as required. The channel roughness for the new sections was set at a Manning's 'n' value of 0.04.

Diagram 6: Typical Realignment Cross Section

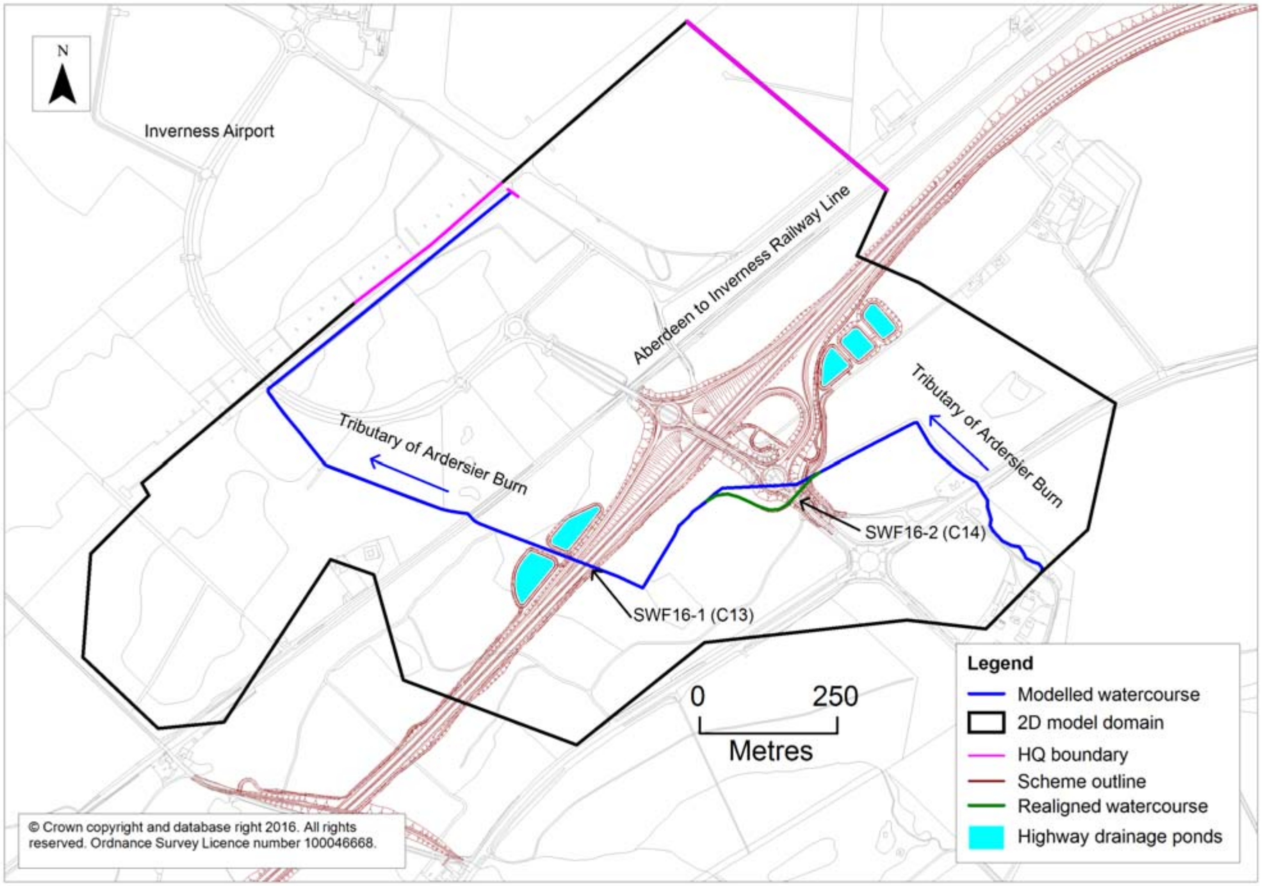


2D Model Updates

5.7 The design features were added to the 2D model. The proposed Scheme road elevations were exported from the MXROAD software as ASCII grids, for inclusion in the hydraulic model. The ASCII grids replaced the ground elevation with the elevations for the proposed Scheme road. The design requires there to be no connection between the flood plain and the highway drainage ponds. The ponds were included in the model as z-shapes with nominally high level to ensure no wetting of these areas.

5.8 The 1D/2D link was updated for the realigned channel.

Diagram 7: 'With-Scheme' Tributary of Ardersier Burn Model Schematisation



6 Modelled events

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

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

Table 9: Modelled Events

Scenario	AEP Event								
	50%	20%	10%	3.33%	2%	1%	0.5%	0.5% + CC	0.1%
Baseline	✓	✓	✓	✓	✓	✓	✓	✓	✓
Roughness Sensitivity (1D and 2D)							✓		
Hydrological Inflow Sensitivity							✓		
Downstream Boundary Sensitivity							✓		
'With-Scheme'								✓	
'With-Mitigation' Measures		✓		✓			✓	✓	✓
'With-Mitigation' Measures – 50% blockage of new culverts								✓	
'With-Mitigation' Measures – 90% blockage of new culverts								✓	

7 Model Proving

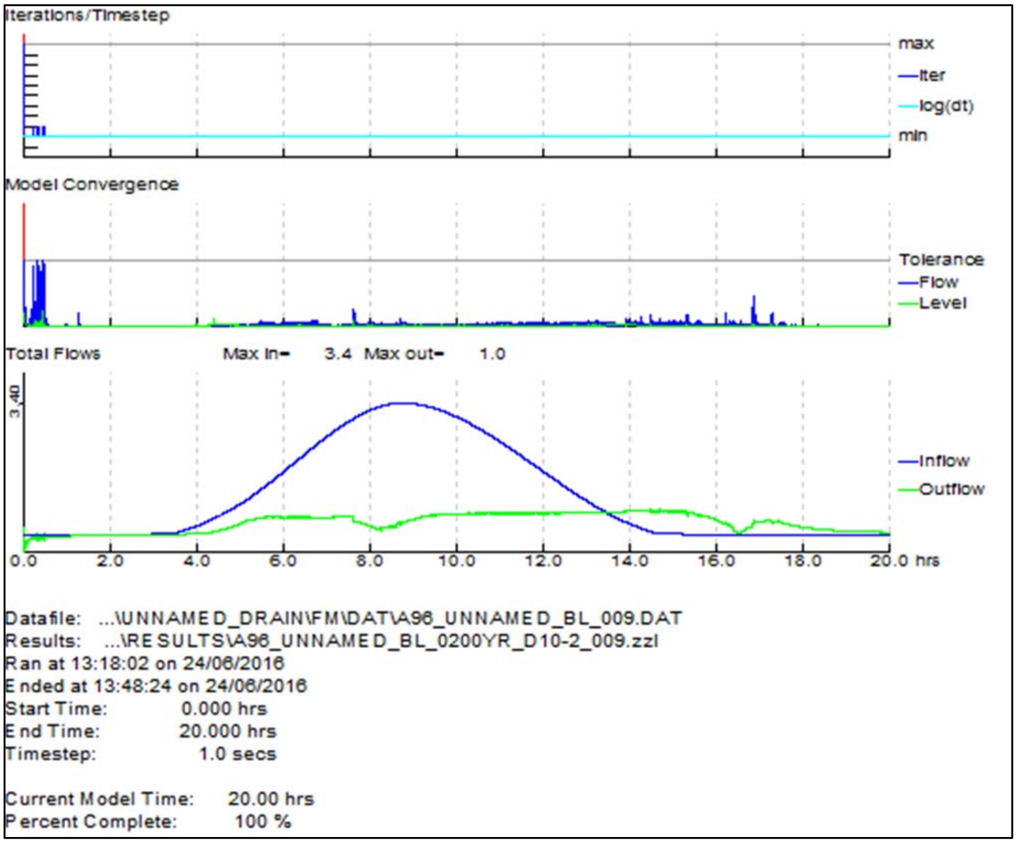
Introduction

7.1 The following sections discuss the model performance and the verification process. In addition, details relating to the additional runs carried out to test the sensitivity of the model to key variables are also discussed.

Model Performance

7.2 Run performance has been monitored throughout the model build process and then during each simulation carried out, to ensure a suitable model convergence was achieved. Convergence refers to the ability of the modelling software to arrive at a solution that is close to the exact solution within a pre-specified error tolerance. As shown in Diagram 8 below, the only 1D non-convergence is at the beginning of the simulation and will not affect the results at the peak. This convergence plot is typical for the events modelled.

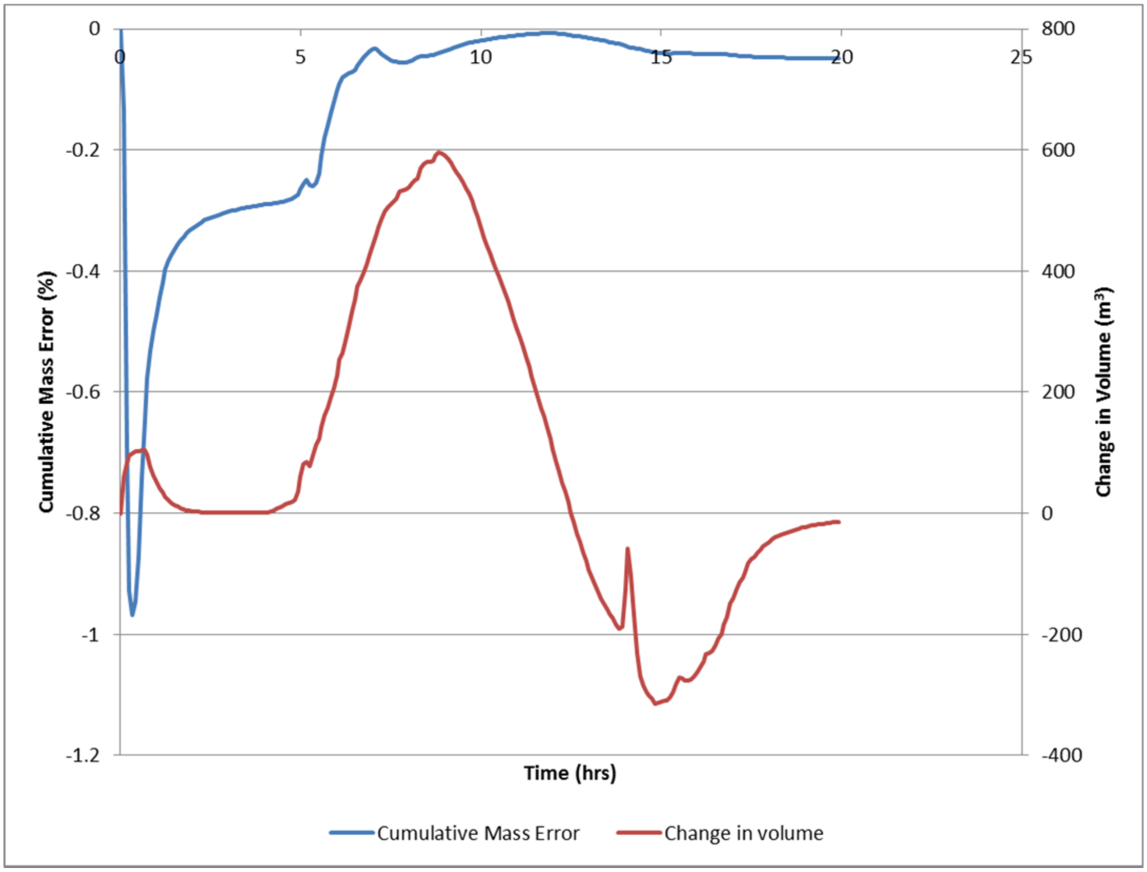
Diagram 8: 1D Model Convergence – 0.5 % AEP Event



7.3 The cumulative mass error reports output from the TUFLOW 2D model have been checked. The recommended tolerance range is +/- 1% Mass Balance error. The change in volume through the model simulation has also been checked and has been found to vary smoothly, which is also an indicator of good convergence of the 2D model.

7.4 Diagram 9 shows that the cumulative mass error is within the tolerance range for the whole simulation. This Mass error diagnostic is typical for all events modelled.

Diagram 9: 2D Cumulative Mass Error and Change in Volume – 0.5 % AEP Event



Calibration and Verification

<u>Calibration</u>

7.5 There are no gauges on Tributary of Ardersier Burn within the extent of the model. Therefore, it was not possible to calibrate the model. However, data is available for a high level verification of the model results.

<u>Verification using Historic Data</u>

7.6 There were two types of historic data available for verifying the Tributary of Ardersier Burn model: 2015 flood incident records and flood remark data.

7.7 The 2015 flood incident data only shows the location of flooding and does not give any further information. There are two records in this dataset within the Tributary of Ardersier Burn study area. Both are close to the proposed Scheme and are likely to be a record of surface water flooding on the road. Therefore, this flooding is not shown by the model results, which only show fluvial flooding.

7.8 Table 10 shows the flood remark data. There is a good match between this data and the modelling results. There are two flood remarks in this dataset within the Tributary of Ardersier Burn study area. Both match with key overtopping on the left bank of Tributary of Ardersier Burn as shown in Diagram 10).

Table 10: Flood Remark Data

ID	Comment	Model Verification
26	Flood risk in this area advised	• Model shows flooding at this location with an onset in the 20% AEP event
48	Seasonal flooding from ditch	• Model shows flooding at this location with an onset in the 50% AEP event

Verification using SEPA Flood Maps

7.9 Flood extent maps are available from the Scottish Environment Protection Agency (SEPA). These maps show the fluvial flood extent for different likelihoods of flooding (high, medium and low). The SEPA medium likelihood of flooding is equivalent to a 0.5% AEP event. Therefore a comparison has been made with the modelled baseline 0.5% AEP event flood extents (Diagram 11). The comparison shows that in some areas, particularly close to the watercourse, there is generally good match between the model results and the SEPA map. However in the wider flood plain at some locations the match is not so good, with a difference in flood mechanism evident. The FRA modelling utilises a finer level of detail, along with refined catchment hydrology analysis, which explains the discrepancy with the published flood map.

Verification Conclusion

7.10 In conclusion, the model shows a good general match with the verification data. A number of points cannot be reconciled. However, it is suggested that these are not significant and that the model has been developed with as much detail as possible within the scope of the present study. The model is thought to be an appropriate representation of the existing situation, for the purpose of flood risk assessment of the proposed Scheme.

Diagram 10: Location of Flood Remarks

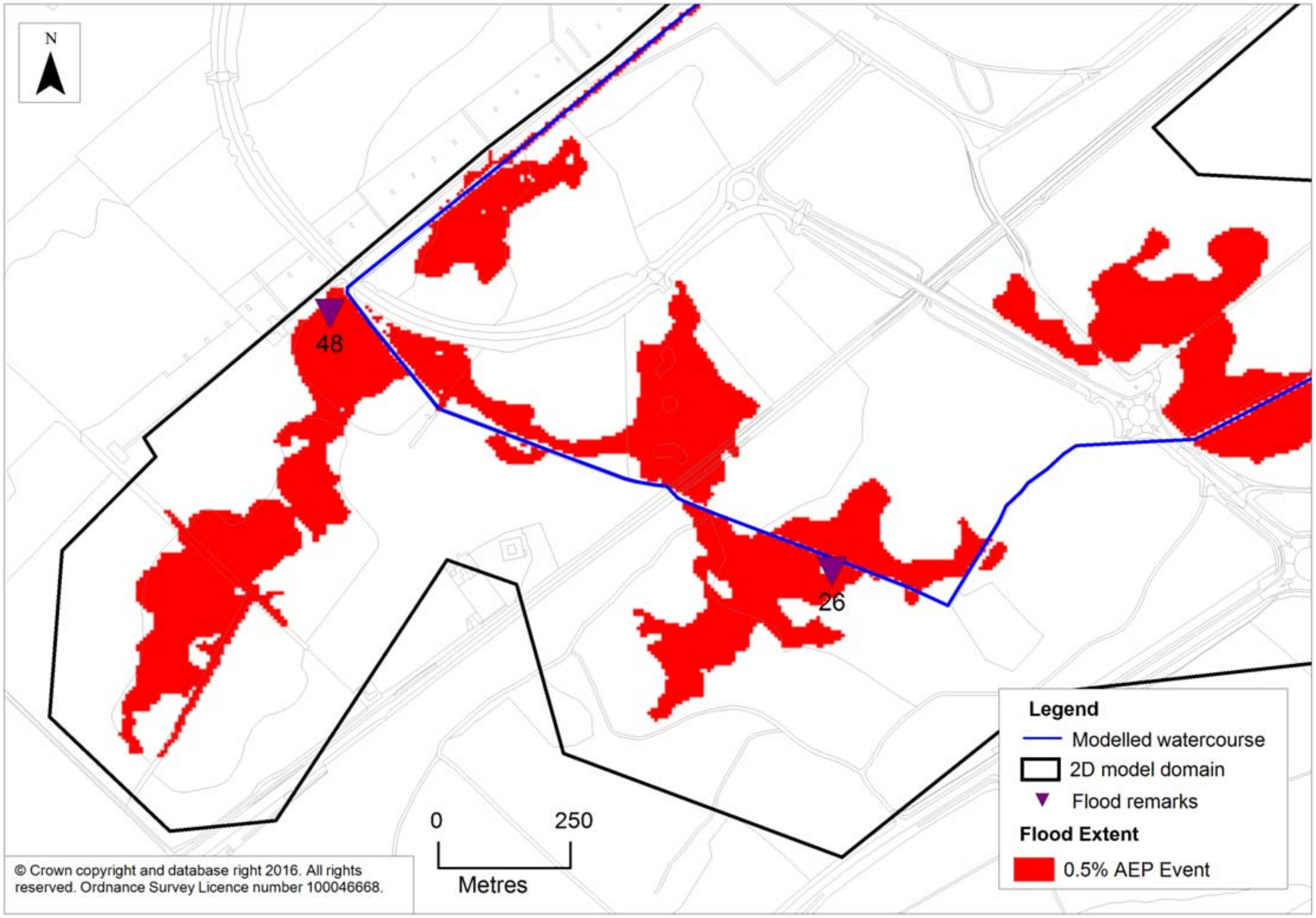
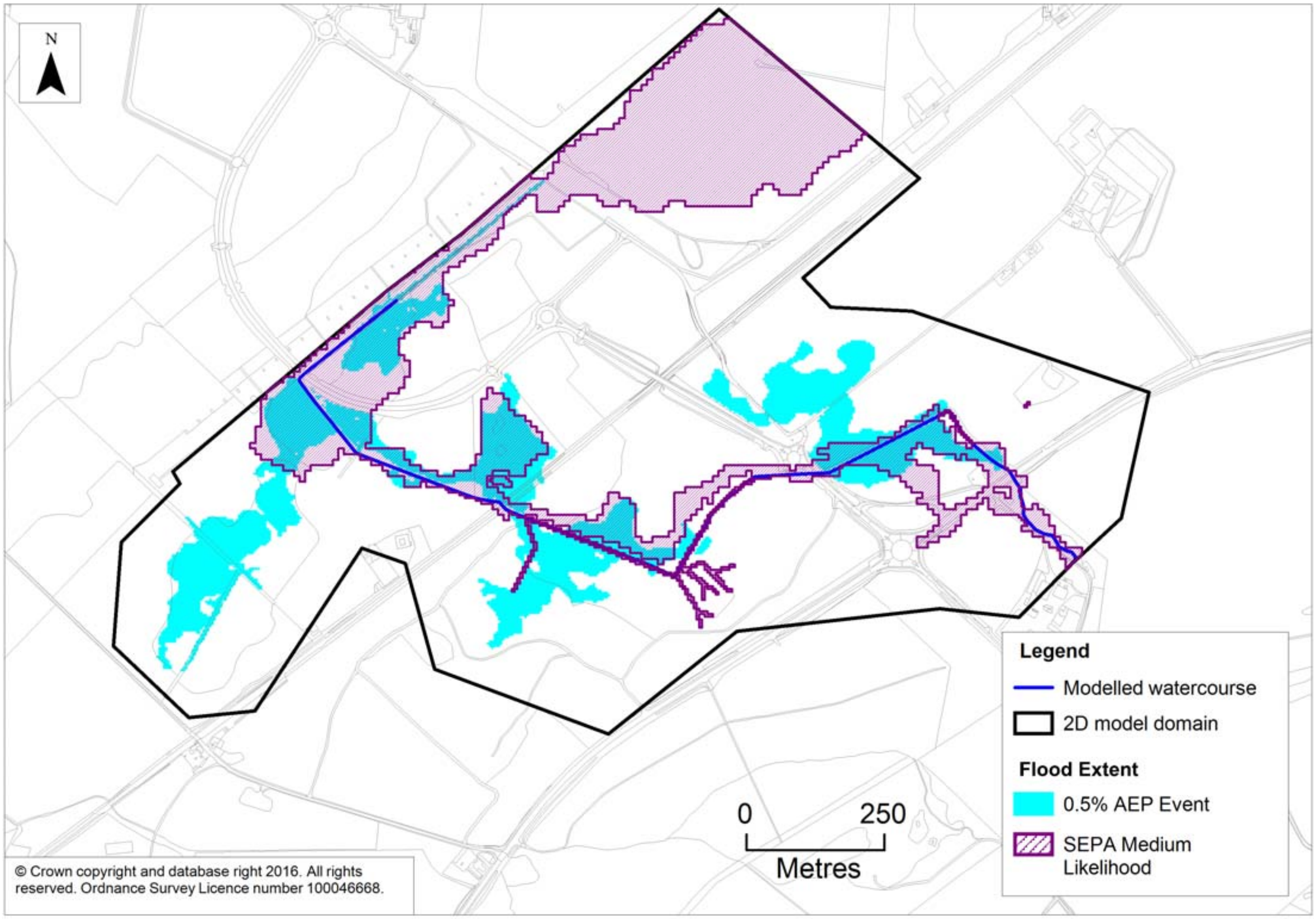


Diagram 11: Modelled 0.5 % AEP Event Flood Extent vs. SEPA Medium Likelihood Fluvial Extent



Sensitivity Analysis

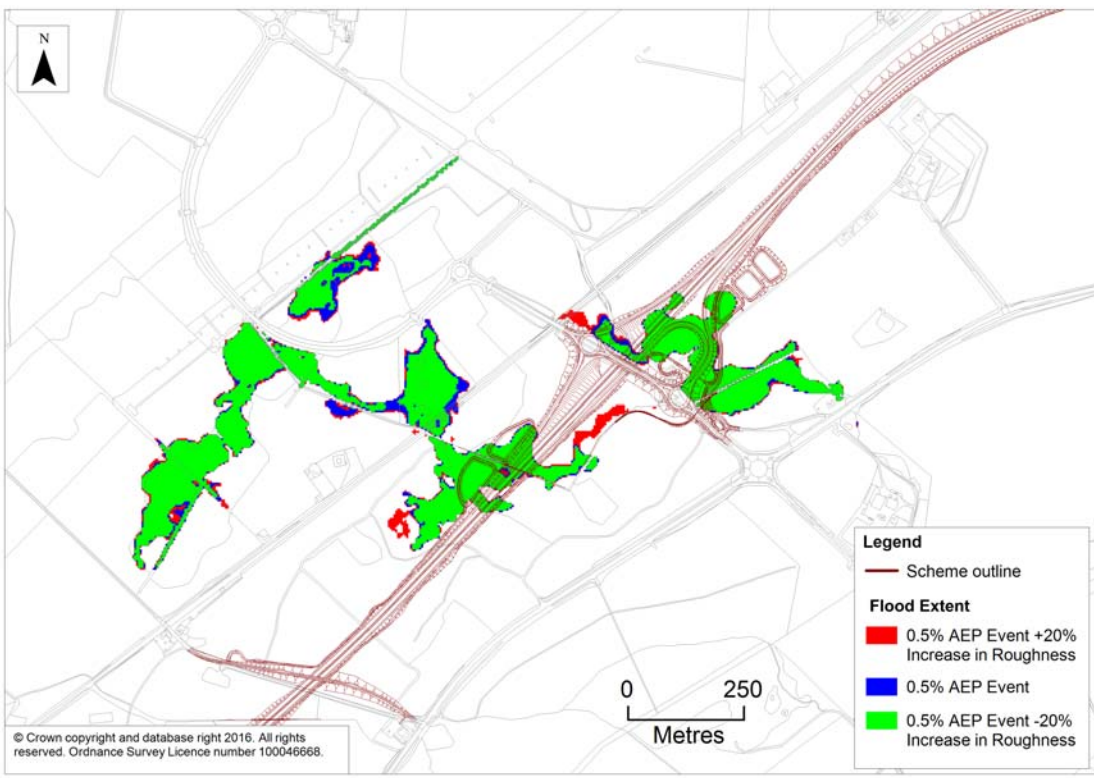
Roughness Sensitivity

7.11 In-channel and flood plain roughness coefficients (Manning's 'n') were changed by +20% and -20%. Table 11 shows the impact of changing the model roughness on in-channel water levels. Results are presented for the 1D reach of Tributary of Ardersier Burn. The differences in water level are also shown for upstream of each proposed Scheme culvert location. The results show that the in-channel water levels are slightly sensitive to changes in roughness. At the proposed Scheme the results are not sensitive to changes in roughness. Diagram 12 shows that changes in flood extent as a result of changing the model roughness are minimal.

Table 11: Roughness Sensitivity Results

Sensitivity	Water Level Difference (m)				
	Max	Min	Average	At SWF16-1 (C13)	At SWF16-2 (C14)
+20% Roughness	0.094	0.000	0.041	0.032	0.025
-20% Roughness	-0.113	0.000	-0.046	-0.041	-0.026

Diagram 12: Change in the 0.5% AEP Event Flood Extent - Roughness Sensitivity



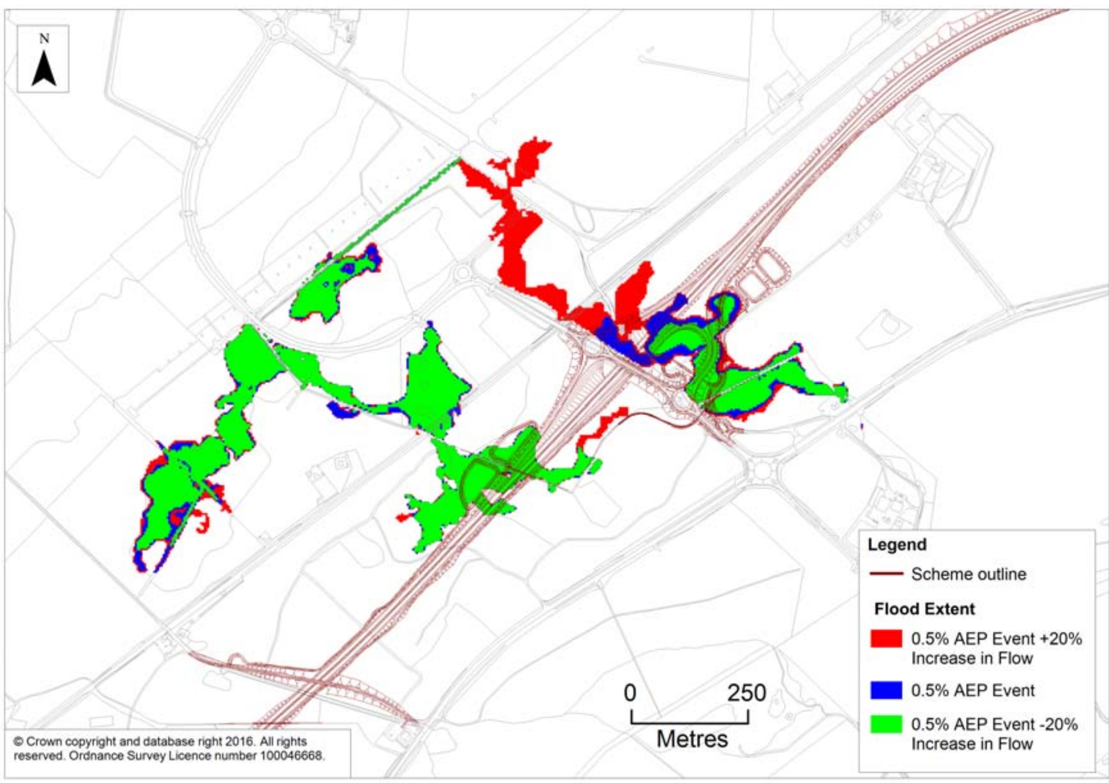
Hydrological Inflow Sensitivity

7.12 The flows into the model were adjusted by +20% and -20%. Table 12 shows the impact of changing the model inflows on in-channel water levels. Results are presented for the 1D reach of Tributary of Ardersier Burn. The differences in water level are also shown for upstream of each proposed Scheme culvert location. The results show that the model is slightly sensitive to changes in flow. At the proposed Scheme the results are not sensitive to changes in flow. Diagram 13 shows how the flood extent changes as a result of changing the model inflows. The results generally show that changes in flood extent as a result of changing the model inflows are minimal. However there is a change in flood extent for the flooding close to the airport.

Table 12: Flow Sensitivity Results

Sensitivity	Water Level Difference (m)				
	Max	Min	Average	At SWF16-1 (C13)	At SWF16-2 (C14)
+20% Flow	0.159	0.000	0.048	0.008	0.129
-20% Flow	-0.163	0.000	-0.049	-0.009	-0.099

Diagram 13: Change in the 0.5% AEP Event Flood Extent - Inflow Sensitivity



Downstream Boundary Condition Sensitivity

7.13 The downstream boundary in the 1D model is dummy HT which passes flow to the 2D model. Therefore the sensitivity analysis was carried out by adjusting the 2D HQ boundaries. The slope of the HQ boundaries was adjusted by +20% and -20%. As expected, adjusting the 2D boundaries does not affect in-channel water levels. There was also little resulting change in flood extent.

8 Model Results – Baseline and 'With-Scheme'

Baseline Scenario

8.1 Maps have been produced to show the baseline scenario flood extent for each modelled event in Section A.2 (Flood Extent Maps). The in-channel water levels at key locations for all modelled events are shown in Section A.1 (Maximum Water Level Tables and Long Section).

8.2 Diagram 14 shows the main flood mechanisms for the 0.5% AEP +CC event and has been analysed in conjunction with the extent maps (see Section A.2 (Flood Extent Maps)) to assess the baseline flooding.

8.3 The results show that there are no properties at risk of flooding within the study area.

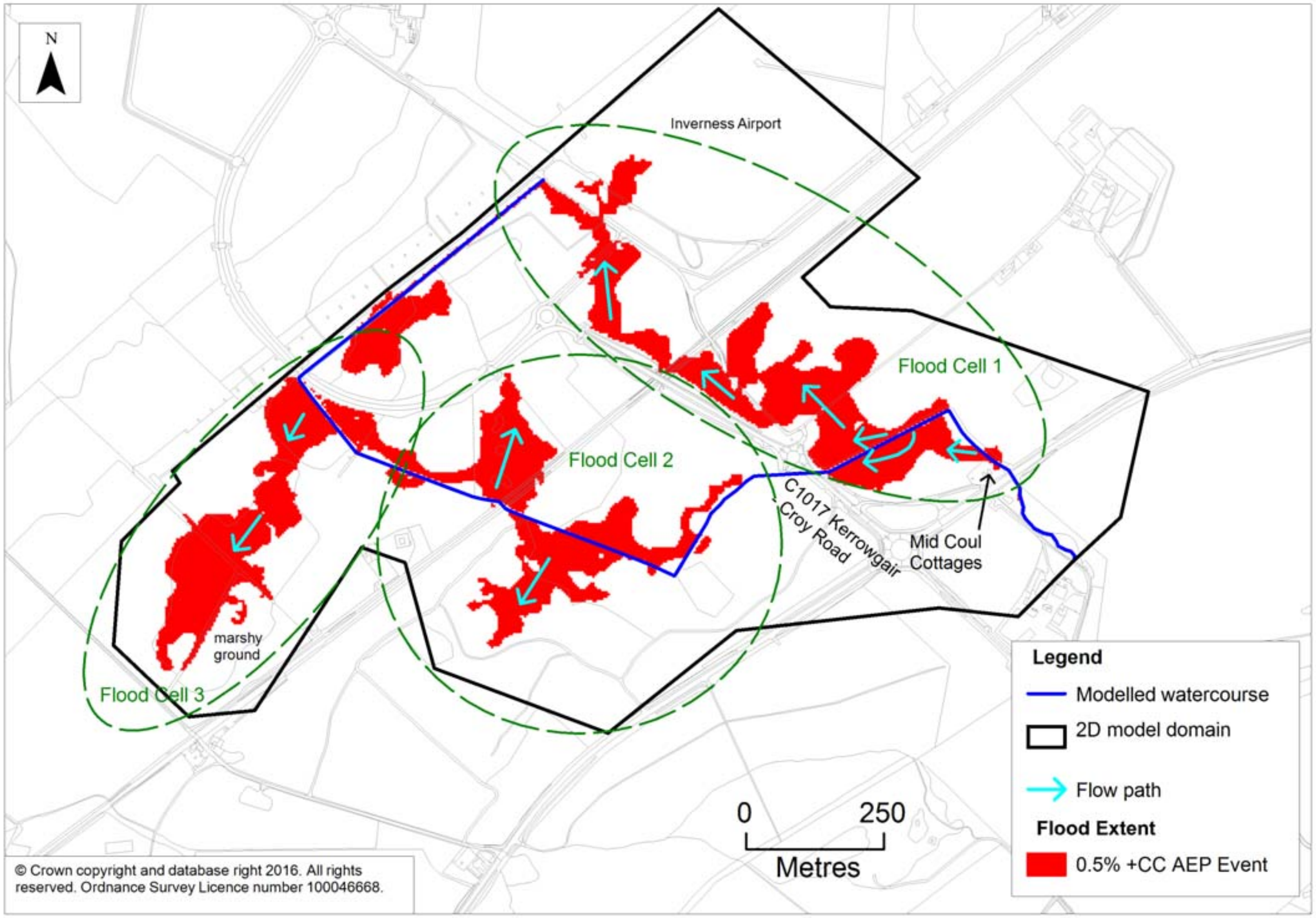
8.4 In Flood Cell 1, water comes out of bank close to Mid Coul Cottages and flows downstream. There is also out of bank flooding further downstream of here, upstream of the C1017 Kerrowgair – Croy Road crossing. The onset of flooding in this area is the 3.33% AEP event. The flood water backs up behind the C1017 Kerrowgair – Croy Road, before spilling to the north-west. The flood water continues flowing north-west towards the airport. Some of the flood water then returns to the channel of the Tributary of Ardersier Burn, at the downstream extent of the modelled watercourse.

8.5 In Flood Cell 2, out of bank flooding inundates low ground. There is a significant flow path to the south-west away from the Tributary of Ardersier Burn channel. Downstream of here there is also a flow path to the north-east away from the watercourse channel. The onset of flooding in Flood Cell 2 is the 50% AEP event.

8.6 In Flood Cell 3 there is significant out of bank flooding to the south-west. Water overtopping here fills up low ground, which Ordnance Survey suggests is marshy ground. The out of bank flooding extends for 500m from the watercourse. The onset of flooding here is the 50% AEP event.

8.7 The pass forward flow at the downstream end of the model, which is a combination of the 1D and 2D flows at the downstream extent, is 1.78m^3/s in the 0.5% AEP +CC event.

Diagram 14: Flood Mechanisms



Comparison of Baseline and 'With-Scheme' Scenarios

8.8 Table 13 shows the changes in in-channel water level between the baseline and the 'with-scheme' scenarios, for the 0.5% AEP +CC event.

8.9 Diagram 15 shows maximum flood depths for the 0.5% AEP +CC event for the 'with-scheme' scenario.

8.10 The results show that upstream of culvert SWF16-2 (C14) there is an increase in water level as a result of the proposed Scheme. At UD_1438 there is an increase of 560mm in the 0.5% AEP +CC event compared to the baseline.

8.11 Backing up of water at culvert SWF16-2 (C14) causes water to overtop onto the proposed Scheme.

8.12 Although there is an increase in water level upstream of culvert SWF16-2 (C14) and some water overtops the proposed Scheme, the proposed Scheme is blocking the baseline flow path to the north-west. This increases the amount of water flowing towards the downstream end of the model, as more water is forced to flow through the watercourse instead of flowing to the north-west.

8.13 Upstream of culvert SWF16-1 (C13) there is an increase of 413mm in the 0.5% AEP +CC event compared to the baseline.

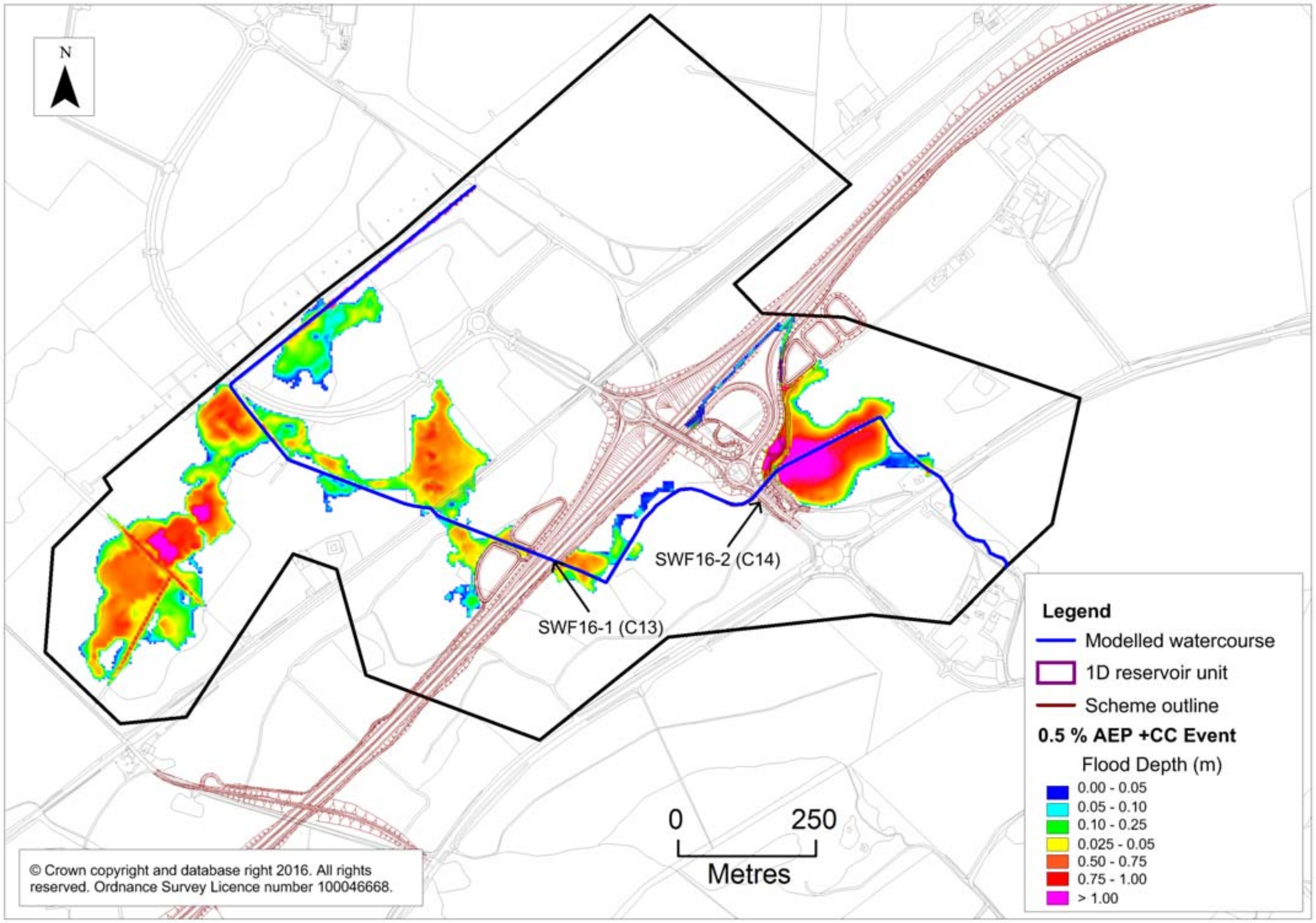
8.14 Increases in maximum flood depths are also seen in the marshy ground to the south-west of the study area.

8.15 The 'with-scheme' model increases the pass forward flow at the downstream end of the model from 1.78m^3/s to 1.79m^3/s.

Table 13: In-Channel Water Level at Key Locations for the 0.5% AEP +CC Event

Model node	Description	Baseline Water Level (mAOD)	'With-Scheme' Water Level (mAOD)	Change in Water Level (m)
UD_1823	Upstream of existing A96 culvert	16.699	16.699	0.000
UD_1801	Downstream of existing A96 culvert	16.174	16.174	0.000
UD_1438	Upstream of watercourse realignment	13.744	14.304	0.560
UD_1203	Downstream of watercourse realignment	11.541	11.612	0.071
UD_0938	Upstream of proposed Scheme culvert	9.017	9.430	0.413
UD_0872	Downstream of proposed Scheme culvert	8.986	9.225	0.239
UD_0277	600m downstream of proposed Scheme culvert	7.861	7.890	0.029

Diagram 15: 0.5 % AEP +CC Event Maximum Flood Depths – 'With-Scheme' Scenario



9 'With-Mitigation' Measures Modelling

9.1 The results of the 'with-scheme' modelling show increases in water level upstream of each of the new culverts, water overtopping the proposed Scheme, increases in water level in the marshy ground to the south-west of the study area and an increase in pass forward flow. Therefore, it was necessary to investigate mitigation measures to remove these increases in flood risk.

9.2 The mitigation measure adopted stores water upstream of culvert SWF16-2 (C14). This was achieved by reducing the size of the culvert to 0.95m wide by 1m high.

9.3 Reducing the size of culvert SWF16-2 (C14) caused the model to become unstable. This a common problem, which occurs in Flood Modeller/Tuflow models, when there are high flood depths on the 1D/2D link. To solve this, the model schematisation, upstream of culvert SWF16-2 (C14), was changed to 1D only with extended cross sections to represent the flood plain, as shown in Diagram 16.

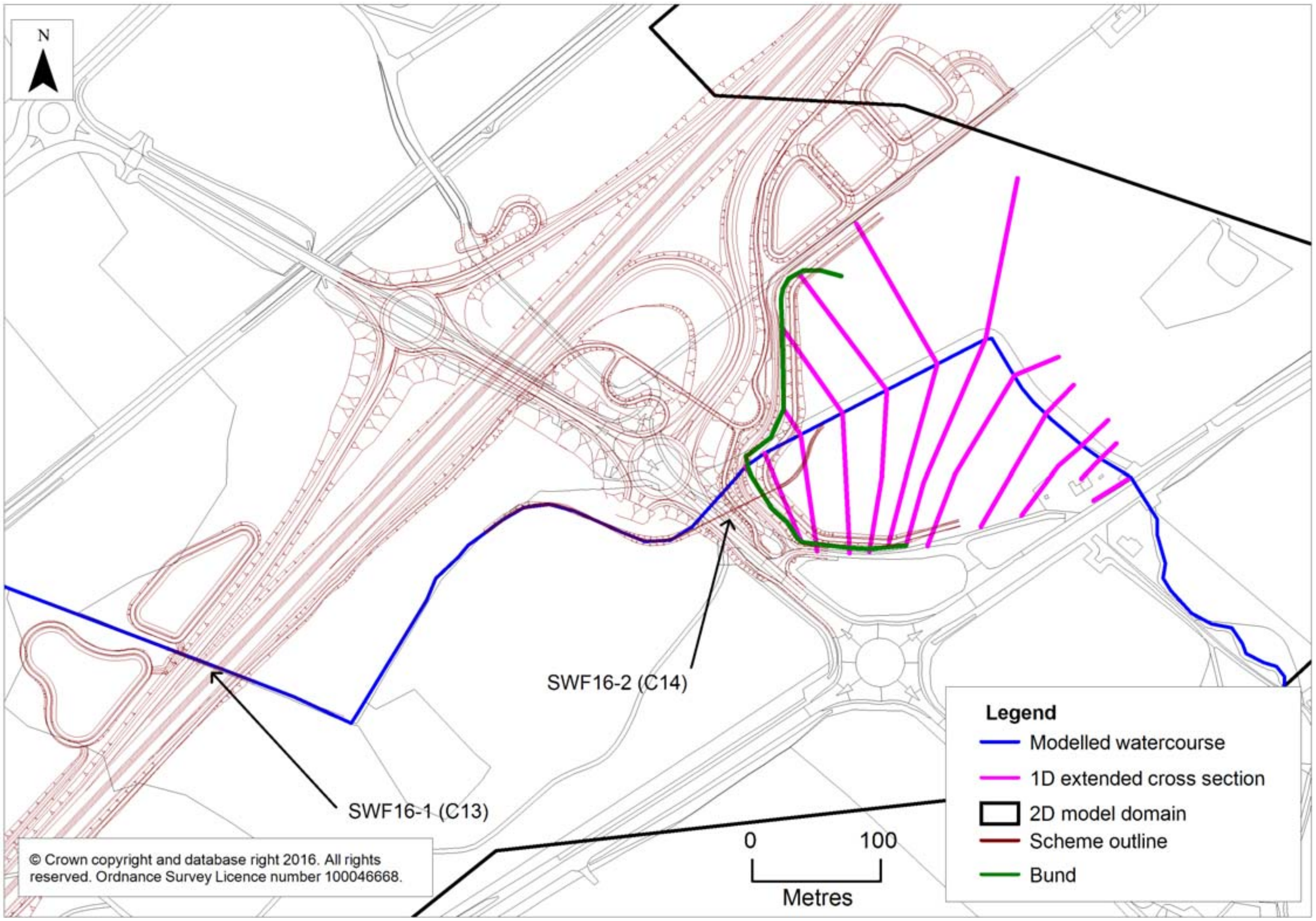
9.4 It was necessary to prevent the water stored upstream of culvert SWF16-2 (C14) spilling onto the proposed Scheme and onto existing roads. This was done by adding a bund on the upstream side of the culvert, as shown in Diagram 16. The bund was modelled by adjusting the levels of the 1D extended cross sections.

9.5 In the 'with-mitigation' model, culvert SWF16-1 (C13) is no longer surcharging. Therefore it was possible to increase the size of the culvert to 1.8m wide by 1.906m high. This allowed for a 600mm debris freeboard, above the 0.5% AEP + CC event maximum water level, a requirement for proposed Scheme culverts which are not acting as a throttle. In addition an allowance was made for a mammal crossing within the culvert.

9.6 The mammal ledge is required to be 170mm above the 4% AEP event maximum water level and to have headroom of 600mm. The mammal crossing takes the form of a ledge on either side of the culvert. However, it was not possible to model this using the symmetrical unit or any other unit available within the Flood Modeller software. Therefore a simplified approach was taken. The width of the culvert was reduced to account for the loss of cross sectional area caused by mammal crossings. The culvert soffit was based on the debris freeboard of 600mm above the 0.5% AEP +CC event, so is in excess of the mammal crossing headroom requirement.

9.7 Since the with-Scheme scenario was modelled there has been a change to a proposed highway drainage Pond on the left bank downstream of culvert C13. This has been modified to avoid a badger set.

Diagram 16: 'With-Mitigation' Model Schematisation



10 Model Results – 'With-Mitigation' Measures

'With-Mitigation' Measures Scenario

10.1 Table 14 and Table 15 show the changes in in-channel water level between the baseline and the 'with-mitigation' scenarios, for the 0.5% and the 0.5% AEP +CC events respectively.

10.2 The 'with-mitigation' model causes an increase in water level upstream of culvert SWF16-2 (C14) of 785mm in the 0.5% AEP event and 858mm in the 0.5% AEP +CC event. This is intentional as this location is proposed as formal flood storage within the scheme.

10.3 The bund upstream of culvert SWF16-2 (C14) should be designed to contain the 0.5% AEP +CC event maximum water level. Therefore, with a 300mm freeboard, the top level of the bund should be set at 14.902mAOD. This would give a maximum bund height of 1.84m at the watercourse location.

10.4 The proposed bund height is 59mm above the 0.1% AEP event maximum water level.

10.5 Diagram 17 shows the change in maximum flood depth for the 0.5% AEP +CC event for the 'with-mitigation' measures scenario compared to the baseline scenario. The impact on flood risk has been categorised in Table 16. The diagram shows the area which would be required to be used as a flood storage area. It also shows that the proposed Scheme is not at risk of flooding.

10.6 For the 0.5% AEP +CC event approximately 30,000m^3 of water would be stored upstream of culvert SWF16-2 (C14).

10.7 At Mid Coul Cottages there is no change in flood extent, from the baseline, as a result of the 'with-mitigation' measures.

10.8 There is no increase in flood risk to properties as a result of the 'with-mitigation' measures.

10.9 The throttling of culvert SWF16-2 (C14) does change the onset of flooding in this area from the 3.33% AEP event to the 20% AEP event.

10.10 Upstream of culvert SWF16-1 (C13), although the culvert is not surcharging, there is an increase in flood depth of 161mm in the 0.5% AEP event and 208mm in the 0.5% AEP +CC event. This is because the proposed Scheme is blocking the wider flow path, which flowed unimpeded in this area in the baseline scenario.

10.11 There is a localised water level increase immediately downstream of Culvert 13 of 100mm in the 0.5% AEP event and 129mm in the 0.5% AEP +CC event. This is due to flow being constricted by the adjacent highway drainage ponds. This water level increase is reduced to zero by approximately 60m downstream from the culvert exit

10.12 There is no significant change in flood extent upstream of culvert SWF16-1 (C13).

10.13 In the marshy area to the south-west of the study area there is a negligible change in flood depth and extent in the 0.5% AEP +CC event.

10.14 The 'with-mitigation' model leads to a reduction in pass forward flow at the downstream end of the model, compared to the baseline, from 1.78m^3/s to 1.65m^3/s

10.15 The 'with-mitigation' in-channel water levels at key locations for all modelled events are shown in Appendix A.1. Maximum Flood Depth change plots for each event modelled are shown in Appendix A.3.

10.16 The difference plots show that significant areas of existing flood extent have been removed within Flood Cells 1 and 2.

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Table 14: In-Channel Water Level at Key Locations for the 0.5% AEP Event

Model node	Description	Baseline Water Level (mAOD)	'With-Mitigation' Water Level (mAOD)	Change in Water Level (m)
UD_1823	Upstream of existing A96 culvert	16.540	16.540	0.000
UD_1801	Downstream of existing A96 culvert	16.154	16.152	-0.002
UD_1438	Upstream of proposed C14 culvert	13.615	14.400	0.785
UD_1203	Downstream of watercourse realignment	11.525	11.483	-0.042
UD_0938	Upstream of proposed C13 culvert	9.009	9.170	0.161
UD_0872	Downstream of proposed C13 culvert	8.976	9.076	0.100
UD_0688	Upstream of Aberdeen to Inverness Railway Line	8.608	8.559	-0.049
UD_0277	600m downstream of proposed Scheme culvert	7.842	7.812	-0.030

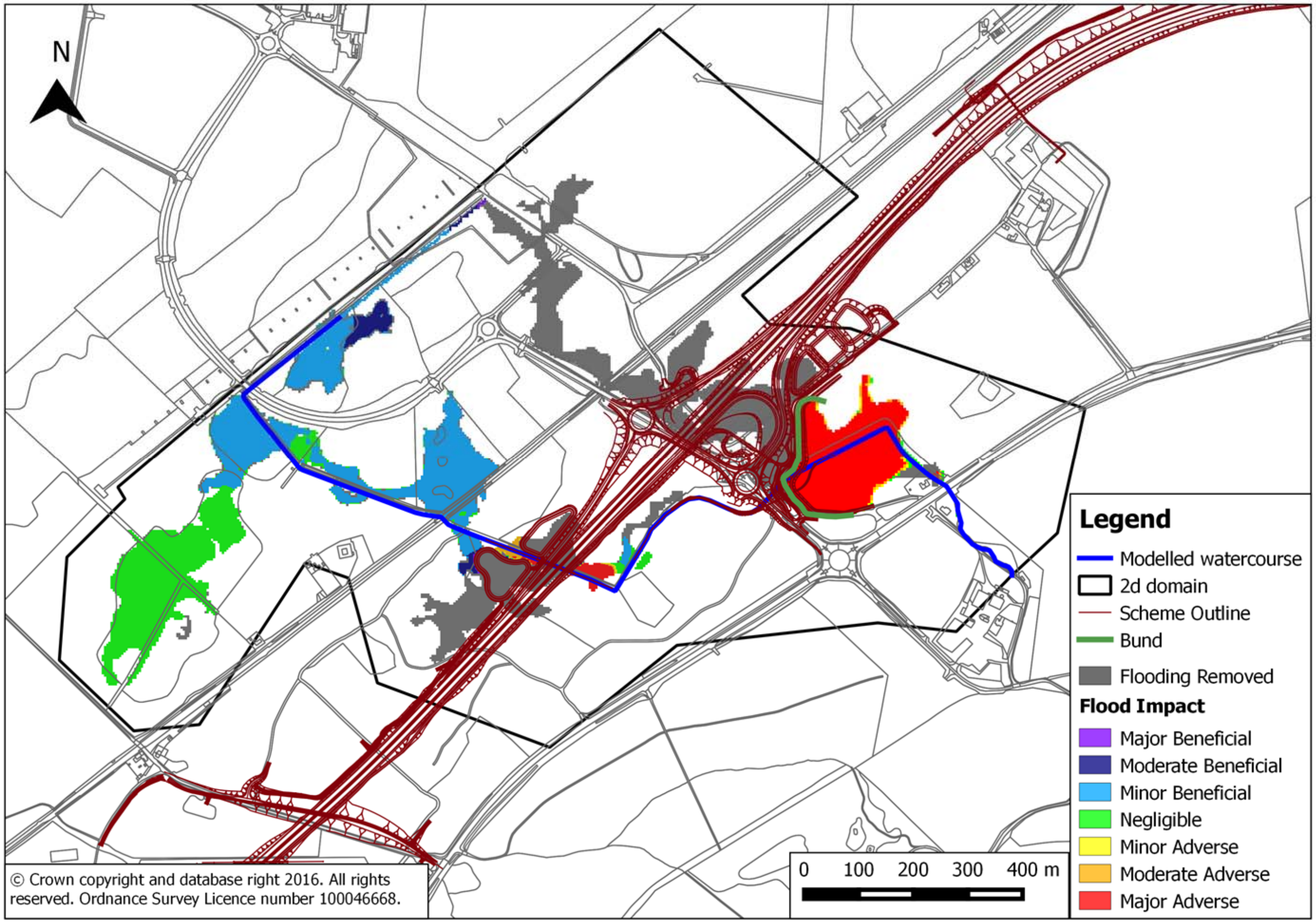
Table 15: In-Channel Water Level at Key Locations for the 0.5% AEP +CC Event

Model node	Description	Baseline Water Level (mAOD)	'With-Mitigation' Water Level (mAOD)	Change in Water Level (m)
UD_1823	Upstream of existing A96 culvert	16.699	16.699	0.000
UD_1801	Downstream of existing A96 culvert	16.174	16.170	-0.004
UD_1438	Upstream of proposed C14 culvert	13.744	14.602	0.858
UD_1203	Downstream of watercourse realignment	11.541	11.524	-0.017
UD_0938	Upstream of proposed C13 culvert	9.017	9.225	0.208
UD_0872	Downstream of proposed C13 culvert	8.986	9.115	0.129
UD_0688	Upstream of Aberdeen to Inverness Railway Line	8.639	8.602	-0.037
UD_0277	600m downstream of proposed Scheme culvert	7.861	7.840	-0.021

Table 16: Categorisation of Difference in Flood Depths

	Potential Flood Impact	Criteria	Flood Risk
	Major Adverse	Results in loss of attribute and/ or quality and integrity of the attribute	Increase in peak flood depth >100 mm
	Moderate Adverse	Results in effect on integrity of attribute, or loss of part of attribute	Increase in peak flood depth 50-100 mm
	Minor Adverse	Results in some measurable change in attributes quality or vulnerability	Increase in peak flood depth 10-50 mm
	Negligible	Results in effect on attribute, but of insufficient magnitude to affect the use or integrity	Negligible change in peak flood depth <+/- 10 mm
	Minor Beneficial	Results in some beneficial effect on attribute or a reduced risk of negative effect occurring	Reduction in peak flood depth 10-50 mm
	Moderate Beneficial	Results in moderate improvement of attribute quality	Reduction in peak flood depth 50-100 mm
	Major Beneficial	Results in major improvement of attribute quality	Reduction in peak flood depth >100mm

Diagram 17: 0.5% AEP +CC Event Maximum Flood Depth Difference Map, 'with-mitigation'



Blockage of the Proposed Scheme Culverts

10.17 In order to assess the impact of the proposed Scheme culverts becoming obstructed, blockage sensitivity scenarios were modelled for the 'with-mitigation' situation for the 0.5% AEP +CC event. The scenarios consisted of a 50% and 90% blockage.

10.18 Each culvert was blocked independently. For example when culvert SWF16-2 (C14) was blocked SWF16-1 (C13) was not and vice versa.

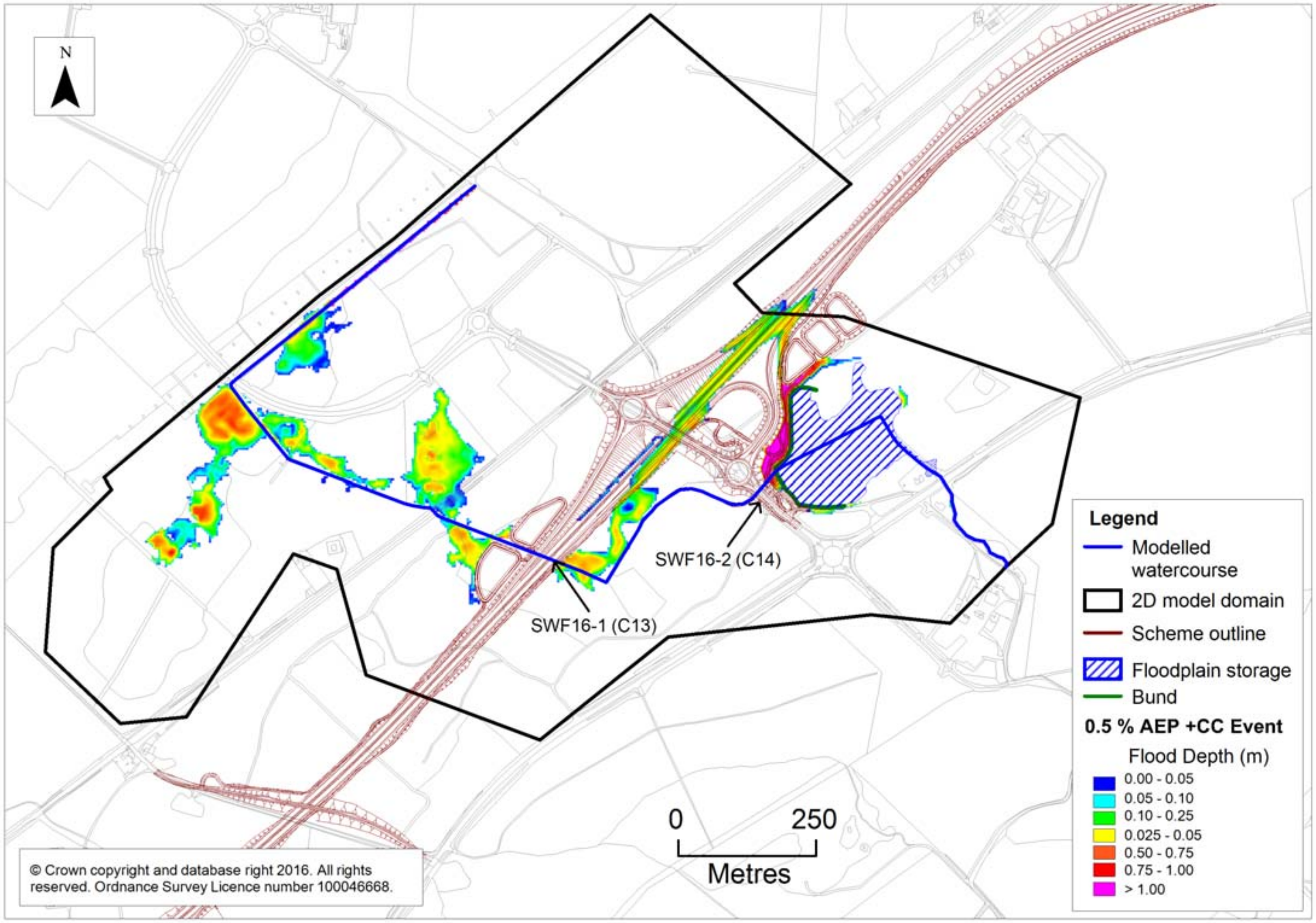
10.19 With a 50% blockage at culvert SWF16-1 (C13) there is an increase in water level of 205mm, upstream of the culvert, from the 'with-mitigation' model. Due to the steep nature of the flood plain here there is only a minimal increase in flood extent.

10.20 With a 90% blockage at culvert SWF16-1 (C13) there is an increase in water level of 1586mm. This leads to an increase in flood extent upstream of the culvert as water backs up against the proposed Scheme. This caused the model to become unstable due to the high depths (similar to the problem discussed in paragraph 9.3). Therefore the section of the model upstream of the culvert SWF16-1 (C13) was changed to a 1D only schematisation. The flood extent upstream of the culvert increases by 190m on the left bank and 109m on the right bank.

10.21 With a 50% blockage at culvert SWF16-2 (C14) there is an increase in water level of 98mm, upstream of the culvert, from the 'with-mitigation' model. This water level is lower than the bund. Therefore the increases would be contained. The increases in water level extend to 330m upstream of the culvert. There is no increased risk to the proposed Scheme or properties. In this scenario there is a decrease in water level of 103mm from the 'with-mitigation' model upstream of culvert SWF16-1 (C13).

10.22 With a 90% blockage at culvert SWF16-2 (C14) there is an increase in water level of 337mm, upstream of the culvert, from the 'with-mitigation' model. This leads to overtopping of the bund and an increased flood risk to the proposed Scheme, as shown in Diagram 18. Water is able to flow along the proposed Scheme highway and increases the flood extent upstream SWF16-1 (C13). In this scenario there is a decrease in water level of 103mm from the 'with-mitigation' model upstream of culvert SWF16-1 (C13).

Diagram 18: 0.5 % AEP +CC Event Maximum Flood Depths – 90% Blockage of Culvert WF16-2 (C14)



11 Model Assumptions and Limitations

Introduction

11.1 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.

11.2 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 and are therefore appropriate for the flood risk assessment.

11.3 The sections below summarise the key sources of uncertainty in addition to the limitations associated with the modelling undertaken for the Tributary of Ardersier Burn.

1D Domain

Cross sections

11.4 For the realignment channels and the bypass channel, a basic cross section form has been used as per the supplied design drawing. Bed levels are based on a linear drop in gradient between the existing channel sections. Bank levels for the realignment are based on the MXROAD ASCII and 2016 point survey data.

11.5 The 'with-mitigation' model uses a 1D only schematisation upstream of the culvert SWF16-2 (C14). This is a coarser representation of the flood plain than would be achieved with a 1D/2D schematisation.

Channel Roughness

11.6 Channel roughness has been assigned using the best available information (site visit, survey data and aerial photographs). The roughness values used are based on available guidance (Chow 1959).

11.7 The realignment channels are assumed to be less heavily vegetated than the existing reaches, the adopted channel roughness is subsequently lower than the existing channels.

Representation of In-Channel Structures

11.8 Hydraulic coefficients for structures have been applied using available guidance within the Flood Modeller software. The dimensions for structures have been based on detailed survey measurements.

11.9 Roughness values for the new culvert inverts match the channel bed roughness.

11.10 Where culverts are used to create a throttle there is no allowance for freeboard or mammal crossing within the culvert.

Downstream Boundary Conditions

11.11 In the 1D model a dummy-head boundary allows flow to leave the 1D model and enter the 2D domain.

2D Domain

Channel Schematisation

11.12 The final 350m of the modelled Tributary of Ardersier Burn have been carved into the 2D domain. The levels in the channel gradually transition from the bed level of the downstream Flood Modeller cross section to the levels in the 2014 photogrammetry data.

Flood Plain Topography

11.13 The Digital Terrain Model (DTM) is a composite of two datasets, the 2014 photogrammetry and the 2016 spot level survey data.

11.14 The 2016 spot level survey data has better vertical accuracy. However this dataset does not cover the whole model extent. Therefore the 2014 photogrammetry was used for the wider flood plain.

Grid Size

11.15 A 4m grid has been used. This is suitable to represent flood plain features to an appropriate level of detail.

Flood Plain Structures

11.16 A review of the flood plain using available aerial photographs, OS mapping and site inspection has shown that there are no additional flood plain structures that require representation in the model.

DTM Modifications

11.17 A modification was required to the baseline DTM to allow flood water to flow along the Aberdeen to Inverness Railway Line.

11.18 For the ‘with-scheme’ situation, the existing ground levels were modified within the proposed Scheme footprint from the MXROAD software.

Downstream Boundary Conditions

11.19 Head-Flow boundaries have been added to the downstream end of the model. This was appropriate as the sensitivity analysis has shown that the downstream extent of the model does not affect water levels at the proposed Scheme

Model calibration

11.20 No calibration was carried out as the modelled catchment is ungauged.

12 Conclusion

12.1 This report has detailed the modelling carried out to assess the baseline flood risk for the Tributary of Ardersier Burn with reference to the location of the proposed Scheme.

12.2 The results of the baseline modelling have shown that there are no properties at risk of flooding. There is a significant flow path across the flood plain from the upstream end of the model towards the airport at the downstream end.

12.3 The results of the initial ‘with-scheme’ modelling show:

- Increases in water level immediately upstream of each of the new culverts,
- Water overtopping the proposed Scheme,
- Increases in water level in the marshy ground to the south-west of the study area
- Increase in pass forward flow at the downstream extent of the model.

Therefore a ‘with-mitigation’ scenario was modelled.

12.4 The ‘with-mitigation’ scenario reduced the size of culvert SWF16-2 (C14) to effect flood attenuation storage upstream of the culvert. The results showed that a bund of 1.84m high would be required to contain the 0.5% AEP +CC event maximum water level, with a 300mm freeboard.

12.5 On the upstream side of SWF16-1 (C13) there is an increase in water level caused by the proposed Scheme blocking the baseline flow path. However there is no significant increase in flood extent.

12.6 The marshy ground to the south-west of the study area is showing negligible change in flood depth in the 0.5% AEP +CC as a result of the proposed Scheme.

12.7 The ‘with-mitigation’ model causes a reduction in the pass forward flow at the downstream end of the model compared to the baseline.

12.8 The difference plots show that significant areas of existing flood extent have been removed as a result of the Scheme.

12.9 There are no areas where the proposed Scheme is at risk of flooding or where there is risk to properties as a result of the ‘with-mitigation’ situation.

13 References

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

Scottish Environment Protection Agency (V9.1, 2015). Technical Flood Risk Guidance for Stakeholders (Ref SS-NFR-P_002)

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A.1 Maximum Water Level Tables and Long Sections

	Baseline Water Levels (mAOD)							
Modelled Event	**Model Node**							
	UD_1823	UD_1801	UD_1438	UD_1203	UD_0938	UD_0872	UD_0688	UD_0277
	Upstream of existing A96 culvert	Downstream of existing A96 culvert	Upstream of watercourse realignment	Downstream of watercourse realignment	Upstream of proposed Scheme culvert	Downstream of proposed Scheme culvert	Upstream of Aberdeen to Inverness Railway Line	600m downstream of proposed Scheme culvert
50% AEP Event	15.877	15.768	12.636	11.245	8.882	8.762	8.264	7.526
20% AEP Event	16.064	16.012	12.803	11.333	8.945	8.838	8.344	7.641
10% AEP Event	16.125	16.056	12.976	11.400	8.962	8.872	8.424	7.728
3.33% AEP Event	16.238	16.107	13.279	11.471	8.981	8.940	8.535	7.802
2% AEP Event	16.310	16.117	13.428	11.496	8.992	8.956	8.560	7.812
1% AEP Event	16.418	16.135	13.541	11.513	9.002	8.968	8.575	7.816
0.5% AEP Event	16.540	16.154	13.615	11.525	9.009	8.976	8.608	7.842
0.5% AEP +CC Event	16.699	16.174	13.744	11.541	9.017	8.986	8.639	7.861
0.1% AEP Event	16.897	16.201	13.814	11.547	9.022	8.990	8.649	7.871

	'With-Mitigation' Water Levels (mAOD)							
Modelled Event	**Model Node**							
	UD_1823	UD_1801	UD_1438	UD_1203	UD_0938	UD_0872	UD_0688	UD_0277
	Upstream of existing A96 culvert	Downstream of existing A96 culvert	Upstream of watercourse realignment	Downstream of watercourse realignment	Upstream of proposed Scheme culvert	Downstream of proposed Scheme culvert	Upstream of Aberdeen to Inverness Railway Line	600m downstream of proposed Scheme culvert
20% AEP Event	16.054	16.000	13.563	11.303	8.929	8.884	8.350	7.650
3.33% AEP Event	16.238	16.086	13.966	11.397	9.043	8.977	8.472	7.773
0.5% AEP Event	16.540	16.152	14.400	11.483	9.170	9.076	8.559	7.812
0.5% AEP +CC Event	16.699	16.170	14.602	11.524	9.225	9.115	8.602	7.840
0.1% AEP Event	16.897	16.197	14.843	11.575	9.279	9.149	8.665	7.873

	Change in Water Level (m)							
Modelled Event	**Model Node**							
	UD_1823	UD_1801	UD_1438	UD_1203	UD_0938	UD_0872	UD_0688	UD_0277
	Upstream of existing A96 culvert	Downstream of existing A96 culvert	Upstream of watercourse realignment	Downstream of watercourse realignment	Upstream of proposed Scheme culvert	Downstream of proposed Scheme culvert	Upstream of Aberdeen to Inverness Railway Line	600m downstream of proposed Scheme culvert
20% AEP Event	-0.010	-0.012	0.760	-0.030	-0.016	0.046	0.006	0.009
3.33% AEP Event	0.000	-0.021	0.687	-0.074	0.062	0.037	-0.063	-0.029
0.5% AEP Event	0.000	-0.002	0.785	-0.042	0.161	0.100	-0.049	-0.030
0.5% AEP +CC Event	0.000	-0.004	0.858	-0.017	0.208	0.129	-0.037	-0.021
0.1% AEP Event	0.000	-0.004	1.029	0.028	0.257	0.159	0.016	0.002

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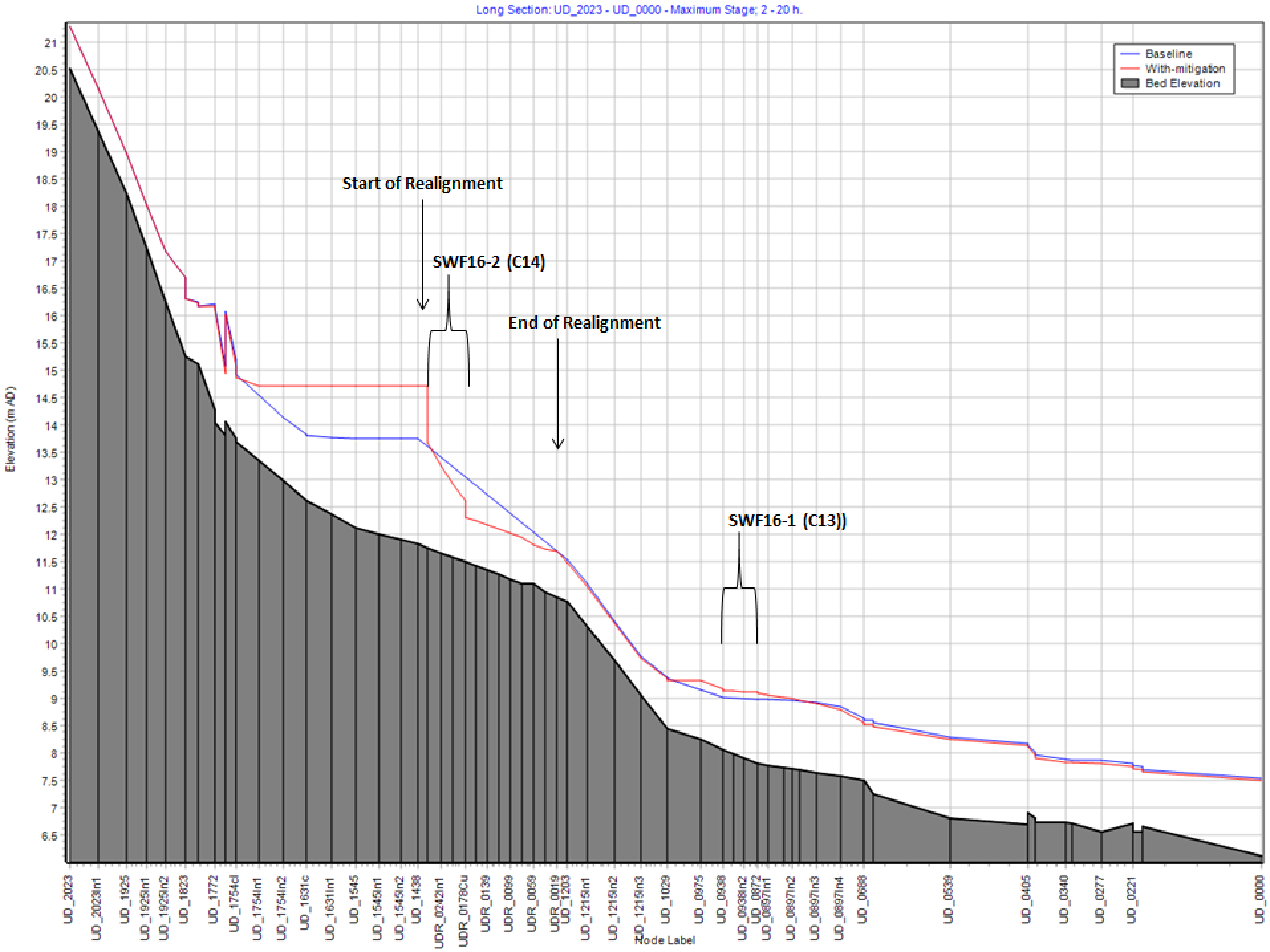
Diagram A1: Tributary of Ardersier Burn Long Section – 0.5% AEP +CC Event - In-Channel Peak Water Levels



NOTE: There are no baseline model nodes within the realignment section.
The baseline water level shown for the realignment section is an interpolation between the upstream and downstream of the section and comparison to the 'with-mitigation' water level is not relevant at these sections.

A.2 Flood Extent Maps

Diagram A2: Baseline flood extent for entire model extent. 50%, 20%, 10%, 3.33% and 2% AEP flood events

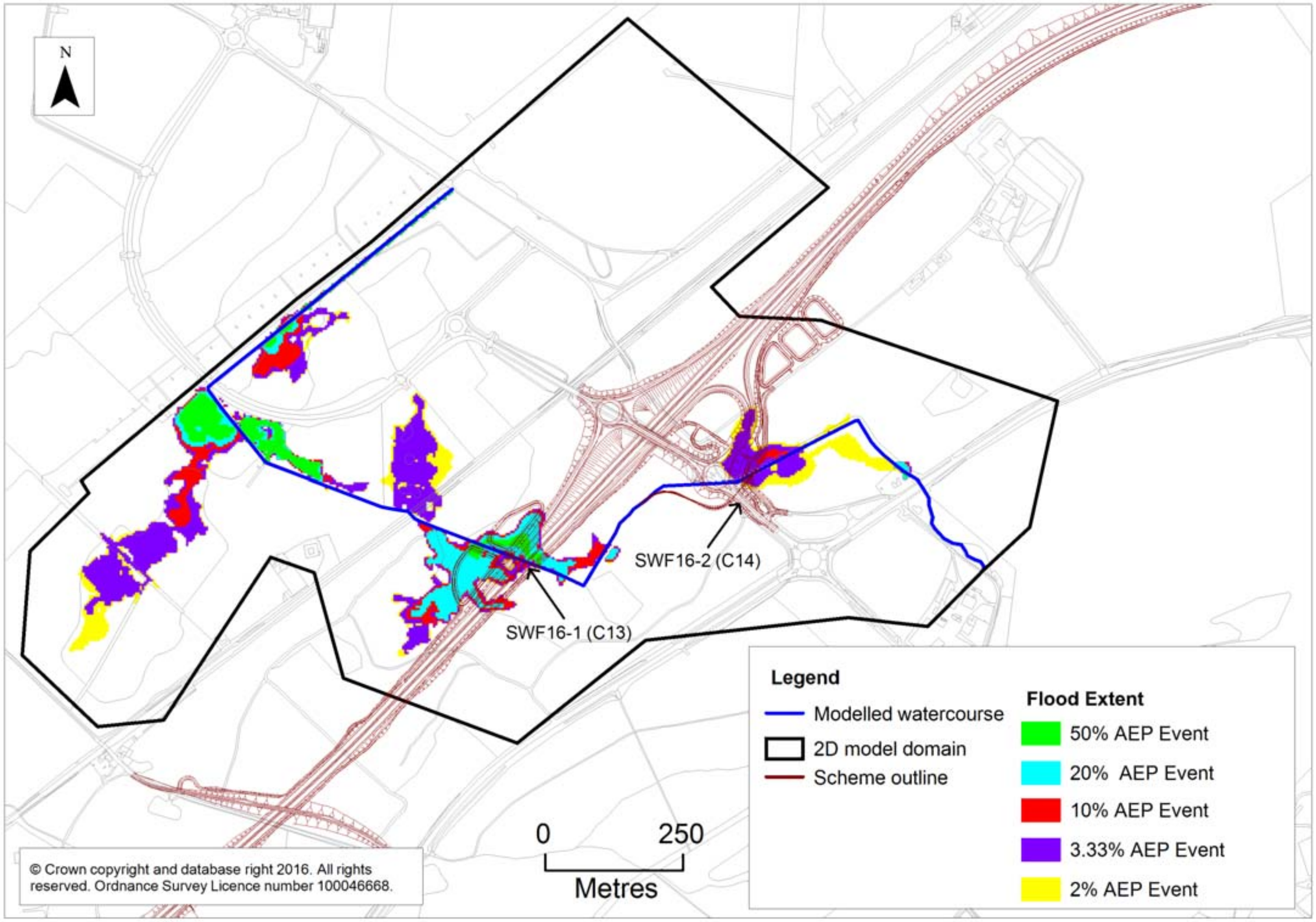
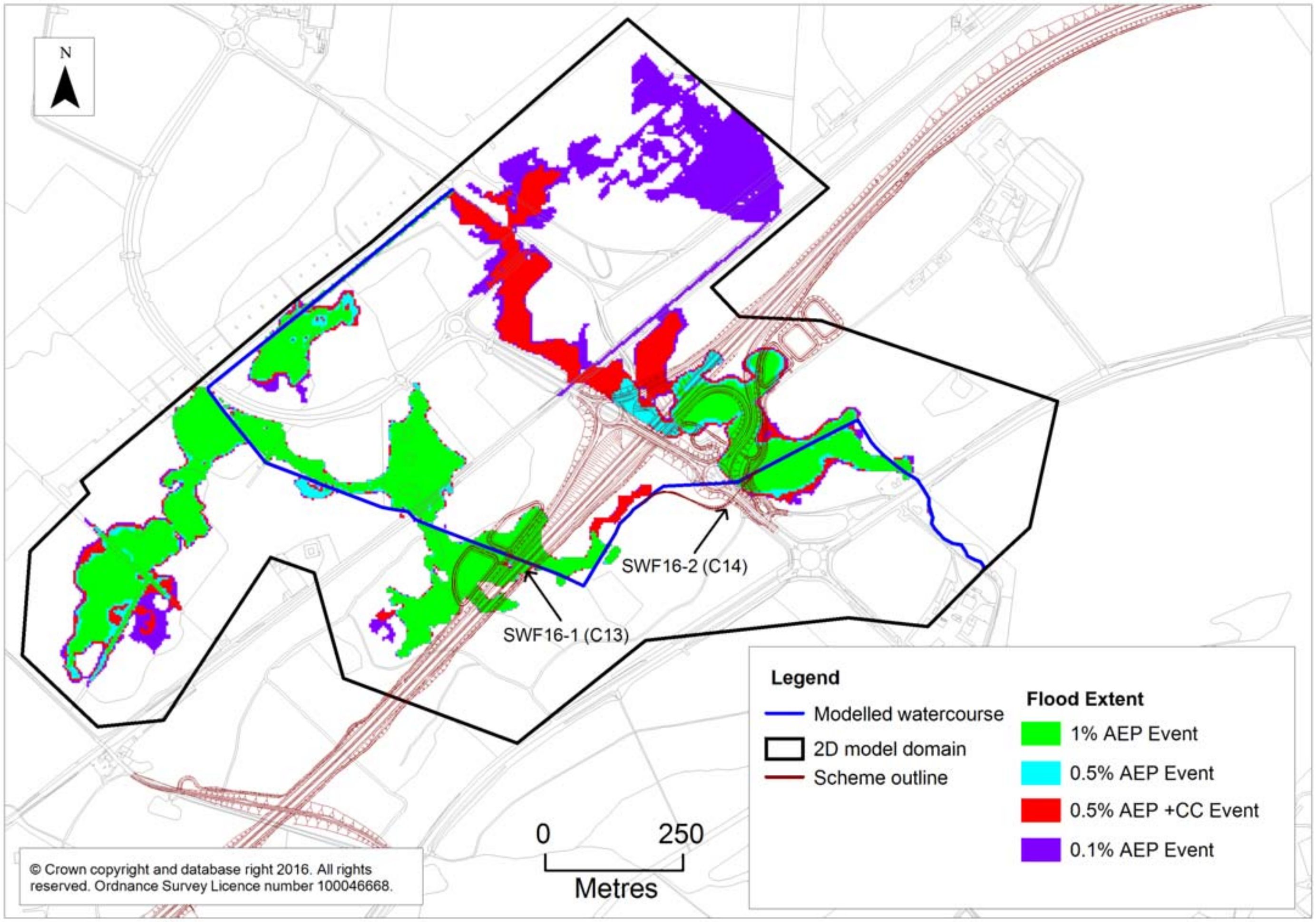


Diagram A3: Baseline flood extent for entire model extent. 1%, 0.5%, 0.5% +CC and 0.1% AEP flood events



A.3 'With-Mitigation' Depth Change Maps

Diagram A4: 20% AEP event Maximum flood depth difference map

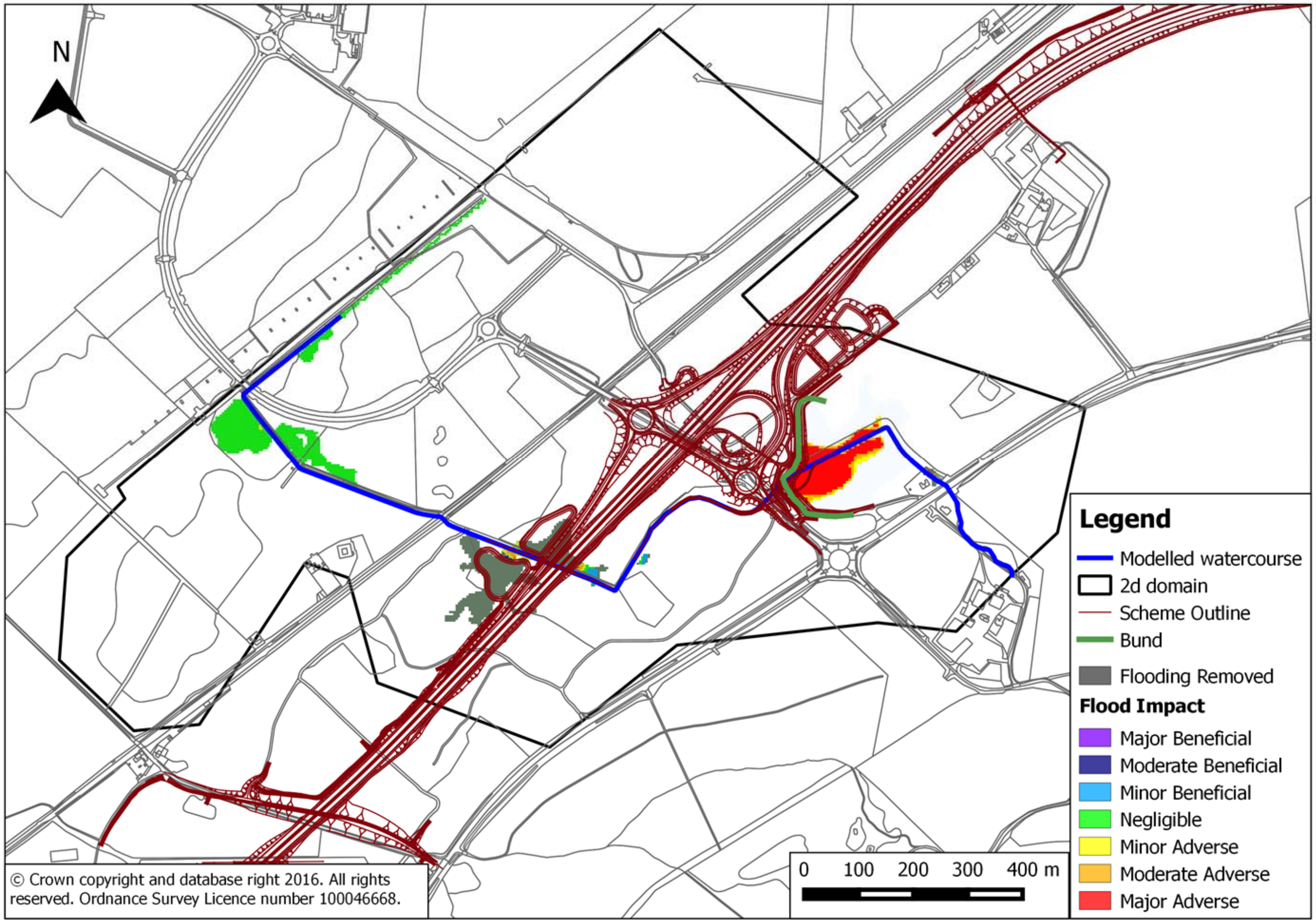


Diagram A5: 3.33% AEP event Maximum flood depth difference map

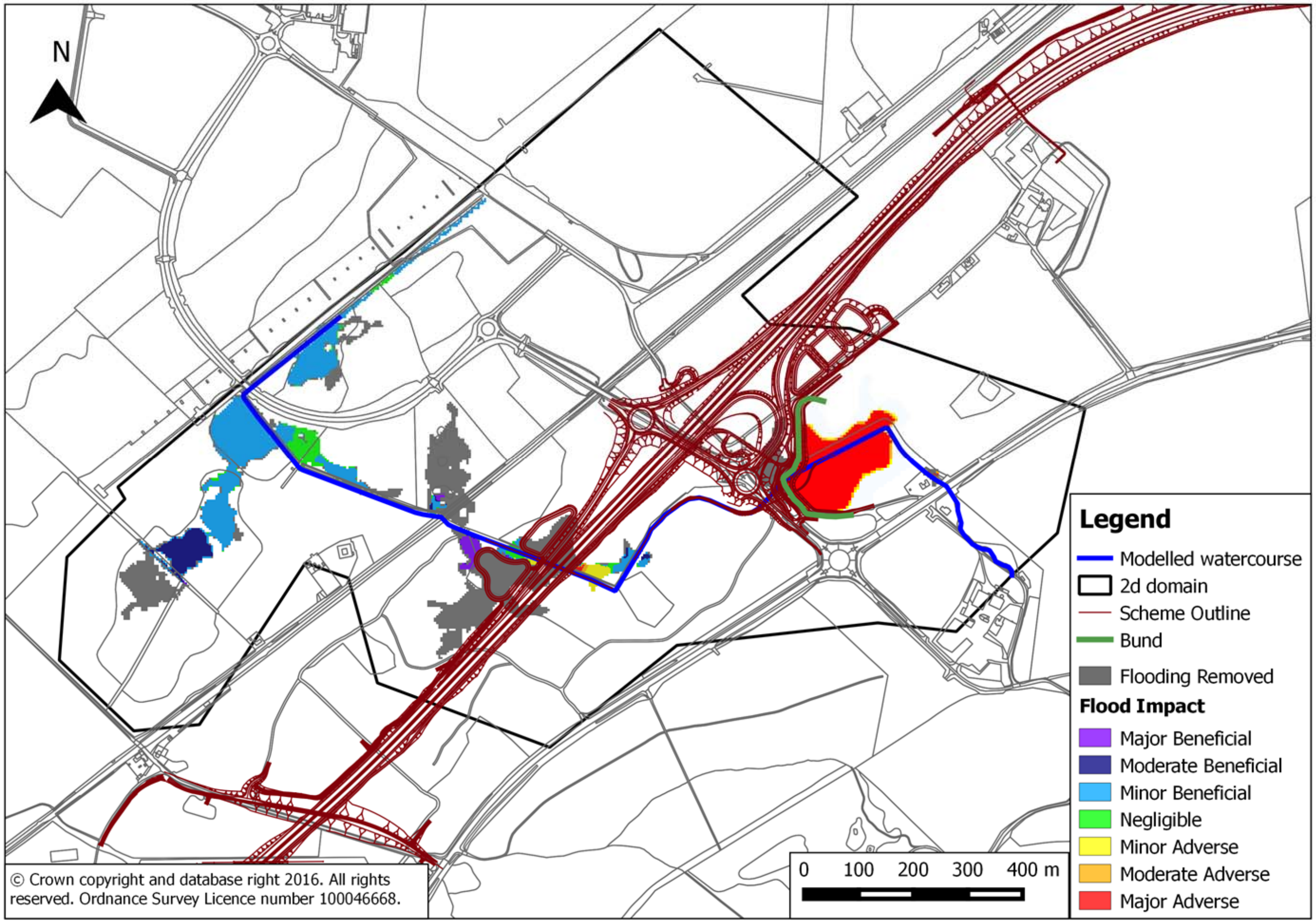


Diagram A6: 0.5% AEP event Maximum flood depth difference map

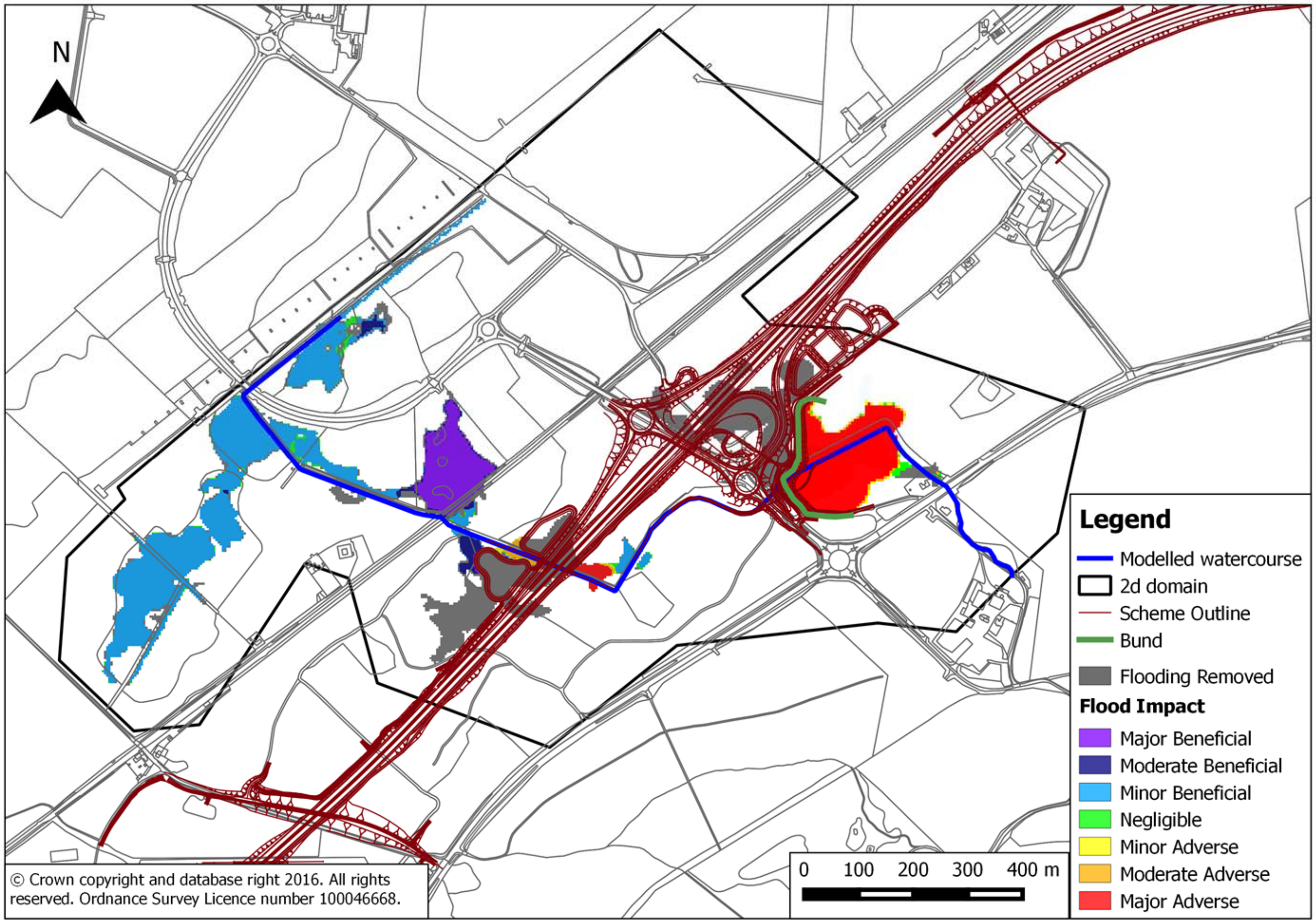


Diagram A7: 0.5% AEP +CC event Maximum flood depth difference map

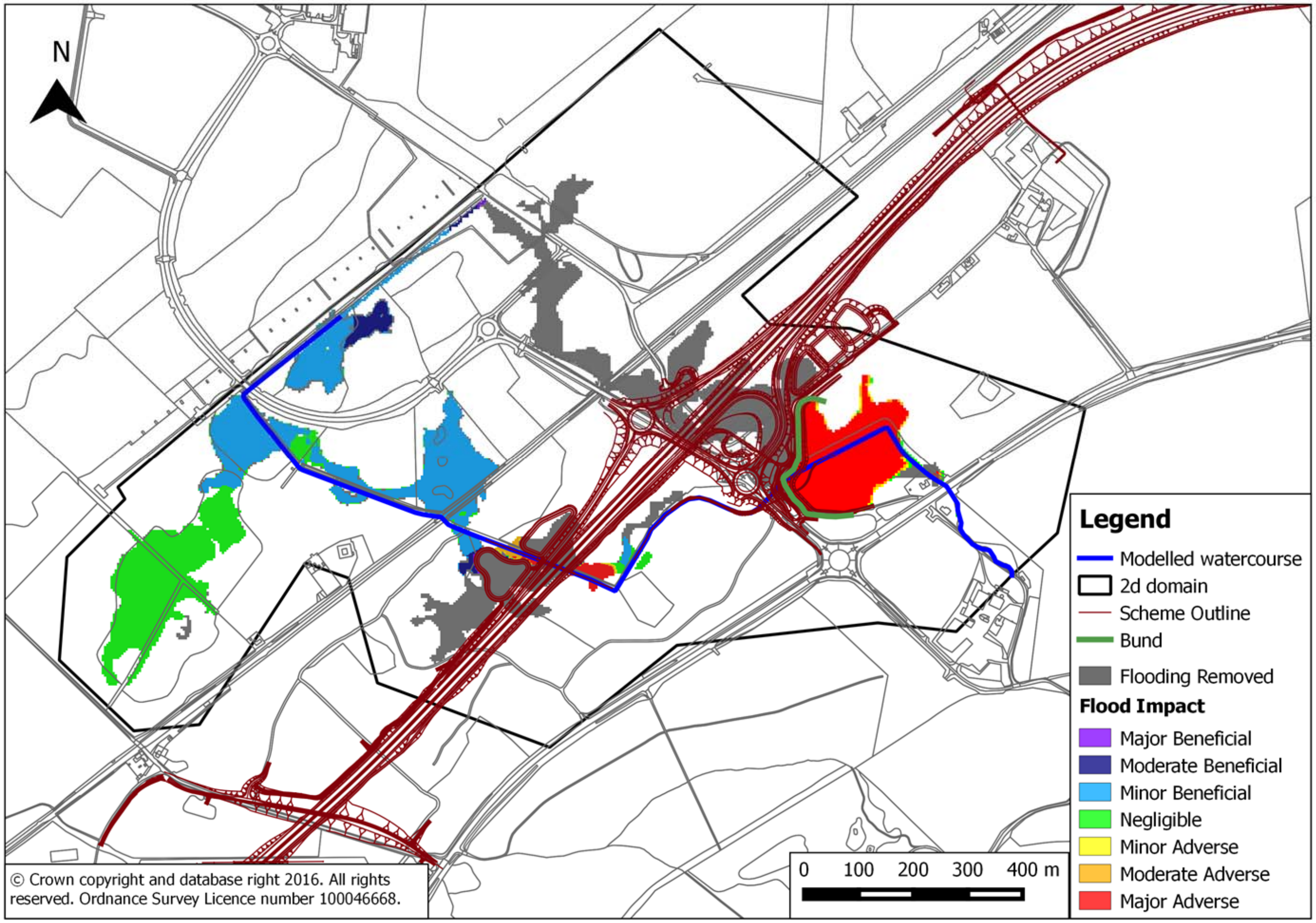


Diagram A8: 0.1% AEP event Maximum flood depth difference map