JBA consulting

Nairn Flood Risk Appraisal

Fluvial & Tidal Flood Risk Assessment

Final

July 2023

Prepared for: The Highland Council

The Highland Council
Comhairle na Gàidhealtachd

www.jbaconsulting.com

Document Status

Issue date	21 July 2023
Issued to	Duncan Sharp
BIM reference	IGZ-JBAU-00-00-RP-HM-0001
Revision	S4-P05
Prepared by	Rozy Shepherd BSc. Geology (Hons) Analyst Rowan Callaghan-Creighton BA. MSc Assistant Analyst Jonathan Garrett BEng (Hons) MCIWEM Senior Engineer
Reviewed by	Angus Pettit BSc MSc CEnv CSci MCIWEM C.WEM Technical Director
Authorised by	David Cameron Technical Director

Carbon Footprint

JBA is committed to championing sustainability and has made The Ten Principles of the UN Global Compact part of its culture and operations. We have a Group-wide objective to be a Net Zero carbon emissions business.

The format of this report is optimised for reading digitally in pdf format; duplex printing in B&W on 100% post-consumer recycled A4 will result in a carbon footprint of 437 CO2e. This will increase to 556 CO_2e if primary-source paper is used. Please consider the environment before printing.

Contract

JBA Project Manager	Jonathan Garrett BEng (Hons) MCIWEM
Address	Unit 2.1, Research Avenue South, Edinburgh, EH14 4AP
JBA Project Code	2022s0654

This report describes work commissioned by Duncan Sharp and Susan Veitch, on behalf of The Highland Council (THC) by an instruction dated 30th May 2022. The Client's representative for the contract was Duncan Sharp and Susan Veitch of THC. Rozy Shepherd, Rowan Callaghan-Creighton and Jonathan Garrett of JBA Consulting carried out this work.

Purpose and Disclaimer

Jeremy Benn Associates Limited ("JBA") has prepared this Report for the sole use of the Highland Council and its appointed agents in accordance with the Agreement under which our services were performed.

JBA has no liability for any use that is made of this Report except to THC for the purposes for which it was originally commissioned and prepared.

No other warranty, expressed or implied, is made as to the professional advice included in this Report or any other services provided by JBA. This Report cannot be relied upon by any other party without the prior and express written agreement of JBA.

Acknowledgements

JBA would like to thank Alayne Finlay and Fiona Mclay from SEPA for their contribution to climate change flood flow uplift advice.

Duncan Sharp, Susan Veitch and Alan Fraser for their important contributions to the FRA and timely response to data request and queries.

Copyright

Contents

List of Figures

List of Tables

Abbreviations

1D ....One Dimensional (modelling)
2D ....Two Dimensional (modelling)
AAD..........................Annual Average Damage
AEP ....Annual Exceedance Probability
AMAX.......................Annual Maximum
AOD ....Above Ordnance Datum
CC............................Climate Change
DM ....Do Minimum (scenario)
DN............................Do Nothing (scenario)
DS ....Downstream
DTM ....Digital Terrain Model
dVol..........................Change in volume in the TUFLOW model since the previous time step (m^3)
EA ....Environment Agency
FAS ....Flood Appraisal Study
FCERM ....Flood and Coastal Erosion Risk Management
FEH..........................Flood Estimation Handbook
FM............................Flood Modeller (Hydraulic modelling software)
FRA..........................Flood Risk Assessment
FRM ....Flood Risk Management
GIS...........................Geographical Information System
HM ....His Majesty
LiDAR.......................Light Detection And Ranging
mAOD ....metres Above Ordnance Datum
MCM.........................Multi-Coloured Manual

NRD ....National Receptor Data

NRFA ....National River Flow Archive

N+20 ....20% increase on roughness (scenario)

N-20 ....20% decrease on roughness (scenario)

OS ....Ordnance Survey

PC ....Pipe Crossing

PV ....Present Value

PVd ....Present Value Damages

SEPA.........................Scottish Environment Protection Agency

S_B ....Sensitivity to blockage (scenario)

S_Def ....Sensitivity to defences (scenario)

THC...........................The Highland Council

TUFLOW ....Two-dimensional Unsteady FLOW (hydraulic modelling software)

US ....Upstream

Note on Flood Probability abbreviation.

This document quotes the probability of a flood magnitude in terms of a return period based on analysis of annual maximum (AMAX) floods. The inverse of the AMAX return period is the annual exceedance probability (AEP). The table below is provided to enable quick conversion between these different measures.

return period (year)	2	5	10	20	30	50	75	100	200	1000
AEP (%)	50	20	10	5	3.33	2	1.33	1	0.5	0.1

Executive Summary

A Flood Appraisal Study has been undertaken for the town of Nairn. Flooding from fluvial and tidal sources were considered. Both the River Nairn and the Auldearn Burn were modelled using a 1D2D model.

As part of the assessment new channel and topographic survey data was taken. New peak flow hydrological estimates were made based on the statistical method, making use of the gauge record and historical flood data. The largest event to occur at the gauge occurred at 20:00 on 1st July 1997. As well as scaling this observed hydrograph to the design peak flows as derived on the River Nairn for the return periods tested in the model, this observed event has also been run in the model for calibration purposes. Photographs and records from recent historic flood events have been provided by the Highland Council for a coastal flood event on 15/12/2012 and fluvial events on the River Nairn (08/10/2014) and Auldearn Burn (11/08/2014). Both the gauge rating and flood event photographs have been used for model calibration and validation purposes. Peak flow data was derived for a range of flood events up to the 1000 year plus climate change flood event. Two climate change flood scenarios were considered. These were based on SEPA's Land use planning document and the extreme upper bound climate change pathway.

The river gauge was used to help calibrate the model in the vicinity of the gauge and flood flow estimates were validated against recorded flood photos. The model was then converted from representing the current condition (Do Minimum) to a walk-away condition (Do Nothing). This meant increased blockage at structures.

Joint probability analysis was undertaken to determine the worst combination of tide and river flooding occurring together. Two sets of simulations were run for each flood event, one with a dominant fluvial event and one with a dominant tidal event. For each event, the largest depth (repeated for the greatest level, fastest flows) from each simulation were combined. This produced a flood map that encapsulated the maximum flood extent from any combination of tidal and fluvial flooding for a given flood return period.

The flood mapping showed that the main areas of flooding affected Fishertown and Househill. Out of bank flooding can be seen from the 1 in 5 year event with the first onset of flooding to properties occurring at the 1 in 30 year event. 52 properties are flooded at the 1 in 30 year event and 294 properties are flooded at the 1 in 200 year event. Figure 1 below is an extract of the 1 in 200 year joint probability flood depth map (the darker colours represent deeper water).

The Multi-Coloured Manual was used to estimate flood direct and indirect damage for each event. The present value damage, based on a 100 year appraisal period, are estimated to be in the order of £12.8 million, which equates to an annual average damage of £430 thousand. This is a large value and suggests that there could be

substantial benefits derived from a flood protection scheme in the form of avoided damages.

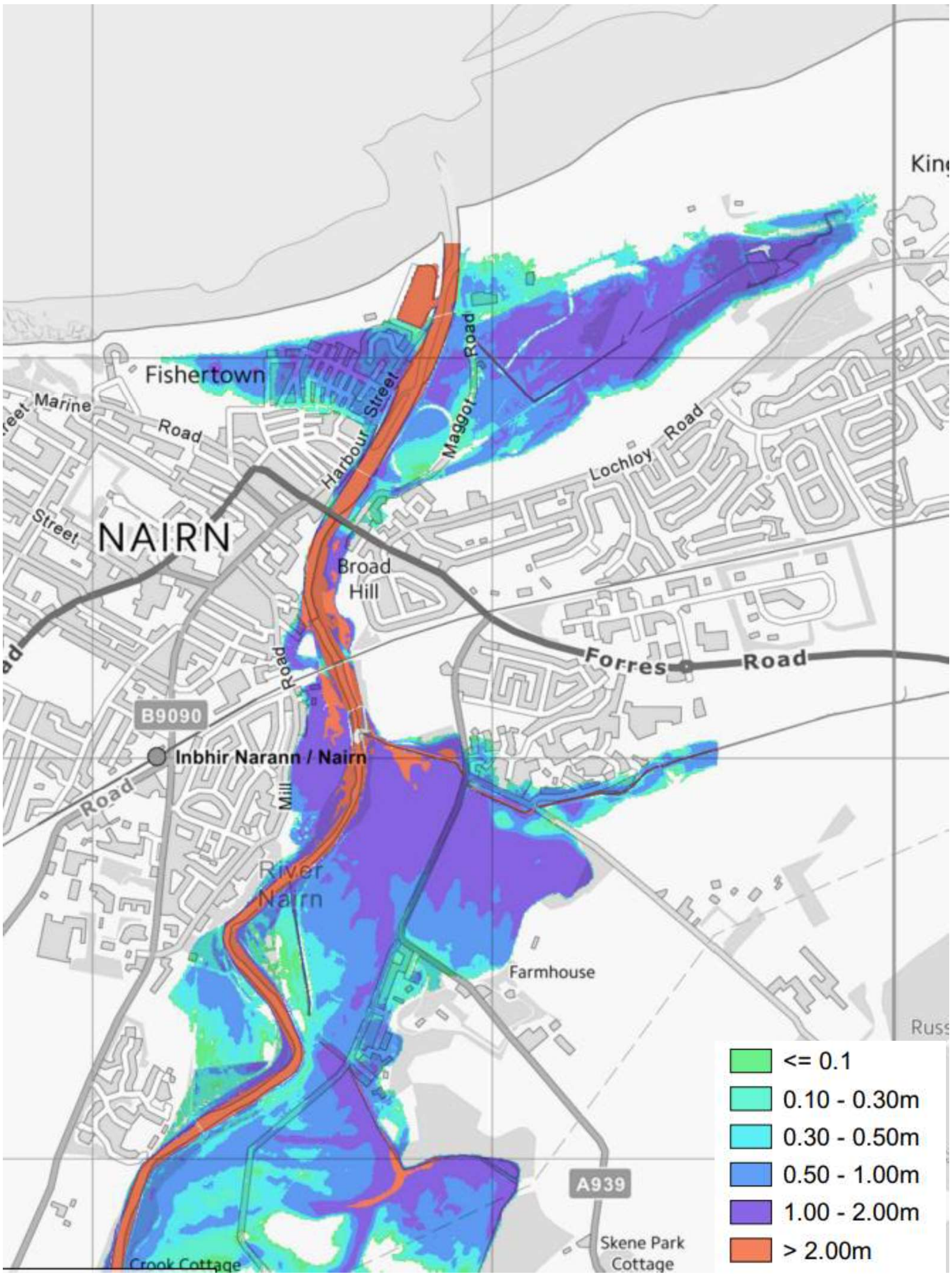

Figure 1: Extract of the combined 1 in 200 year fluvial and tidal flood map

1 Introduction

1.1 Background

This study was commissioned by The Highland Council to contribute towards meeting two key actions for Nairn as outlined in The Highland Council's (THC) Flood Risk Management Plan for Findhorn, Nairn and Speyside[1], these actions are to produce a 'Flood Protection Study' and 'Strategic Modelling and Mapping'. The purpose of the study is to undertake a Flood Appraisal Study for the town of Nairn in the Highlands. An assessment is needed to understand the fluvial and tidal flood risk, including an allowance for the impacts of climate change, to the town so that if flood mitigation measures are needed they can be targeted to the areas that need them the most. This baseline assessment identifies properties at risk and estimates the annual average damage (AAD) caused by fluvial or tidal flooding.

THC's Local Flood Risk Management Plan[2] is consistent with SEPA's (Scottish Environmental Protection Agency) Flood Risk Management Plan[3]. The plan consists of repeating 6-yearly cycles, and the current plan (Cycle 2) runs from 2022 to 2028. During the first cycle (Cycle 1), SEPA's Flood Risk Management Plan was known as the Flood Risk Management Strategy (FRMS) and ran from 2015 to 2021. The FRMS was a national scale assessment which identified communities most at flood risk, it estimated number of people at risk and the potential annual average damage (AAD). The FRMS set out a series of recommendations, one of which was to carry out a flood risk appraisal. This recommendation has been carried forward to SEPA's FRMP Cycle 2[4] and the Highland Council's Local Flood Risk Management Plan for Findhorn, Nairn and Speyside[5].

Nairn is covered in one Potentially Vulnerable Area (PVA) in Cycle 2 of the FRMP[6]. The FRMP predicted that 760 homes and businesses are currently at risk of flooding from all sources in Nairn, and this is estimated to increase to 990 homes and businesses by the 2080s due to climate change. In Cycle 1 of the FRMP, key areas identified in the PVA report[7] for Nairn regarding flood risk included Church Road and

1 Flood Risk Management Plan | Findhorn, Nairn and Speyside Final Report November 2022 (highland.gov.uk)

2 https://www.highland.gov.uk/info/1226/emergencies/81/flooding/3

3 SEPA Flood Risk Management Plans: https://www2.sepa.org.uk/frmplans/

4 Nairn is in Potentially Vulnerable Area 02/05/08 in SEPA's Flood Risk Management Plan for Findhorn, Nairn and Speyside. Page 64 describes the actions proposed for the PVA, including undertaking a flood study. https://www2.sepa.org.uk/frmplans/documents/lpd5-findhorn-nairn-and-speyside-frmp-2021.pdf

5 https://www.highland.gov.uk/downloads/file/26353/findhorn_nairn_and_speyside_lfrmp_cycle_2_dec_2022. Section 2.2.

6 SEPA FRM Plan, Page 62. Nairn PVA 02/05/08. https://www2.sepa.org.uk/frmplans/documents/lpd5-findhorn-nairn-and-speyside-frmp-2021.pdf

7 Nairn East and Auldearn (PVA 05/08). https://www2.sepa.org.uk/frmstrategies/pdf/pva/PVA_05_08_Full.pdf. The PVA for Cycle 2 does not list local areas in Nairn at risk of flooding.

Howford Road as well as the Househill area of Nairn. It is also noted that surface water flood risk is evident in localised built up areas across Nairn and at Househill. The surrounding agricultural land of Nairn is also affected by surface water flood risk.

1.2 Purpose

The purpose of this assessment is to determine the baseline flood risk to Nairn from the River Nairn, Auldearn Burn and tidal flooding. This report describes the investigations and analysis carried for this flood risk assessment, it discusses the results and presents them graphically via a series of flood maps which are contained in Appendix A.

The new modelling required the collection of a new channel topographic survey, a hydrological assessment to derive flood hydrographs and construction of a new baseline hydraulic model. A range of flood events were tested, these were the 2-year, 5-year, 10-year, 30-year, 100-year, 200-year, 1000-year and 200-year with climate change (+cc) and 1000-year (+cc). The model has been validated against recent flood photos.

To understand the influence of different elements the following factors have been tested:

- Bridge and culvert inlet blockage
- Inclusion of informal flood wall in Fishertown and earth embankment opposite Househill
- Model roughness

The model has been used to understand the flood risk from the River Nairn and its tributary the Auldearn Burn as well as tidal flooding. Flood risk will be informed by level, depth, velocity and flow data from the modelling outputs. The model is a linked 1D-2D hydraulic model that has been used to represent the river, flood frequency, mechanism of flooding (both fluvial and tidal and how they interact), out of bank flood routing, flood depth and velocity.

It should be noted that whilst this is a new detailed baseline model, its intended purpose is to inform the requirements of a Flood Appraisal Study for the town of Nairn as a whole, it may not be suitable for site specific FRA requirements.

1.3 Deliverables

The deliverables from this Flood Appraisal Study are listed below. All the non-licenced result outputs will be entirely owned by THC on project completion. The following is a summary of the model deliverables:

- For each return period the following grids from the 2D domain shall be output:
    - Coastal maximum depth and velocity grids (raster format)
    - Fluvial maximum depth and velocity grids (raster format)

- Combined maximum depth, velocity and level grid (raster format)
    - Flood extent map (pdf format)
- A longitudinal section of 2-year and 200-year modelled water levels through the River Nairn and the Auldearn Burn.
- The model build GIS files used in the final model runs have been provided to allow the model to be rerun by others. This data is in CSV, shapefile and raster format.
- Model check files - run check files including mass balance and change in volume, as well as the standard check files produced by TUFLOW have been provided. At each 1D model cross section the water level, depth and velocity has been tabulated.
- Model log - A model log file stating which run files were used to produce each set of results and what files make up each run, including initial condition files if used.
- This FAS report, including Model Build (section 4).

In line with the scope, the model methodology was reviewed externally by a third party, Kaya Consulting, prior to JBA building the hydraulic model. This is included in the appendix G.

A Hydrology Method Statement was undertaken separately to derive fluvial and tidal inputs for the River Nairn and the Auldearn Burn for the hydraulic model. This method statement which was reviewed and approved by SEPA[8].

1.4 National policy

While this study was being undertaken the National Planning Framework was updated. National Planning Framework 4 was adopted by the Scottish Government[9] in February 2023. A key change between this guidance and previous guidance is that for planning purposes the functional floodplain is now defined as the 0.5% AP (200 year) event with an allowance for climate change whereas previously, an allowance for climate change was not required. Two climate change scenarios tested against the 200-year event were included as part of this assessment so the functional floodplain, based on the new definition, is still represented in the model results.

SEPA's 'Technical Flood Risk Guidance for Stakeholders' is currently under review by SEPA. This study is consistent with reporting requirements detailed within SEPA's

8 Email from Alayne Finlay, SEPA, to Jonathan Garrett, JBA Consulting, dated 25th August 2022.

9 National Planning Framework 4, adopted by the Scottish Government on 13th February 2023. https://www.transformingplanning.scot/national-planning-framework/adopted-npf4/

‘Technical Flood Risk Guidance for Stakeholders’[10], which supersedes Annex B of SEPA Policy 41[11].

1.5 Site description

Nairn is a seaside town located to the east of Inverness. It is a popular tourist destination and has a residential population of circa 10,000 people making it the third largest population centre in the Highlands. The majority of the settlement is built on high ground and is outwith the fluvial or coastal flood extent. An undeveloped riverside walk, on both channel banks, runs for the majority of the length of the watercourse as it passes through the town. The park land areas adjacent to the banks are also the areas that flood frequently. The key low lying areas are Fishertown and Househill. Fishertown benefits from an informal flood defence wall, approximately 3.65 mAOD to 4.70 mAOD high (ranging between 0.64 m and 1.27 m above surrounding ground level), along the left bank of the channel. An informal agricultural embankment is present along the right bank of the River Nairn for a length of approximately 850 m and height of 7.68 mAOD (northern end) to 10.90 mAOD (southern end) from a short distance upstream of the Auldearn Burn tributary to upstream of the gauge. This provides some degree of protection to the properties of Househill.

The River Nairn is large in the vicinity of Househill and the gauge (around 20-30 m in width) and also relatively steep at this point in its course. The river bed is composed of gravel and cobbles with bedrock in places. The banks are heavily wooded upstream of the town, through the town the trees give way to parkland and reclaimed coastal land. For the lower portion of its reach the Nairn is constrained by an engineered channel. The width of the channel in the lower portion is approximately 25 m to 35 m at the pier walls (estuary) and 40-60 m wide in the vicinity of the footbridges and at swan island. Historic mapping shows an area between the Nairn and Riverside Crescent called the Saltings along the right bank of the Nairn where a psuedo harbour was created.

10 SEPA: Technical Flood Risk Guidance for Stakeholders, Version 13, June 2022 https://www.sepa.org.uk/media/162602/ss-nfr-p-002-technical-flood-risk-guidance-for-stakeholders.pdf

11 Scottish Environment Protection Agency Policy No. 41: A SEPA- Planning Authority Protocol, Development at Risk of flooding: Advice and Consultation, 2011.

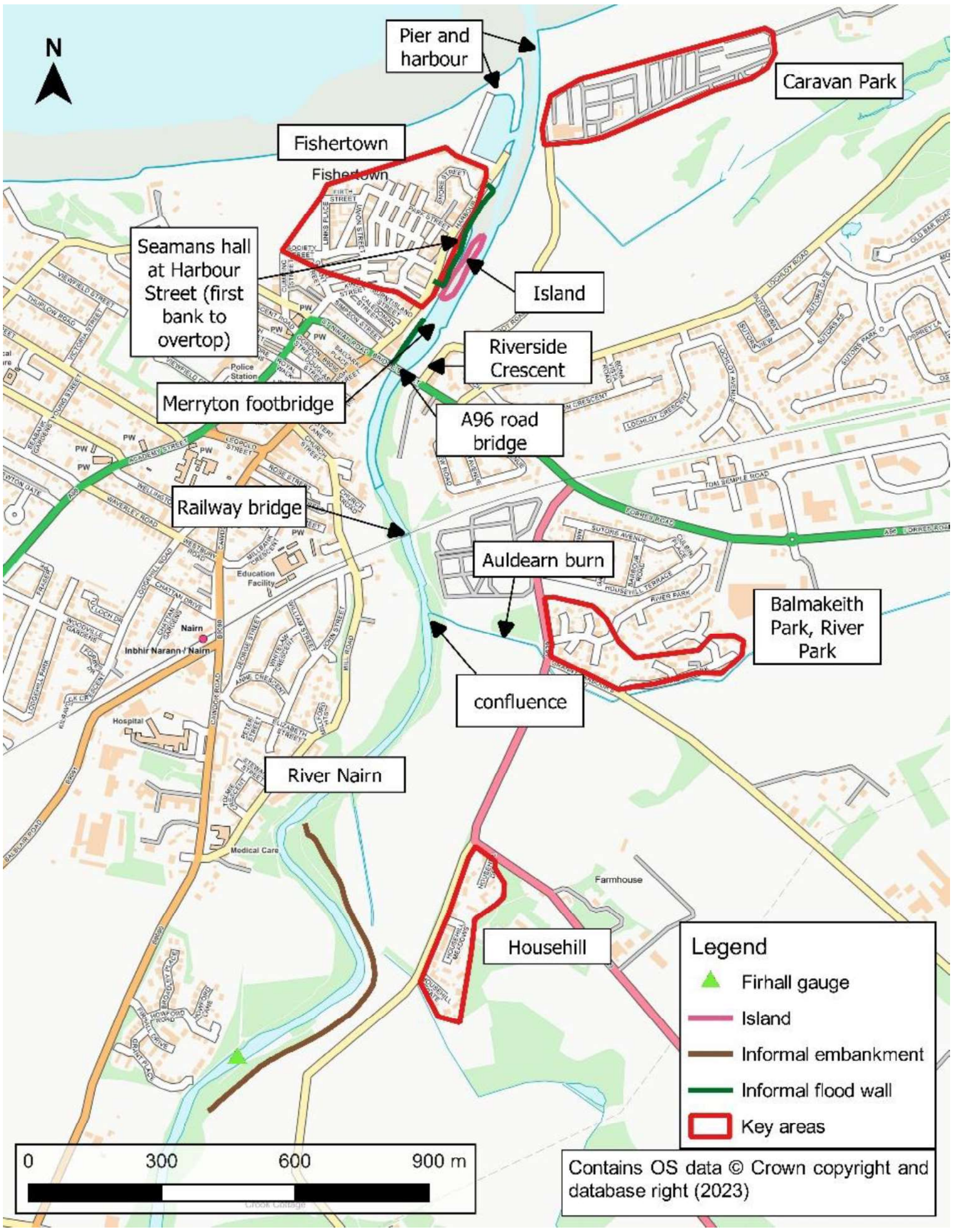

Figure 1-1: Key locations in Nairn

2 Hydrology

A comprehensive hydrology assessment was undertaken for the River Nairn and the Auldearn Burn. An assessment on peak still water level for a range of return periods was also derived. A detailed description of this analysis is provided in the Hydrology Method Statement[12] which was reviewed and approved by SEPA[13]. This chapter provides a short high-level summary.

2.1 Overview

The hydrology calculations included:

1. Derivation of peak flows and hydrographs as required for both the River Nairn and the Auldearn Burn for input into the hydraulic model. Peak flows for various return periods were estimated, including the 2-year, 5-year, 10-year, 30-year, 50-year, 100-year, 200-year, 1000-year for each catchment.

2. Applying an allowance for climate change to the 0.5% AP and 0.1% AP events using the most up to date guidance from SEPA at the time of study[14].

3. Review of historic flood events and derivation of an observed hydrograph from Firhall gauging station, were used as the design hydrograph for the Nairn (this is consistent with work recently undertaken by Jacobs for Transport Scotland in this area[15]). For the Auldearn Burn, a hydrograph from ReFH2 was output and scaled to FEH Statistical method peak flows, a hybrid FEH method as described within EA Flood Estimation guidelines[16]. This derived ReFH2 hydrograph used the same storm duration as the observed event from the Nairn, for consistency.

As this study was commissioned in May 2022, NRFA peak flows dataset version 10, released September 2021, has been used for this study.

2.2 Catchment summary and gauge location.

The catchment area for the River Nairn to Firhall gauge is 305.0 km^2 and the catchment area for the Auldearn Burn to the confluence with the River Nairn is 26.3 km^2. The River Nairn catchment is rural with hills and peat moorland in the upper reaches although the lower 20% of the catchment is cultivated. There is also significant forest cover and Loch Duntelchaig in the headwaters (FARL: 0.911). The town of Nairn is the main urban area in the catchment (URBEXT: 0.001). Underlying

---

12 IGZ-JBAU-00-00-MS-HO-0001-S4-P02-Hydrology_Method_Statement - JBA - August 2022

13 Email from Alayne Finlay, SEPA, to Jonathan Garrett, JBA Consulting, dated 25th August 2022.

14 https://www.sepa.org.uk/media/594168/climate-change-guidance.pdf

15 https://www.transport.gov.scot/media/6971/app-a13_2-flood-risk-assessment-app-13_2-e-h.pdf

16 https://www.jbaconsulting.com/wp-content/uploads/2020/10/Flood-Estimation-Guidelines-2020-197_08.pdf (section 3.5).

geology consists of Predominantly Old Red Sandstone largely overlain by superficial deposits (BFIHOST19: 0.563).

There are two flow gauges on the River Nairn; Firhall in the outskirts of Nairn and Balnafoich, in the headwaters of the catchment; approximately 30 km upstream. Firhall is within the modelled reach and has a longer record of 43 years in length. The record length at Firhall begins in 1978, and the largest event on record occurred on 1st July 1997 (circa 314 m^3/s).

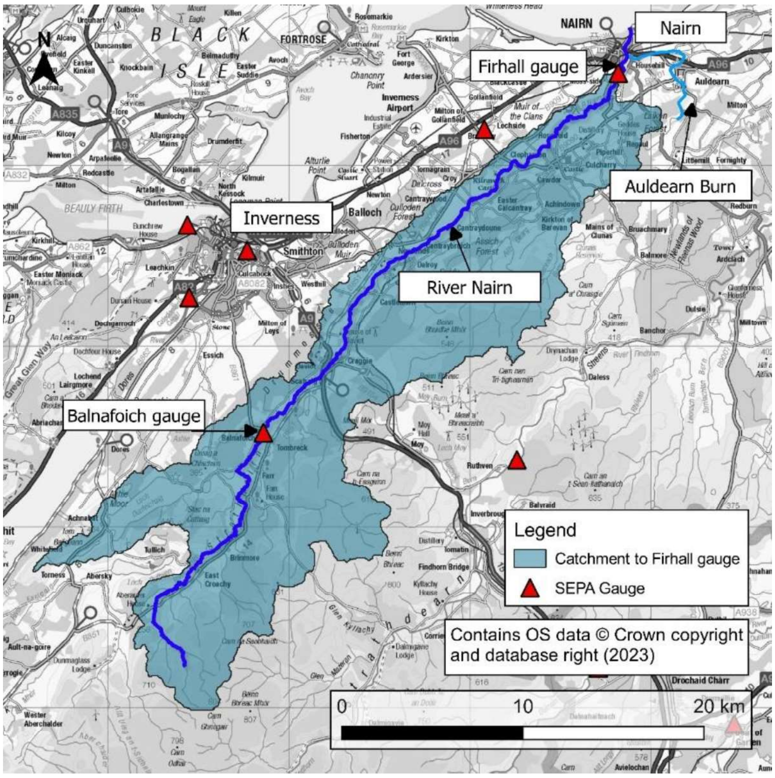

Figure 2-1: Gauge locations

2.3 Peak flow derivation.

In summary, peak flow derivation was required for a lumped fluvial inflow at both the upstream extent of the River Nairn and Auldearn burn, and two lateral flows. The lateral flows are the intervening catchment areas between the upstream extent of the Nairn model and the confluence with the Auldearn Burn, and between the confluence and downstream extent of the model.

River Nairn lumped: FEH Statistical method comparison was carried out between single site, enhanced single site, and single site with historical data to include flood events from: 1782, 1829, 1915, 1956 and 1970. Following comparison of the growth curves, the single site with historical data analysis was chosen.

Reason for choice of FEH method: Moderately sized, gauged, rural catchment.

Hydrograph: July 1997 event (largest event on gauged record) scaled to design flow.

Auldearn Burn lumped: FEH Statistical method (pooling) was chosen, following checks using ReFH2 and FEH rainfall runoff.

Reason for choice of FEH method: Catchment is over 20 km^2 (i.e. not particularly small) and a high BFIHOST19 of 0.731 suggests the catchment is not best suited to rainfall runoff approaches. Hydrograph: ReFH2 hydrograph with similar storm duration to the Nairn observed event in 1997 (i.e. 15 hours), scaled to FEH statistical pooled estimates.

Lateral inflows: Peak flows for the lateral inflow from Firhall gauge to the confluence were obtained by scaling statistical estimates from Firhall (i.e. the River Nairn lumped estimates) to the catchment area from the confluence, and then subtracting the Firhall (River Nairn lumped) estimates. Peak flows for the lateral inflows from downstream of the Auldearn Burn confluence to the coast have been scaled by catchment area from the Auldearn Burn estimates.

Both lateral inflows utilise the July 1997 event observed hydrograph, scaled to design flows.

Table 2-1: Design peak flow (m^3/s) for the following return periods (in years) for the River Nairn, Auldearn Burn and laterals.

Return Period (years)	2	5	10	30	100	200	1000
River Nairn	97.0	141.0	178.0	250.0	363.0	450.0	743.0
Auldearn Burn	2.4	3.5	4.2	5.5	7.1	8.2	11.2
Lateral inflow Upstream	1.5	2.1	2.7	3.8	5.5	6.8	11.2
Lateral inflow Downstream	0.2	0.2	0.3	0.3	0.4	0.5	0.7

2.4 Model inflows

The model has both fluvial and tidal inputs (described in 2.5). The fluvial inputs are a combination of lumped inflows and distributed (lateral) inflows. All inflows have been applied to the model as Flow-Time (QT) boundaries.

The fluvial inputs are listed below and are presented graphically in Figure 3-1.

- Lumped inflow at Firhall gauge - This inflow will represent all the flow in the catchment reaching the gauge. As well as running the design fluvial hydrographs (i.e. the observed hydrograph from the 1st July 1997 event scaled to design peak flows, section 2.3), the observed hydrograph from this event (without scaling) was also run in the model. By running an observed event in the model, this allowed for the Firhall gauge level record to be compared against the water levels predicted by the model for a given flow rate, to aid model calibration (section 4.5).

- A lumped flow was applied at the upstream extent of the Auldearn Burn. This lumped flow was derived by making a flow estimate on the Auldearn Burn confluence and therefore represents the entire flow anticipated on the Auldearn Burn.
- The two lateral flows have been added to four cross sections each (eight in total) along the Nairn, between the US extent of the Nairn and the confluence with the Auldearn Burn, and then between the confluence and DS extent of the model. The cross sections that the laterals have been applied to are generally equidistance apart, to distribute the flow evenly along the modelled reach to represent the intervening catchment areas (using the same weighting ratio for each cross section for applying the flow).

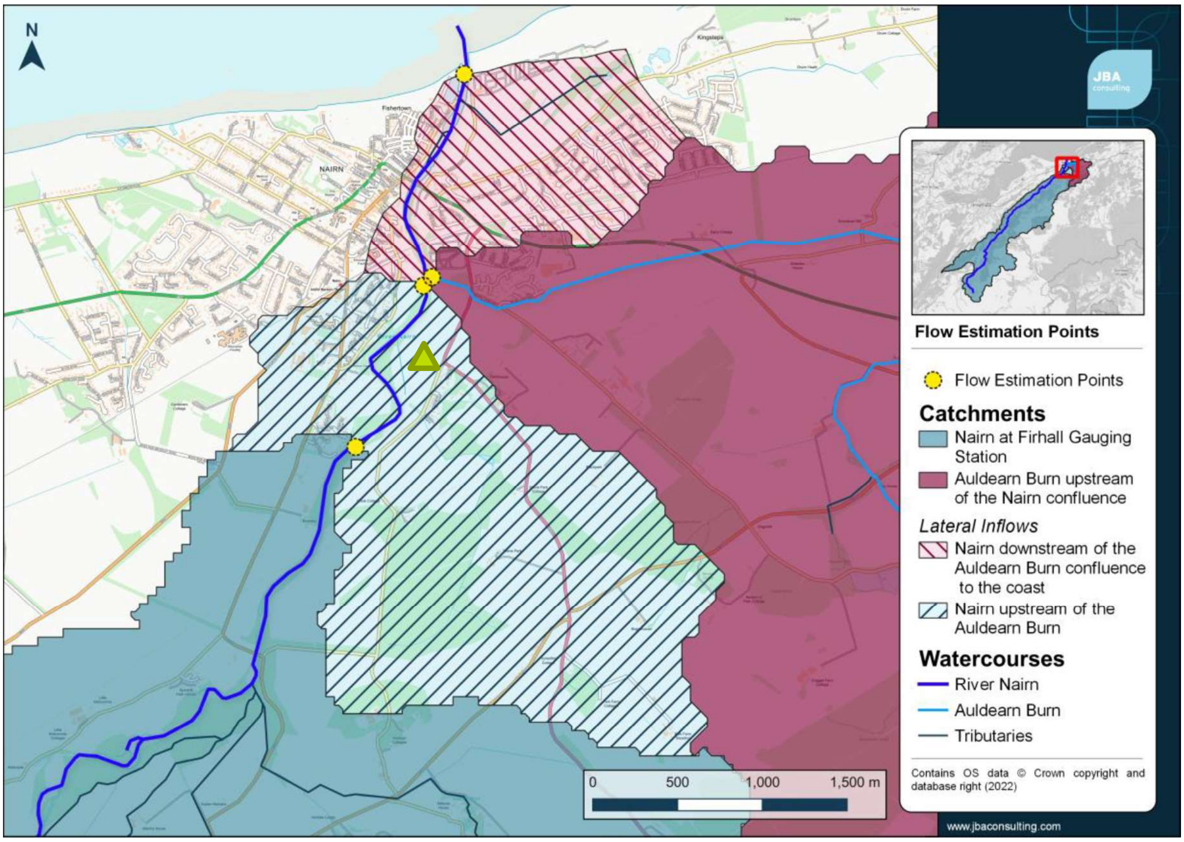

Figure 2-2: Catchments and FEP locations. The green triangle marks the location of the Firhall gauge.

2.5 Peak still water sea level derivation

The tidal curves as input into the model were created from four principal sources of data:

- Extreme still water sea level estimates
- A design astronomical tide

- A design surge shape
- UCKP18 sea level rise projections

Only the still water level (SWL) boundary was used to create the tidal maximum level (from the four datasets, as outlined above) and wave overtopping has not been included as part of the coastal boundary in this study, as agreed in the scope. Design tidal curves were generated for the MHWS and the same eight design events as the fluvial inputs, as well as for the two climate change events (200-year, 1000-year), section 2.8. The derived tidal boundary inputs were used alongside the fluvial boundary inputs as part of a joint probability study (section 4.7). Table 2-2 shows the maximum water levels adjusted for sea level rise (i.e. the peak of the tidal curves).

Table 2-2: Extreme sea levels (m AOD) adjusted for sea level rise (design events)

Return Period	AEP	SWL Base year (2017)	Present Day (2022)
MHWS	-	2.26	2.35
T2	50%	2.90	2.99
T5	20%	2.99	3.08
T10	10%	3.06	3.15
T30	3.33%	3.15	3.25
T50	2%	3.20	3.29
T100	1%	3.27	3.36
T200	0.50%	3.33	3.42
T1000	0.10%	3.48	3.57

2.6 Application of fluvial and tidal model boundaries

The design tide curves were applied in the model as a Head-Time (HT) boundary offshore, with the peak tide cycle coinciding with the fluvial peak at the downstream of the fluvial extent. To help with model stability, the tidal curves have been cropped at 1.5 mAOD, in that all values below this level (i.e. including negative values below 0 mAOD) have been set to 1.5 mAOD. This helps with stability, as the fluvial flow isn't 'forced down' to meet a very low tidal level, that would be below 'normal depth', during the model run.

For running the observed event (1st July 1997) in the model, 15 minute estimated time series tidal data (based from predictions at Invergordon) was obtained from TotalTide software. This observed data was taken from 01/07/1997 01:45:00 to 02/07/1997 09:45:00 (i.e. the same time period as the 1st July 1997 fluvial event ran in the model).

The coastal input is a downstream boundary along the coast. However, the sand dunes offer a degree of protection against wave run-up, with elevations along the dune and harbour area all exceeding the maximum tidal level from the 1000-year coastal event of 3.57 mAOD. Figure 2-3 shows all ground that is above this level, in red. As such, high sea levels for all events up to and including the 1000-year coastal event will flow through the estuary (pier walls) of the River Nairn only (with regard to still water levels, not taking into account wave overtopping). As such, the 1D-2D model shares the same downstream boundary in the 1D component for all present day runs, this is in the form of a 1D Head-Time (HT) boundary at the estuary (outflow of the River Nairn, at the pier walls). For the climate change coastal flood events where sea level is significantly higher, the tidal curves have been applied to both the 1D and 2D domain, as peak tidal levels reach up to 5.38 mAOD (1000-year event climate change scenario 2). To aid stability, the 1D and 2D boundary as used for the climate change events were placed adjacent to each other to form a continuous boundary that runs along the northern edge of the dunes to the north of Fishertown and the caravan park, and along the northern edge of the harbour area (on the left bank, at the estuary). The same HT tidal curve has been used in the 1D and 2D domain, for each event, respectively.

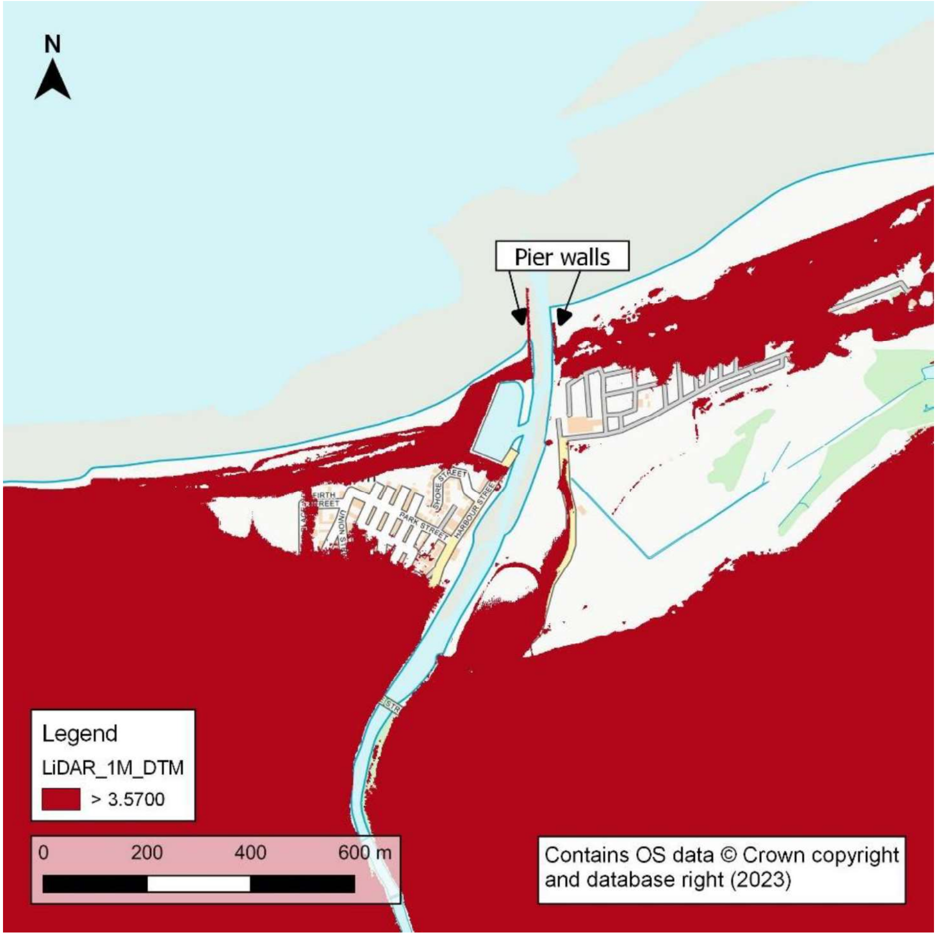

Figure 2-3: Elevations above 3.57 mAOD (the 1000-year maximum tidal still WL).

2.7 Alignment of flood sources

As described above, the model has several boundaries which provide water to the model. The purpose of this assessment is to determine the peak flood level for an event, therefore, the sources of inflow into the model has been aligned. The model simulates 32 hours for each tested event. This run time was informed from the largest recorded flood on Firhall gauge (1997 event). This simulation time is long enough to represent both the rising fluvial peak and maximum flood inundation extent of the out of bank flooding and 3 tidal peaks. The model runs from 18.25 hours prior to the peak of the fluvial flood event (from observed data, occurring at 01/07/1997 01:45:00), to 13.75 hours after the peak (occurring at 02/07/1997 09:45:00). There are three tidal cycles within this time period, with the largest tidal curve peaking at the same time as the fluvial hydrograph peaks (at 18.25 hours into the model run, occurring at 01/07/1997 20:00:00 regarding the observed event). As such, three tidal cycles have been included in the model run, with the second tidal cycle (that is the largest tidal cycle and the maximum tidal water level) coinciding with the fluvial hydrograph peak (Figure 2-4). Figure 2-5 below shows the 200-year fluvial hydrographs for the Auldearn Burn and the laterals, with peaks also coinciding.

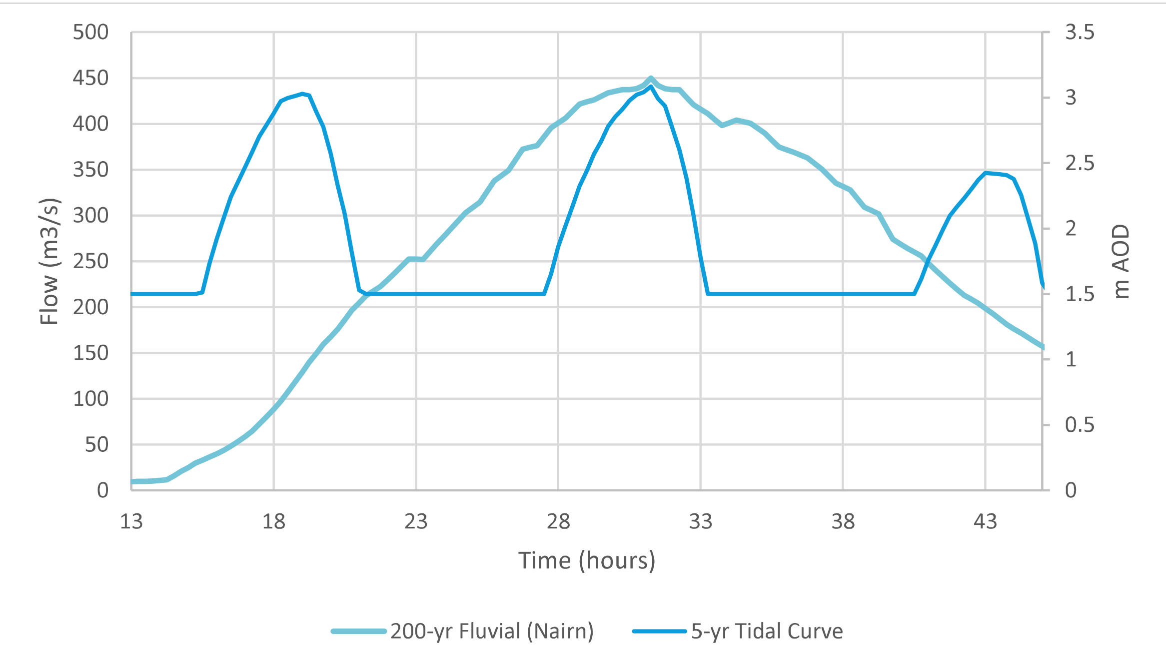

Figure 2-4: Example 200-year fluvial flow (m³/s) and 5-year tidal curve (mAOD) as input into the model. Notice peaks coincide at 31.25 hours.

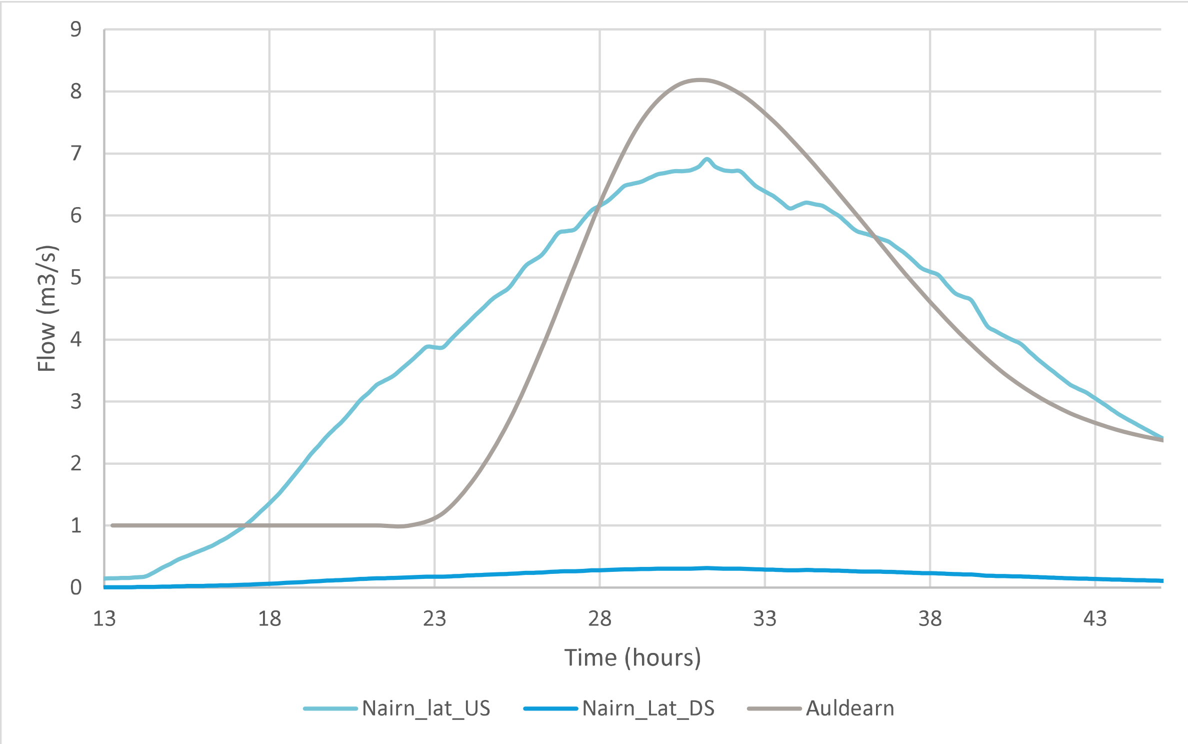

Figure 2-5: Example 200-year fluvial flow (m³/s) for Auldearn Burn and both lateral inflows (peaks coincide at 31.25 hours).

2.8 Climate change

As agreed with the Highland Council on commission of the study, two climate change scenarios were tested for both the 200-year and 1000-year events. From discussion with SEPA[17], it was agreed that these climate change scenarios would be as follows.

Fluvial climate change scenario 1

- 40% increase in flows on the River Nairn[18]
- 42% increase in rainfall for the Auldearn (equates to about a +59% increase in flow for the 200-year event, and +62% increase in flow for the 1000-year event)[19].

Fluvial climate change Scenario 2

- 51% increase in flows on the River Nairn[20]

17 Email from Alayne Finlay, SEPA, to Jonathan Garrett, JBA Consulting, dated 8th September 2022

18 As based on the 67% percentile projection for 2100s as per SEPA climate change guidance for peak flows. https://www.sepa.org.uk/media/594168/climate-change-guidance.pdf

19 As based on the 50% percentile projection as per SEPA climate change guidance for peak rainfall. https://www.sepa.org.uk/media/594168/climate-change-guidance.pdf

20 Utilises the 95th% percentile projection for the 2070s, as per SEPA climate change guidance (Table 5). https://www.sepa.org.uk/media/594168/climate-change-guidance.pdf

- 42% increase in rainfall for the Auldearn (i.e. same as scenario 1)

Coastal climate change scenario 1

- An increase in +1.16 m on the tidal maximum level (derived from UK Climate Projections (UKCP) 2018 Guidance and SEPA guidance for Climate change allowances for flood risk assessment in land use planning). Further details included in the Hydrology Method Statement.

Coastal climate change Scenario 2

- Sea level based on H++ scenario: an increase in still water sea level of +1.81m (added to the still water level)[21].

Combinations to run:

Fluvial scenario 1 was paired with coastal scenario 1 and Fluvial scenario 2 paired with coastal scenario 2. From Joint Probability analysis (section 4.7), the 5-year event and 200-year event were used together (i.e. for fluvial and tidal boundaries) and 10-year and 1000-year event. As such, the climate change peak flows and tidal levels for these four events were required for running the 200-year and 1000-year climate change events. The tables below show the peak flows and maximum tidal levels as used in the model for the climate change events.

Table 2-3: Climate change design peak flow (m^3/s) for the following return periods (in years) for the River Nairn, Auldearn Burn and laterals

RP	5 CC1	5 CC2	10 CC1	10 CC2	200 CC1	1000 CC1	200 CC2	1000 CC2
River Nairn	197	213	249	268	630	1040	679	1122
Auldearn Burn	4.9	4.9	5.9	5.9	10.1	13.5	10.1	13.5
Lateral inflow Upstream	2.9	3.2	3.7	4.0	9.5	15.6	10.2	16.9
Lateral inflow Downstream	0.3	0.3	0.4	0.4	0.69	0.95	0.75	1.02

21 As discussed with SEPA and based on guidance as per Appendix 2 of SEPA climate change guidance. https://www.sepa.org.uk/media/594168/climate-change-guidance.pdf

Table 2-4: Derived climate change tidal levels

Return Period	Climate Change Scenario 1 (2122)	Climate Change Scenario 2 (2122)
T5	4.21	4.89
T10	4.28	4.96
T200	4.55	5.23
T1000	4.70	5.38

2.9 Historical flooding

Sources of historic flooding consulted include:

Readily available archives including the internet and internet based British Hydrological Society Chronology of British Hydrological Events. There are 5 notable flood events in Nairn in this archive, including in 1865, 'the damage on the Nairn was serious…. the River Nairn became much swollen, and consequently the river rose to an unusual height.' The description of this event informs that channel banks and part of a mill were washed away[22]. Description of an event in 1914 informs that "An unusually heavy fall of rain took place throughout Nairnshire, and the River Nairn came down in a great flood, rising to a height which has not been exceeded for the last forty years"[23]. Notable events from the River Nairn also occurred in 1874, 1878 and 1893.

Records from 'The great Muckle Spate of August 1829' informs that the bank at Firhall was undercut and undermined the buildings that were set back about 30 m from the river in this area, and also that there was flooding at Househill, on the right bank in the vicinity. Flood inundation between Househill and Nairn was about a mile in length and half a mile in breadth[24]. Web pages from 'a gurn from nurn[25]' shows that Riverside Park at Mill Road was completely flooded during a flood event in 1956.

During the Flood Risk Management Plan cycle one (2015 to 2021)[26], Nairn was included within a number of SEPA FRM Potentially Vulnerable Areas (PVA). One of these PVA documents, 'Nairn East and Auldearn'[27] notes that the earliest recorded flood in Nairn occurred in 1782 and resulted in one half of a bridge in Nairn being

22 Event no. 6594. https://www.cbhe.hydrology.org.uk/

23 Event no. 6278. Occurred on 85th May 1914. Quote from the Scotsman. https://www.cbhe.hydrology.org.uk/

24 'The Great Floods of August 1829 in the Province of Moray and Adjoining Districts (Chapter 2)' Written by Sir Thomas Dick Lauder.

25 A Gurn from Nurn: Floods of 1956 (gurnnurn.com)

26 The second cycle that is currently active runs from 2022 to 2028. Nairn is included in one PVA in the current cycle. The PVA's in the current cycle do not list historic flood events.

27 SEPA FRM Strategy. PVA_05_08. PVA_05_08_Full (sepa.org.uk)

washed away. The document also notes major floods on the River Nairn in 1820, 1825, 1829 (The Great Muckle Spate), 1865, 1874, 1877, 1914, 1915, 1937, 1956, 1993 and 1997. The Firhall Suspension Bridge and the Jubilee Bridge both collapsed, and properties were affected during the July 1956 flood on the River Nairn. It also informs that in July 1997 (largest event at the Firhall gauge), January 2005 and in 2014, properties and roads in Nairn were flooded from the Auldearn Burn.

The British Chronology of Flash Floods produced by JBA Trust informs that on 23rd July 1873, a flood event in Nairn caused flooding to the High Street by which several shops and houses were flooded and that the river rose with great rapidity during this event[28].

As well as providing photographs and records from recent historic flood events that have been used for model validation purposes (15/12/2012, 08/10/2014 and 11/08/2014), The Highland Council also provided reports from 1990 and 2000. The 1990 report informs that surface water flooding has previously occurred at the Caravan Park and of flooding at Fishertown. An event on 11th February 1990 from a high tide caused overtopping of the Harbour Wall on the left bank of the River Nairn, where the old council depot used to be (now Mooring flats). The 2000 report refers to a flood event on 24th / 25th December 1999, that appeared to affect the Fishertown area. Further discussion on the photographs and records (including a map of historic flood locations), as provided by the Highland Council, is included in section 4.5.

Historical Maps from the National Library for Scotland were viewed for comparison with the present day. The maps show that the general path of the River Nairn and Auldearn Burn has remained much the same over the last 100 years. Some areas that show differences are in the mid-section of the River Nairn at the meanders in the vicinity of Househill. Outline maps from 1885 to 1900 and OS maps from 1949 to 1972 suggest the meanders were slightly larger and the formation of small sediment deposits was prevalent in these areas.

28 https://www.jbatrust.org/Scotland.pdf (jbatrust.org)

3 Topographic survey

3.1 Existing survey data

From liaison with the Highland Council during the project outset, it was confirmed that there is an existing detailed hydraulic model of the upper section of the River Nairn, as developed by Jacobs for Transport Scotland. By permission, survey data obtained in November 2015, for this existing Jacobs model, has been incorporated into the upper reach of the new model, as built for this FAS. The existing survey extends from upstream of Firhall gauge on the River Nairn and ends a short distance downstream of the Auldearn Burn confluence. This survey provided an additional 14 cross sections that were added along the upper reaches of the model. The locations of these cross sections are included in Figure 3-1.

3.2 Survey sections

The primary source of survey data for development of the hydraulic model was the survey collected internally by JBA Consulting in August 2022.

The surveyed locations are shown in Figure 3-1 and comprises of the following:

- 23 open channel cross sections (17 on the Nairn, 6 on the Auldearn)
- 14 structure cross sections, including 7 on the Nairn and 7 on the Auldearn, these are located at the US faces of bridge structures and pipe crossings and the entrances and exits of culverts.

In addition, 14 cross sections from the Transport Scotland model were added to the upper model extent of the Nairn reach and 22 cross sections from the Highland Council survey were added to the Auldearn Burn reach.

The survey locations were chosen to capture key geometry changes in the river channels and to allow for a reasonable representation of the channel to be reproduced in the hydraulic model whilst also taking a sustainable approach to the number required. All structures and pipe crossing on both watercourses have been surveyed and all structures apart from the small footbridge on the Auldearn Burn near the confluence have been included in the model (further information on the model build is provided in section 4.1). The lower reach of the River Nairn and the modelled length of the Auldearn Burn have been heavily modified. This has resulted in long lengths of uniform or gradually changing channel. Changes in channel geometry occur gradually or occur at structures. Between the railway bridge and the main road bridge, the River Nairn is contained in a relatively narrow floodplain where there are no receptors so this stretch has been considered rural for the purpose of the cross section spacing. In addition, the river cross section survey is complemented in critical areas by a top of bank survey.

However, along the Auldearn Burn, it was decided that a Highland Council survey of this watercourse would be added to the model, following third party review of the model methodology. This included the addition of 22 cross sections, based on spacing and geometry of cross sections that were considered to best refine the channel reach in the model to compliment the survey undertaken by JBA.

In additional to the JBA cross section survey, a number of topographic points were undertaken at the following locations:

- A number of buildings/static caravan threshold levels have been surveyed.
- The gravel island, locally known as Swan Island, has been captured by survey data.
- A number of supplementary points to identify location and level of flap valves, grilles, harbour entrance and a manhole which has been known to flood have also been identified and surveyed.
- The top of defence wall levels on the left bank near Fishertown have been surveyed.
- A number of check points along the top of the earth embankment near Househill have also been surveyed.

Comparison between the JBA survey of the embankment and existing survey (at spot check locations) showed that JBA survey points were approximately + 0.03 m higher in vicinity of cross section NAI01_02365, and there is more discrepancy where the embankment is larger, + 0.1 m near NAI01_02500. At the southern section of the embankment, discrepancy is also around + 0.1m. The JBA levels are generally marginally higher along the top of the embankment, though both of the surveys give similar levels to the LiDAR.

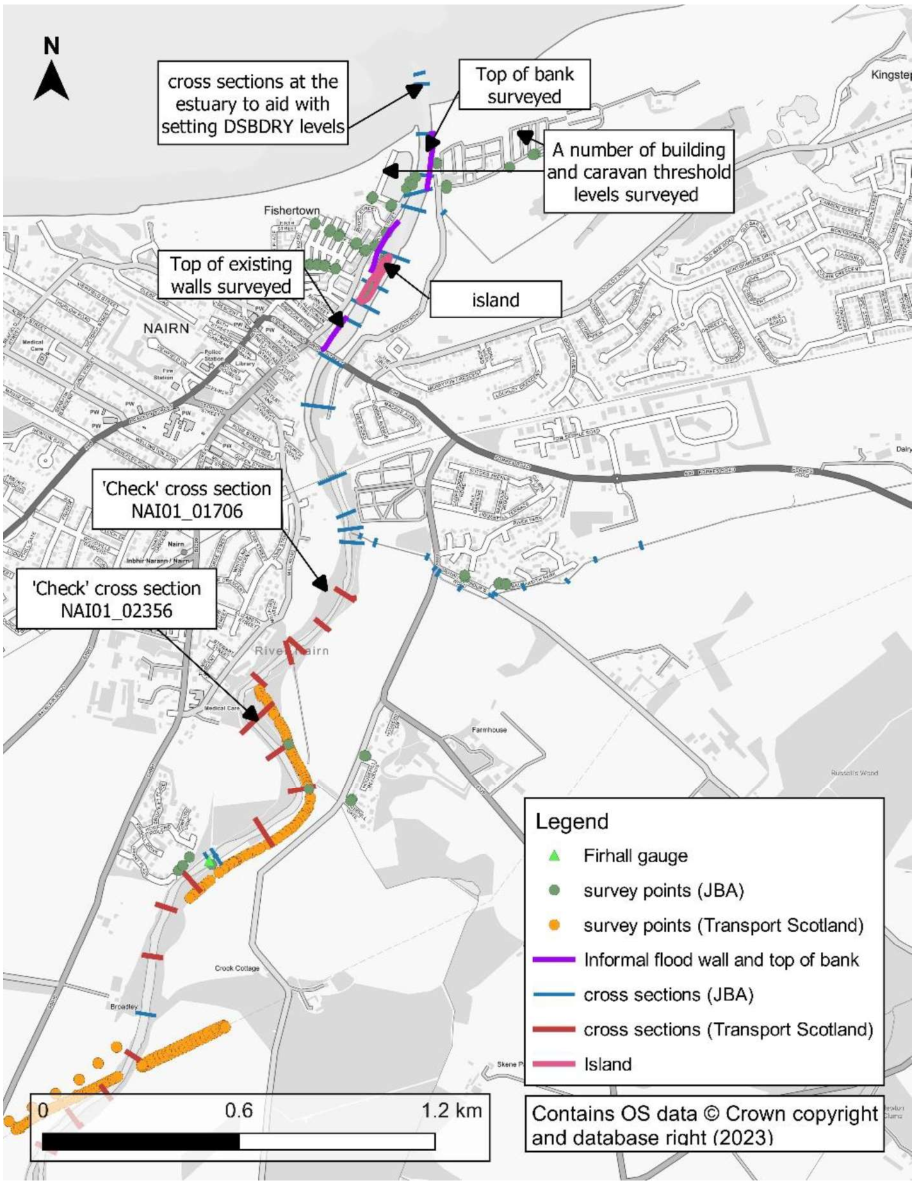

Figure 3-1: Cross section survey locations

3.2.1 Cross section tie-in check

Two 'check' cross sections were undertaken, where a new survey cross section has been taken at a cross section previously surveyed for the Jacobs model. The overlapping cross sections have been used to estimate the degree of change over time. The new survey has been used where there is an overlap of cross-sectional data. These 'check' cross sections are JBA Cross section NAI01_01706 and NAI_02356. Figure 3-2 shows the channel comparison at cross section NAI01_01706 and Figure 3-3 at cross section NAI01_02356. The age of the survey varies by seven years. At NAI01_01706, the change is small with the main difference being a retreat of the right bank by circa 2.5m but it has also grown by approximately 0.75m on the left bank. This suggests some movement in planform while the bed level has remained the same. At NAI01_02356, the chainage offset was amended by 1m between the JBA and Jacobs survey to align the cross sections, the comparison showed that the channel bed is a similar elevation and width, though some growth of the right bank appears to be evident.

Hard features such as the gauge datum and the soffit at the underside of the footbridge downstream of the gauge were also surveyed for comparison purposes with the old survey's datum, as shown in Table 3-1. The difference between the JBA survey and Jacobs survey was 0.045 m at the soffit level of the footbridge downstream of the gauge, with less difference at the gauge location. This is a relatively small discrepancy for river channel surveys, giving confidence that the survey data used in the model is accurate to +/- 0.05m (5 cm) and that the two sets of survey data could be combined without applying a global correction.

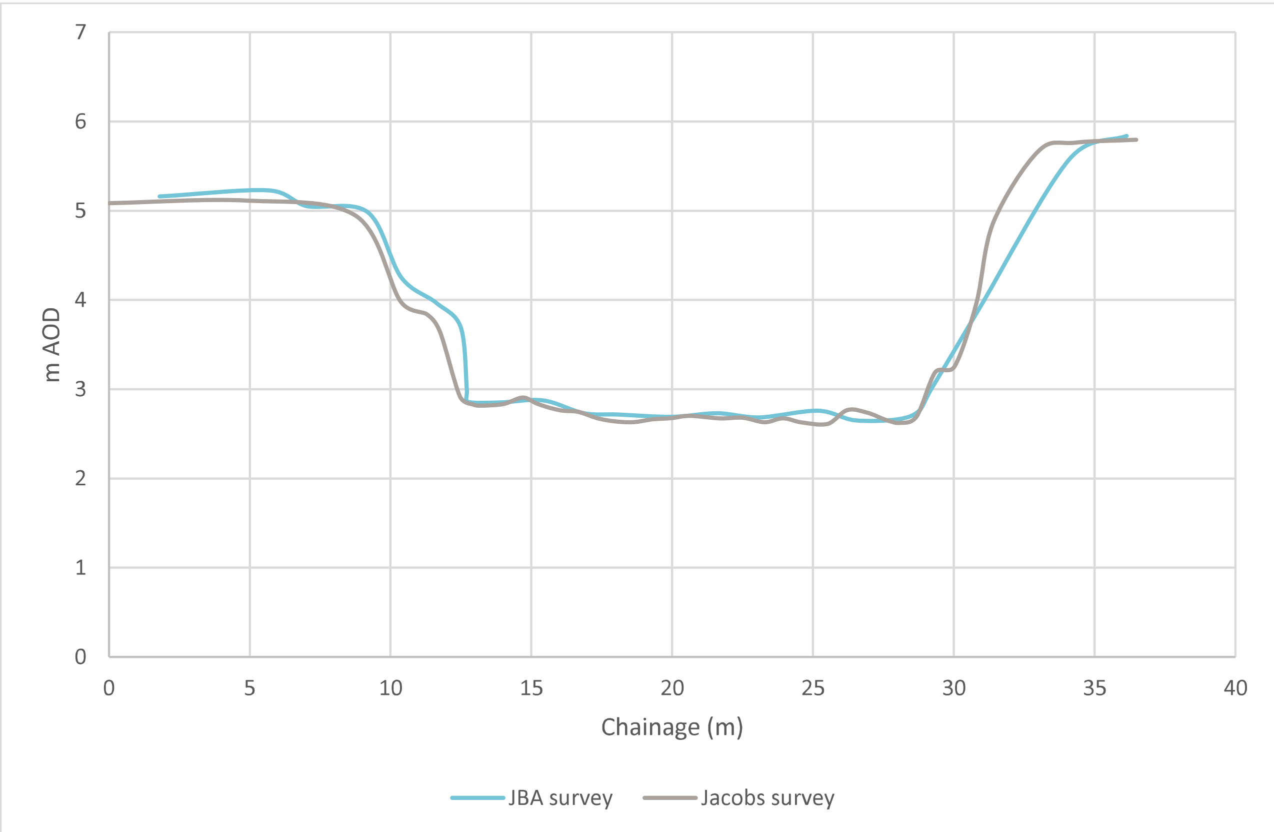

Figure 3-2: Comparison between the JBA and Jacobs survey at NAI01_01706

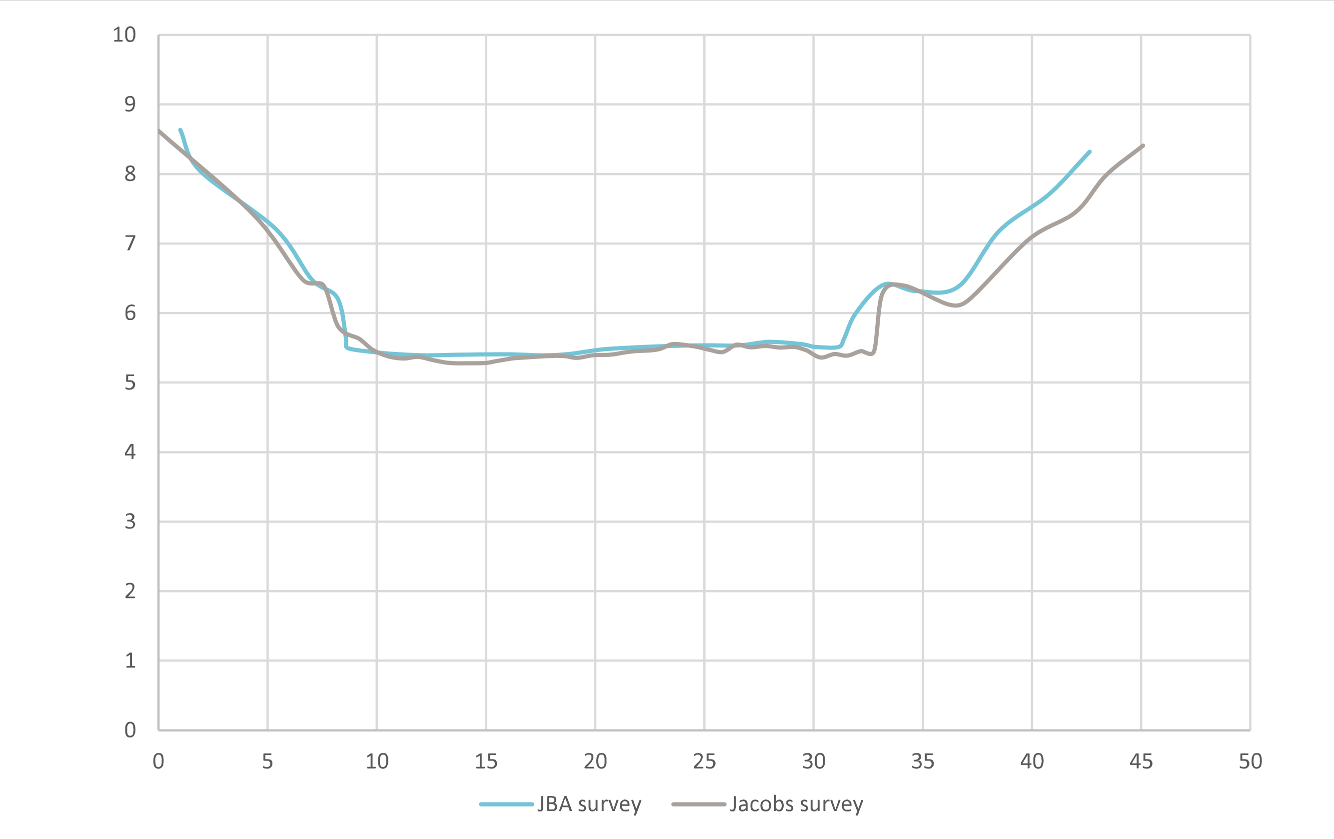

Figure 3-3: Comparison between the JBA and Jacobs survey at NAI01_02356

Table 3-1: Comparison between hard levels (JBA vs Jacobs survey) at select locations.

Location	JBA Survey	Jacobs survey	NRFA	Difference
Gauge datum (NAI01_02853)	7.2	7.182	7.182	0.018
Soffit level at footbridge (NAI01_02830)	10.79	10.735	N/A	0.045

3.3 Lidar

Phase 1 and Phase 2 Open-Source LIDAR Digital Terrain Model (DTM) provides coverage of the Nairn, as available from the Scottish Remote sensing portal at a 1m coverage (flown between March 2011 and April 2014). This data has been used to provide topographic data for the 2D model domain. There is an overlap between the Phase 1 and Phase 2 grids. The Phase 2 was used over Phase 1 where there is an overlap, as Phase 2 data is newer. Inspection of the LiDAR grids showed generally good continuity between the datasets where they overlapped (generally < 0.1m discrepancy), as such feathering of the datasets at the boundary was not required. It is noted there was more discrepancy between Phase 1 and Phase 2 LiDAR datasets at the Auldearn Burn, though this watercourse is in the 1D domain and as such channel survey data is used instead of LiDAR to represent the channel.

3.3.1 Lidar accuracy check

To compare the accuracy of the LiDAR it was compared against surveyed points on wide, open and generally flat, surfaces. The comparison in levels is shown in Table 3-2. The LiDAR data available included Digital Terrain Model (DTM) of Phase 1 and 2. Where the LiDAR grids overlapped they were also compared against each other close to the boundary edge to check that an artificial step does not occur. There is an overlap between both LiDAR datasets for points 33 to 40. The results show that LiDAR Phase 2 had a more accurate readings when compared against surveyed points. Points 101 to 105 were located on the harbour wall. The LiDAR data processing removed the harbour wall, hence the difference between the surveyed and LiDAR levels is very high, with an average difference in height of 3.95m. The harbour wall was reinserted into the model based on a number of survey points. Overall (excluding the large harbour wall difference), the difference between the LiDAR and the surveyed points is approximately 0.02m.

3.3.2 Property threshold levels

A targeted topographic survey of select locations in the residential area of Fishertown, caravan park near the estuary of the River Nairn and other points of interest within Nairn was undertaken for the purpose of improving model representation of the existing condition. The survey included threshold level of buildings, boundary walls and points along the river. Figure 3-4 and Figure 3-5 identifies the location of surveyed points.

Figure 3-6 presents the properties threshold increase in height above surveyed ground level adjacent to the property. The difference in height were calculated by taking the surveyed floor level height of the properties and subtracting the surveyed ground levels. Where multiple survey points were taken over a small geographic area the threshold height above ground level was averaged. The average value was then applied to a cluster of adjacent properties as shown in Figure 3-6. Note that in some cases the threshold height is at or lower than the ground level.

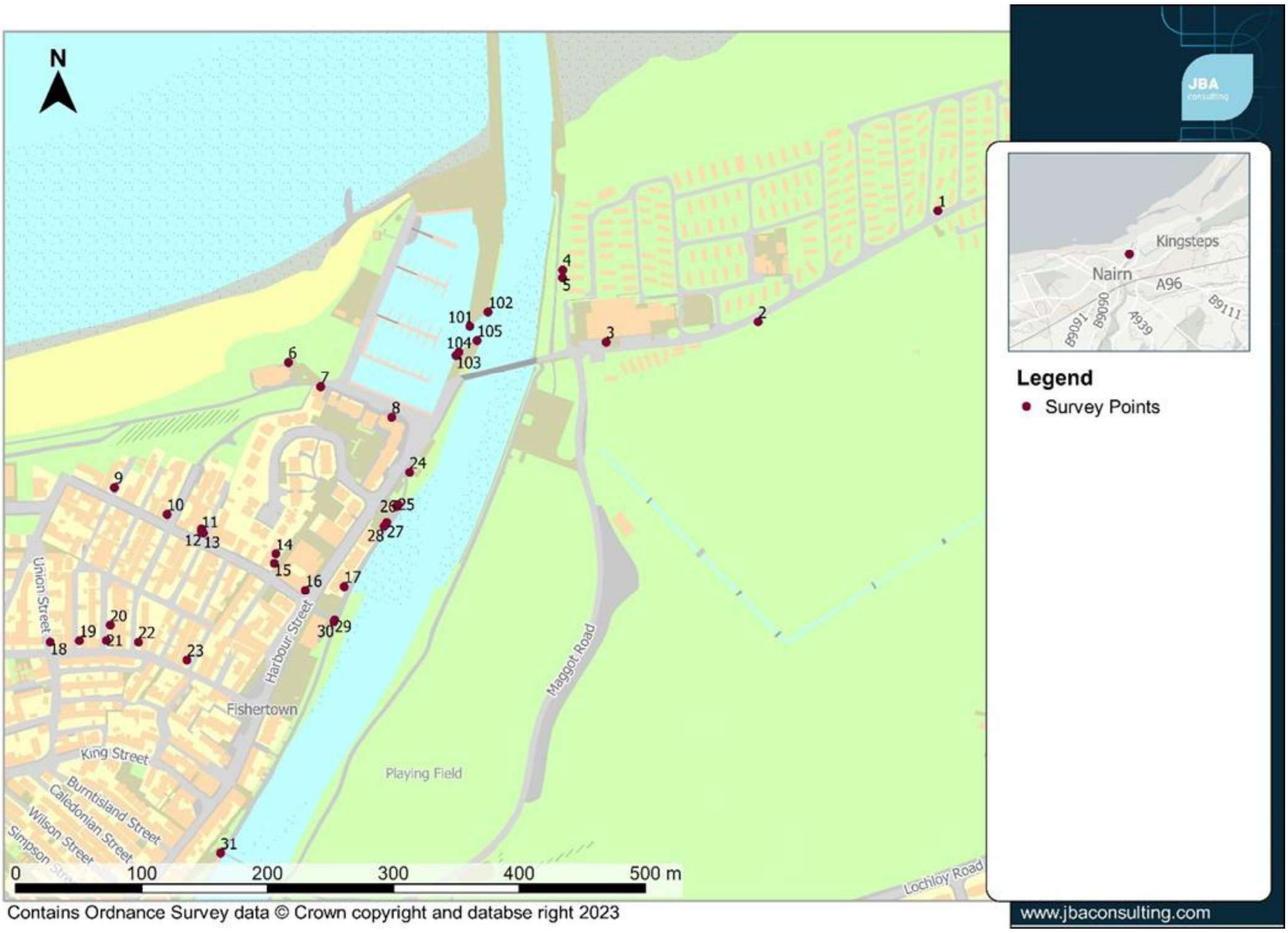

Figure 3-4: LiDAR point comparison with survey - lower reach

Figure 3-5: LiDAR point comparison with survey - Centre reach

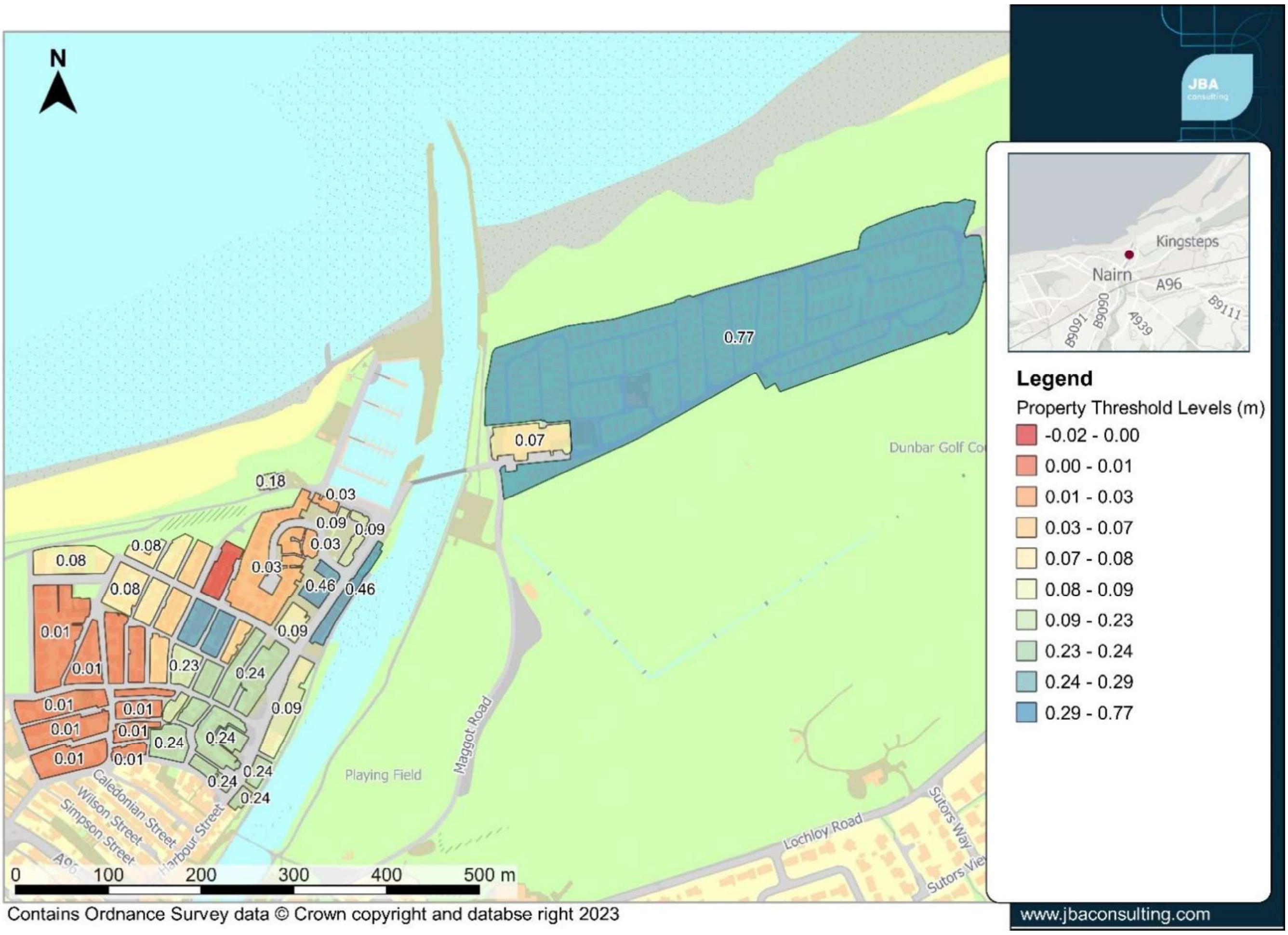

Figure 3-6: Property Threshold Levels

Table 3-2: Comparison between survey and LiDAR elevations at surveyed points

Description	Survey Point	Survey Elevation (mAOD)	LiDAR 1 Elevation (mAOD)	Difference Survey – LiDAR 1 (mAOD)
Caravan Site 1	1	3.20	3.07	0.13
Manhole Concrete Level	2	3.54	3.40	0.14
Drifters Reception	3	3.34	3.27	0.07
Caravan Site 2	4	2.87	2.88	-0.01
Caravan Site 3	5	2.83	2.85	-0.02
Sun Dancer, Bar and Restaurant	6	5.02	4.93	0.09
186 Harbour Street	7	4.22	4.17	0.05
Basil I Harbour Street	8	3.84	3.88	-0.04
55 Park Street2	9	2.80	2.76	0.04
33 Park Street	10	2.86	2.84	0.02
22 Park Street	11	2.89	2.83	0.06
22 Park Street	12	2.96	2.93	0.03
22 Park Street	13	2.69	2.79	-0.10
8 Park Street	14	3.11	3.03	0.08
8 Park Street	15	3.19	3.19	0.00
96 Harbour Street	16	3.32	3.23	0.09
2 Harbour Street	17	3.10	3.03	0.07
32 Union Street	18	3.58	3.63	-0.05
45 Society Street	19	3.88	3.81	0.07
37 Society Street	20	3.52	3.49	0.03
35 Society Street	21	3.82	3.77	0.05
27 Society Street	22	3.76	3.68	0.08
6 Society Street	23	3.72	3.66	0.06
Bottom of Wall	24	3.61	3.67	-0.06
Bottom of Wall/ Flood Gate	25	2.94	2.98	-0.04
Bottom of Wall/ Flood Gate	26	2.94	3.10	-0.16
Top of drain cover	27	2.85	2.86	-0.01

Description	Survey Point	Survey Elevation (mAOD)	LiDAR 1 Elevation (mAOD)	Difference Survey – LiDAR 1 (mAOD)
Top of drain cover	28	2.84	2.86	-0.03
Bottom of Wall/ Flood Gate	29	3.00	3.00	0.00
Bottom of Wall/ Flood Gate	30	3.00	2.99	0.01
Bottom of Wall	31	4.45	4.40	0.05
Bottom of Wall	32	5.20	5.25	-0.05
6 Granny Barbours Rd	33	6.77	6.67	0.10
1 Balmakeith Park	34	6.33	6.26	0.07
2 Balmakeith Park	35	6.50	6.31	0.19
1 Househill Meadows	36	7.38	7.42	-0.04
9 Househill Meadows	37	7.94	7.81	0.13
8 Househill Meadows	38	8.10	7.97	0.13
Househill Gate - Uluru	39	8.46	8.39	0.07
15 Howford Road	40	11.65	11.56	0.10
Harbour Top of Wall	101	3.74	-0.36	4.10
Harbour Top of Wall	102	3.71	-0.38	4.09
Harbour Top of Wall	103	3.75	0.04	3.71
Harbour Top of Wall	104	3.71	-0.04	3.75
Harbour Top of Wall	105	3.69	-0.43	4.12

3.4 Overview of structures

Details on the structures are provided in section 4.3.

4 Hydraulic model build

4.1 Previous models

There is an existing detailed hydraulic model of the upper section of the River Nairn, as developed by Jacobs for Transport Scotland (A96 dualling, model dated 2015) and also existing survey data of the Auldearn Burn from the Highland Council. Surveyed cross sections from these models have been incorporated in to the new 1D-2D hydraulic model of the Nairn, with permission[29].

4.2 Model approach

In line with the scope, a Flood Modeller-TUFLOW 1D-2D model was built for this study. This model was run with unsteady flow (includes time variation of flow within the reach) and used to translate the peak flow estimates to water level and flow direction in Nairn. The 1D component of the model represents the watercourse channel and the 2D domain models the town of Nairn and surrounding vicinity (i.e. out of bank flooding and flow paths). The hydraulic model outputs were used to estimate water levels, depths, velocities, flow paths and resulting flood outlines for the various scenarios and climate change events. Flood Modeller version 5.0, developed by Jacobs and TUFLOW version 2020-01-AB-iSP-w64 were used.

Prior to building the hydraulic model, an independent third party review of the proposed model methodology was undertaken by Kaya Consulting[30] (included in appendix G). The main finding raised in their review was in relation to cross section spacing along the Auldearn Burn being greater than that recommended by SEPA guidance. As described in section 3.2, it was decided that a Highland Council survey of this watercourse would be added to the model, to compliment the survey undertaken by JBA.

4.3 Model schematic

4.3.1 1D model extent

The 1D model extent is shown in Figure 4-1. The location of the upstream extent of the model on the River Nairn was chosen as it is a short distance upstream of Firhall Gauge and there is a slight constriction in the floodplain. The upstream extent of the Auldearn Burn is located where the channel is confined by natural topography upstream of Balmakeith Park (the most upstream urban area adjacent to the Auldearn Burn, downstream of the A96). The River Nairn modelled reach is approximately 3800 m long and Auldearn Burn reach approximately 1100 m long.

29 Email from Alastair Templeton, Transport Scotland, to Duncan Sharp, The Highland Council, dated 8th July 2022

30 Email from Michael Stewart, Kaya Consulting, to Jonathan Garrett, JBA Consulting, dated 7th September 2022.

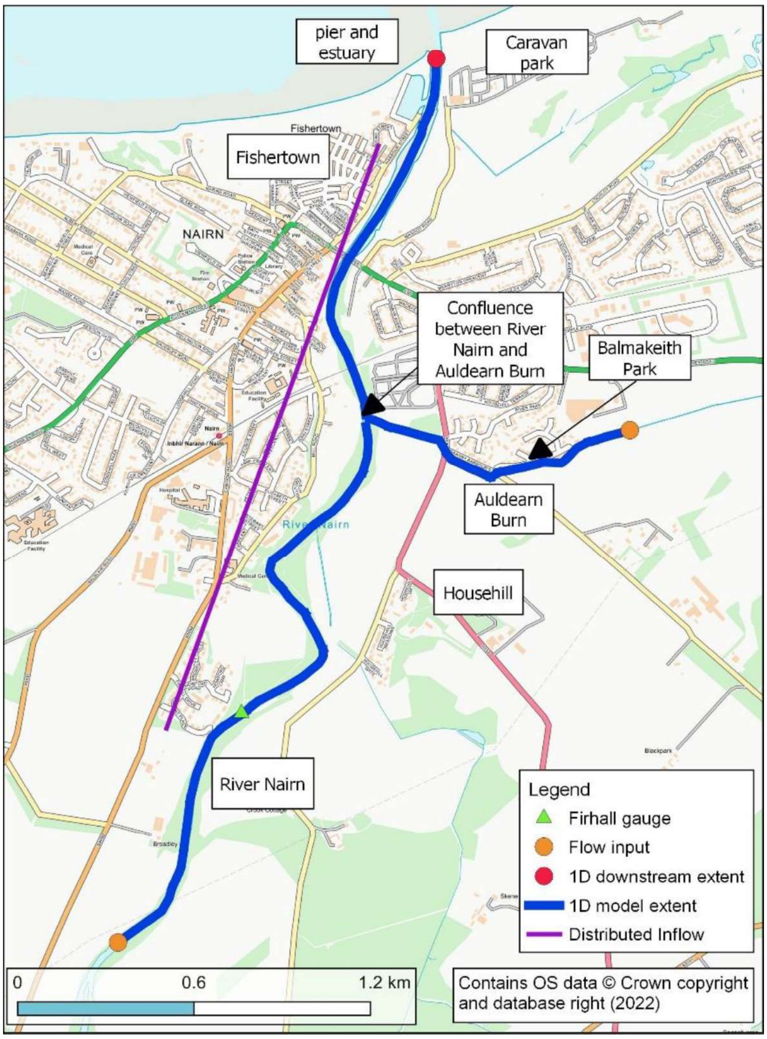

Figure 4-1: 1D model extent

4.3.1.1 Labelling convention

Cross section labelling has been based upon a naming format AAABB_XXXXX. AAA is an abbreviation for the watercourse name, NAI for Nairn and AUL for Auldearn and B is the number 01 to represent the tributary in question (although there is only one River Nairn and one Auldearn Burn watercourse, so both numbers used is 01). This aims to help with the application of an audit trail and understanding of where the base channel data has originated. A spacer (e.g. '_') is used for clarity. XXXXX is the chainage of the section (distance measured from the downstream extent of the watercourse) expressed as a whole number. The labelling of structures uses the following prefix prior to the chainage number:

- B: This denotes a bridge.
- CUL: This denotes a culvert
- PC: This denotes a pipe crossing

4.3.1.2 1D structures

The River Nairn and the Auldearn Burn are crossed by several structures within the study area. These structures have been tabulated in Table 4-1 and their location is shown graphically in Figure 4-2. Survey data was available for all channel structures and has been utilised in the model.

All of the structures along the reaches have been included in the hydraulic model apart from the small single span bridge over the Auldearn Burn. This was not included in the model due to instability issues, however, there are no properties or roads in the surrounding area.

Only the upstream face of bridges were surveyed and as such, a duplicate of the cross sectional profile has been used to represent the channel at the downstream face of the bridge. Manning's 'n' values used at the channel geometry at bridges are the same as those used for the cross sections at the upstream and downstream faces of the bridges. For culverts, survey data was available at both the inlet and outlet, and has been incorporated into the model. Culverts have been represented using the circular culvert unit in Flood Modeller, with Manning's 'n', invert levels and diameters taken from surveyed data.

Two of the bridges have a skew angle (B_00363 and B_01461, Table 4-1). The skew angle has been input in the bridge FM unit and represented by geometry in the 2D Tuflow shapefiles. The survey has been taken across the face of the bridge structure (at the skew angle) and cross section profile survey data input into the cross sections immediately upstream and downstream of the bridge structures, whilst accounting for the skew angle by trigonometry calculations (as per standard procedure).

The bridge structures are represented by a USBPR bridge unit in Flood modeller with survey data input to represent the bridge piers, arches (as appropriate) and soffit levels of the bridge. A Flood Modeller spill unit has been used to represent overtopping of bridge decks, with levels informed from survey data. Where the bridge deck is wide such as for main the road and rail bridge and the addition of solid parapets, water overtopping the upstream face of the bridge will flow along the rail or road system long before the downstream face is overtopped. Therefore, at these locations the bridge deck has been modelled in 2D to allow for this to occur. For the decks represented in 1D the weir coefficient of the spill unit has been amended to represent the efficiency of the spill i.e. a metallic rail or tarmac bridge deck uses a higher weir coefficient (1.7, as at PC_02834) compared to overtopping of a stone wall (as at B_02830, weir coefficient 1.2). Pipe crossings have been represented using the same concept (a bridge unit to represent the underside of the pipe crossing, and spill unit used to represent overtopping of the structure).

Table 4-1: 1D structures

Cross section no.	Structure	Description	Photo
PC_02834	pipe crossing	Weir co-efficient for spill that represents pipe crossing upstream of the bridge was set to 1.7. The pipe crossing is represented as a spill for all events smaller than and including 100-year FL events (and represented as a cross section for larger events i.e. 200-year and greater). Further model schematisation regarding the pipe crossing near the gauge is included in section 4.9.	 Pipe crossing (facing towards right bank)

Cross section no.	Structure	Description	Photo
B_02830	Footbridge	No skew. Soffit = 10.79 mAOD Length of structure = 2.1 m Weir co-efficient for spill at bridge = 1.2 (represents stone wall)	 US face of structure
B_01461	Footbridge	8 degree skew applied. Soffit = 6.35 mAOD Length of structure = 2.9 m Weir co-efficient for spill = 1.2	 US face of structure

Cross section no.	Structure	Description	Photo
NAI01_01343	Railway bridge	No skew. Deck is in 2D allowing flow onto the bridge from the floodplain on either bank. Soffit = 13.74 mAOD Length of structure = 8.2 m	 US face of structure, middle arch
NAI01_00942	Single carriageway road bridge	No skew. Deck is in 2D allowing flow onto the bridge from the floodplain on either bank. Soffit = 8.23 mAOD, 7.31 mAOD, 6.75 mAOD (left to right arches) Length of structure = 12.3 m	 US face of structure, left and middle arch

Cross section no.	Structure	Description	Photo
B_00809	Footbridge	No skew. The spill level represents the top of the tarmac path over the bridge, instead of the top of the railings, as a considerable amount of water is expected to be able to flow through the railings. Soffit = 3.70 mAOD Length of structure = 0.9 m Weir co-efficient for spill = 1.7	 DS face of structure
B_00363	Footbridge	31 degrees skew applied. Spill level for bridge deck is set to top of railings due to the wire mesh on the railings that might catch debris. Soffit = 3.46 mAOD Length of structure = 3.2 m Weir co-efficient for spill = 1.7	 US face of structure

Cross section no.	Structure	Description	Photo
CUL_00857	Small road bridge	Overtopping of road deck represented in 1D domain by a spill (weir coefficient of 1.2) due to short length of structure. US invert = 4.44 mAOD DS invert = 4.44 mAOD Culvert diameter = 1.5 m Manning's 'n' value used = 0.025 to represent corrugated metal. Length of structure = 3.55 m	 Culvert entrance
CUL01_00520	Small road bridge	Granny Barbour Culvert (AUL01_00520) overtopping of road deck represented in 2D domain due to length of structure. US invert = 4.46 mAOD DS invert = 4.44 mAOD Culvert diameter = 1.8 m Manning's 'n' value used = 0.025 to represent corrugated metal. Length of structure = 10.55 m	 Culvert exit

Cross section no.	Structure	Description	Photo
PC_00327	Pipe crossing	Weir coefficient of 1.7 used to represent overtopping of pipe. Assumed 100% blocked for DN (baseline) scenario. The height difference between the top of the pipe and the channel bed is 1.45 m.	 DS face of structure
CUL_00319	Small road bridge	Overtopping of road deck represented in 2D domain due to length of structure. US invert = 3.90 mAOD DS invert = 3.71 mAOD Culvert diameter = 1.7 m Manning's 'n' value used = 0.025 to represent concrete. Length of structure = 22.09 m	 Culvert entrance

Cross section no.	Structure	Description	Photo
AUL01_00041	Footbridge at confluence	Given this bridges location at the confluence with the River Nairn (it is overwhelmed by the River Nairn from the 1 in 10 year event), the flood extent in proximity to this bridge is governed by the River Nairn rather than the Auldearn Burn it was not included in the model. (It was initally included for completeness but was removed for stability issues)	 US face of structure

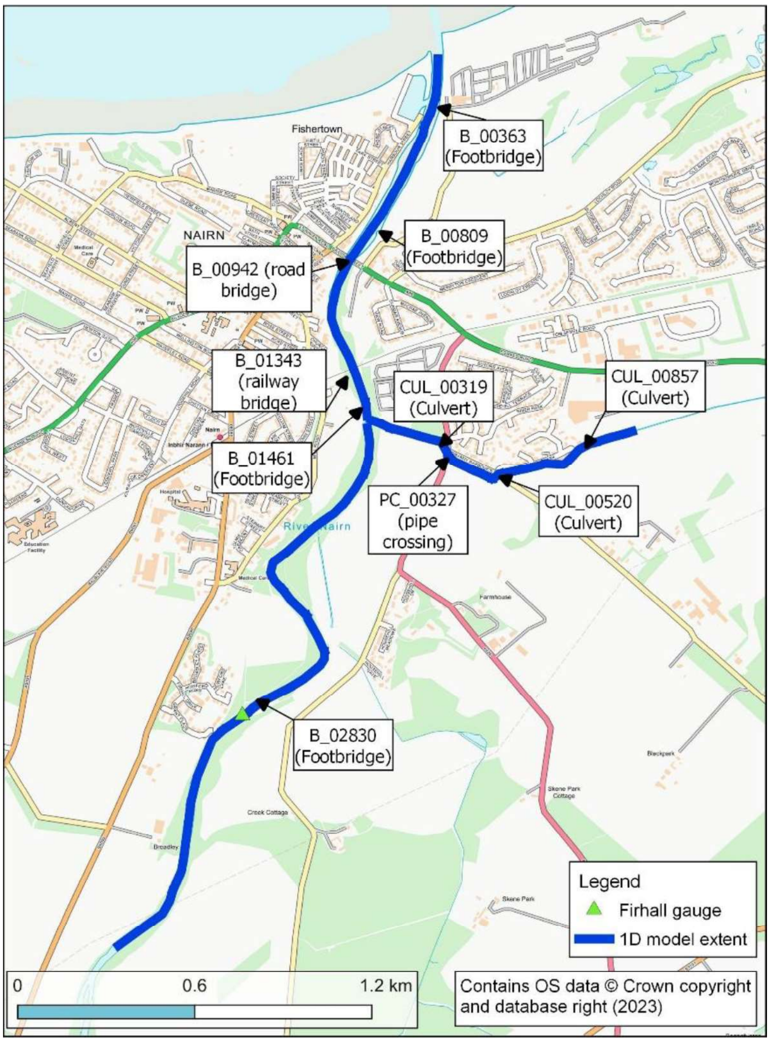

Figure 4-2: Structure locations along modelled reach

4.3.1.3 1D model roughness

Channel and floodplain roughness values have been represented in the model by Manning's 'n' values. Manning's 'n' values are considered to be a conveyance factor rather than simply a roughness coefficient, and in the context of channels, take account of channel meanders (sinuosity), contraction and expansion such as changes in cross sectional area between sections, bed material effects and obstacles, as well as the vegetation of the banks and floodplains. As such, it is appropriate to define values on a reach basis, taking account of the overall features of that reach.

The 1D model roughness was informed from site photos of the channel at each cross section. The initial 1D channel roughness values used are shown in Table 4-2 below. These values have been taken with reference to Chow[31].

31 Chow. River Channel Conveyance – Manning's Equation Friction Factors. April 2001.

A manning's 'n' value of 0.04 is generally used throughout the Nairn reach, although downstream of cross section NAI_00360, values of 0.02 and 0.017 are used to represent the fine sand and silty estuary environment. Between cross section NAI01_02834 and NAI01_02828 (including at the bridge), Manning's 'n' has been amended to 0.05 as photographs showed cobbles and boulders in the channel. The channel bottom of the Auldearn Burn is generally represented by a manning's 'n' value of 0.045.

Manning's 'n' values differ between the channel bottom and channel banks for all cross sections on the Nairn reach, to represent the vegetation (or paths / concrete walls) on the channel banks.

For the Manning’s ‘n’ sensitivity test runs, all 1D cross sections and structures have been multiplied by +20% and -20% as appropriate.

Table 4-2: 1D model roughness

Surface	Manning's 'n'	Photo example
Unfinished concrete	0.017	
Estuarine silts, formed concrete sides	0.020	

Surface	Manning's 'n'	Photo example
Clean, straight, full stage channel without features	0.030	
Pasture, no brush, short grass	0.030	
Clean, winding channel with some features	0.040	

Surface	Manning's 'n'	Photo example
Clean, winding channel with some features (channel only, maximum)	0.045	
Brush, scattered with heavy weeds (banks only)	0.050	
Cobble and boulder bottom bed	0.050	

Surface	Manning's 'n'	Photo example
Brush, medium to dense (banks only) (photo taken facing downstream)	0.070 (left bank) 0.1 (right bank)	

4.3.2 2D model extent

The extent of the 2D domain is approximately 3.2 km^2 and the ultimate extent of the 2D model was based on the Do Nothing 1000-year plus climate change scenario 2 flood extent. The hydraulic model grid resolution used was 4m. LiDAR data was used to represent the 2D domain topography with some geometric amendments made with reference to survey data, as described in section 4.3.2.3 (and shown in Figure 4-3). Section 3.3 discusses the checks made regarding the LiDAR data used.

The grid was orientated to align with the dominant direction of flow along the River Nairn, particularly along the lower reach. This is where the greatest out of bank flows occur and where flood water first overtops the banks in the vicinity of properties.

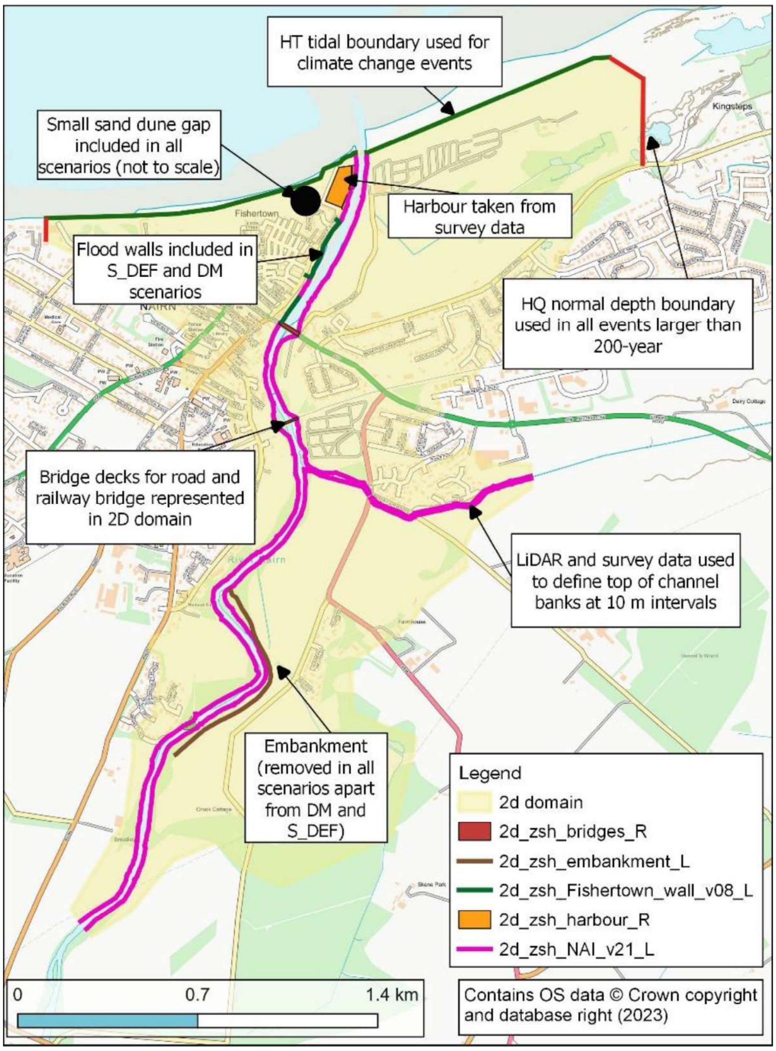

Figure 4-3: 2D model extent.

4.3.2.1 2D Manning's 'n' roughness

MasterMap mapping was used to represent the extent of 2D features such as roads, woodland, open parkland etc. These features have had the following Manning's 'n' roughness values applied:

- Roads - 0.025
- Buildings - 0.300
- Gardens - 0.050
- Woodland - 0.100
- Water - 0.030
- Park land - 0.035
- Arable land - 0.06

It is noted that using a value of 0.06 for arable land / fields was quite high regarding typical Manning's 'n' roughness values for this land cover. However, from photographs of fields around Auldearn Burn and the upper extent of the model, a value of 0.06 to represent 'Brush: scattered with heavy weeds ' was chosen as appropriate. Grass areas and parkland (including the golf course near the caravan park) have been assigned a value of 0.035 to represent 'Pasture, no brush: high grass' for the Current Condition (Do Minimum) scenario and increased to 0.045 for the Do Nothing (baseline) scenario.

4.3.2.2 Buildings

The LiDAR DTM was used to represent 2D floodplain features. The site visit showed that there is significant variability in building threshold levels. A sample of residential threshold levels were surveyed. However, for modelling purposes the buildings were not raised above the DTM. Instead, a high Manning's 'n' value was applied to represent the impedance of flood flows through buildings. The actual building threshold level was informed from the survey data and accounted for at flood damage estimation stage (section 6). This will allow for a rapid update of the damage estimation and number of properties flooded should additional survey data become available in future. Each building's footprint was informed from OS MasterMap.

4.3.2.3 2D topographic edits (i.e. flood defences, embankments)

Top of flood defence levels (at Fishertown) have been applied as a 2D geometric line shapefile (2d_zsh.shp) with the survey points snapped to its vertices. The line feature is represented as one cell width. Likewise, channel top of banks are represented in the model from survey data where available and LiDAR data between survey points (i.e. the channel banks have at least one vertex point every 10 m, taken from LiDAR along the channel banks, to aid in defining the banks).

The elevations of the harbour at Fishertown have also been refined by survey data, as well as a low 'gap' used as a path in the sand dune near the harbour and an informal flood defence embankment on the right bank of the River Nairn upstream of the Auldearn Burn confluence (Figure 4-3). This informal flood defence embankment is large and is picked up to some degree by LiDAR. However, for the Do Nothing (baseline) scenario, a geometry modification patch has been applied over this area to remove the embankment from the model, as it is not expected to withstand flood flows.

A list of all the topographic edits made, and scenarios they apply to, are shown in Table 4-3.

Table 4-3: Topographic amendment shapefiles

shapefile	Scenario	description
2d_zsh_NAI_v25_P.shp 2d_zsh_NAI_v21_L.shp (for larger fluvial events,	All	Defines left and right top of banks using survey data where available or LiDAR data otherwise, at approximately 10 m chainage length. The raised walkway at

shapefile	Scenario	description
2d_zsh_Nairn_Large_Events_v02_P.shp, 2d_zsh_Nairn_Large_Events_v02_L.shp)		the right bank in the vicinity of the caravan park has been incorporated into these shapefiles, with reference to site photographs and as taken from JBA survey data.
2d_zsh_harbour_P.shp 2d_zsh_harbour_R.shp	All	Defines top and bottom of harbour walls, based on survey
2d_zsh_bridges_P.shp 2d_zsh_bridges_R.shp	All	Defines top of bridge decks at railway and road bridge based on survey, to allow overtopping of these structures in the 2D domain.
2d_zsh_sand_dune_gap_v02_P.shp 2d_zsh_sand_dune_gap_v02_R.shp	All	Defines a low point in the sand dune near the Sun Dancer bar.
2d_zsh_embankment_P.shp 2d_zsh_embankment_L.shp	DM | S_DEF	Embankment data points as taken from previous survey (2d_zln_DefSurvey_NAIR_001) were checked against the JBA survey and utilised to represent the top of the embankment
2d_zsh_Fishertown_wall_v08_P.shp 2d_zsh_Fishertown_wall_v08_L.shp	DM | S_DEF	As taken from JBA survey and site photographs. The flood walls are at two locations, both on the left banks. One flood wall starts US of NAI01_00681 and ends between NAI01_00570 and NAI01_00416 and the other flood wall starts at NAI01_00930 (DS face of road bridge) and ends at NAI01_00809 (US face of footbridge)
2d_zsh_remove_embankment_R.shp	DN | N+20 | N-20 | S_B | S_B_AUL	Removes the embankment from the model by interpolating the LiDAR at the base of the embankment, across the embankment.

4.3.2.4 1D-2D linking

In the hydraulic model, the surveyed cross sections have been reduced to the top of bank as overbank areas have been represented in the 2D domain.

The standard approach to linking 1D Flood Modeller and 2D TUFLOW models has been adopted. Within the 2D domain, a lateral spill (HX boundary) is defined for the left and right banks and the channel area in between classified as 'inactive' in the 2D grid. The HX boundaries are linked to the respective nodes in Flood Modeller using CN connection lines and are discontinued at bridge and culvert structures. Along these boundaries, water levels in the channel and floodplain interact dynamically and thus control floodplain wetting and drying.

4.3.2.5 Field drain at golf course

The representation of the field drain is included in the 2D domain of the model, from LiDAR data only. Initially, the field drain was included in the model with the main inflow into the field drain from a HT boundary to represent sea water overtopping the dunes and into the field drain. However, the LiDAR at the dunes, between the field drain and the coast, is above the 200-year peak coastal level of 3.43 mAOD). As such, including a HT boundary as an inflow to the field drain (to represent tidal levels) caused excess flooding in the area for events smaller than and including the 200-year event, as in reality most of the tidal flood water wouldn't overtop the dunes and also be restricted by the narrow channel (and culverts) of the field drain at the dunes. In addition, it's also noted that there are no receptors in the golf course area. As such, it was decided that an inflow to the field drain wouldn't be included and that the field drain would be represented in the geometry only (as a flow route) via LiDAR data, and fills from the River Nairn overtopping it's banks.

4.4 Inflows and boundary conditions

Details on the flow hydrographs input and tidal curves used for the downstream boundary are provided in section 2.4 and 2.5. This section informs the location of the 1D and 2D tidal downstream boundaries, with the latter included for the climate change events. These form a continuous boundary from the end of the pier / estuary (1D boundary) and run both eastward and westward along the northern edge of the dunes to the north of Fishertown, the caravan park, and the harbour area. In addition to the 2D tidal boundary, a 2D HQ normal depth boundary (based on slope gradient) has been added to define the 2D domain extent to the west of Nairn Leisure centre and to the east of Kingsteps. These normal depth boundaries prevent glass-walling. They are only used for the climate change events and 1000-year event. For lesser events the flood extents do not reach these boundaries.

4.5 Model proving - validation and calibration

Current condition (Do Minimum) model

The Current Condition model was calibrated against the gauge rating. The gauge rating was plotted against the model rating at the gauge location for comparison, and the Manning's 'n' and representation of the pipe crossing downstream of the rating (as described below) amended to refine the model rating until it appropriately matched the observed rating. The observed gauge rating is taken as accurate; SEPA have stated that they have high confidence in this gauge rating.

The gauge record was also used to determine the flow in the river which caused recent flooding on the River Nairn. The Current Condition model flood level and extent on the River Nairn was compared against photographic evidence of the recorded fluvial flood event which occurred in October 2014 and the flooding from the Auldearn Burn in August 2014. This flow rate from the gauge was assigned a return period event (with regard to the hydrological calculations) and this was used to check if the relative frequency of the flood event is sensible given the flood history knowledge on the burn.

In addition, photographic evidence from the coastal dominated flood event that occurred in December 2012 were compared against predicted coastal flood levels to estimate its return period frequency and checked to see if this is realistic return period frequency.

Calibration from 1997 event (modelled vs observed rating)

There are four cross sections within the vicinity of the gauge in the model; one at the gauge, another at the pipe crossing a short distance downstream and two at the bridge (US and DS face). The pipe crossing is represented by either a spill unit or cross section in the model, depending on the size of the event[32]. The largest fluvial flood event at the Firhall gauge is the July 1997 event and the peak flow for this event is estimated to be 314.1 m^3/s from the gauge rating. Observed time series stage and flow data is available for this event, as such, this observed event was run in the model and used for model calibration.

Stage zero from the JBA survey data is 7.2 mAOD and from the NRFA website and Transport Scotland survey was 7.181 mAOD. This latter stage zero (of 7.181 mAOD) was chosen for use as it is to 3 decimal places. The maximum stage reached during the 1997 observed event was 3.002 m at 20:00 hours on 1st July 1997. As such, the maximum water level to mAOD reached during the event is estimated to be 10.183 mAOD.

Following refinements of Manning's 'n' in the vicinity of the gauge[33] and representation of the pipe crossing[34], the model gives an output of 10.160 mAOD as the max level reached during this event (occurring at 20:00 hours on 1st July 1997, 31.25 hours into the model run). The figures below compare the modelled to the observed stage-time and flow-time hydrograph at the gauge location for the 1997 event.

32 All fluvial events smaller than and including the 100-year event represent the pipe crossing as a spill unit, and all fluvial events larger than and including the 200-year event represent the pipe crossing as a cross section.

33 This included increasing Manning's 'n' to 0.05 in the gauge's vicinity, to represent the rocky channel at this location (evident from photographs).

34 A weir co-efficient of 1.7 was found to be the most appropriate value to use, both in terms of the rating and also to represent the relatively smooth surface of the metallic pipe.

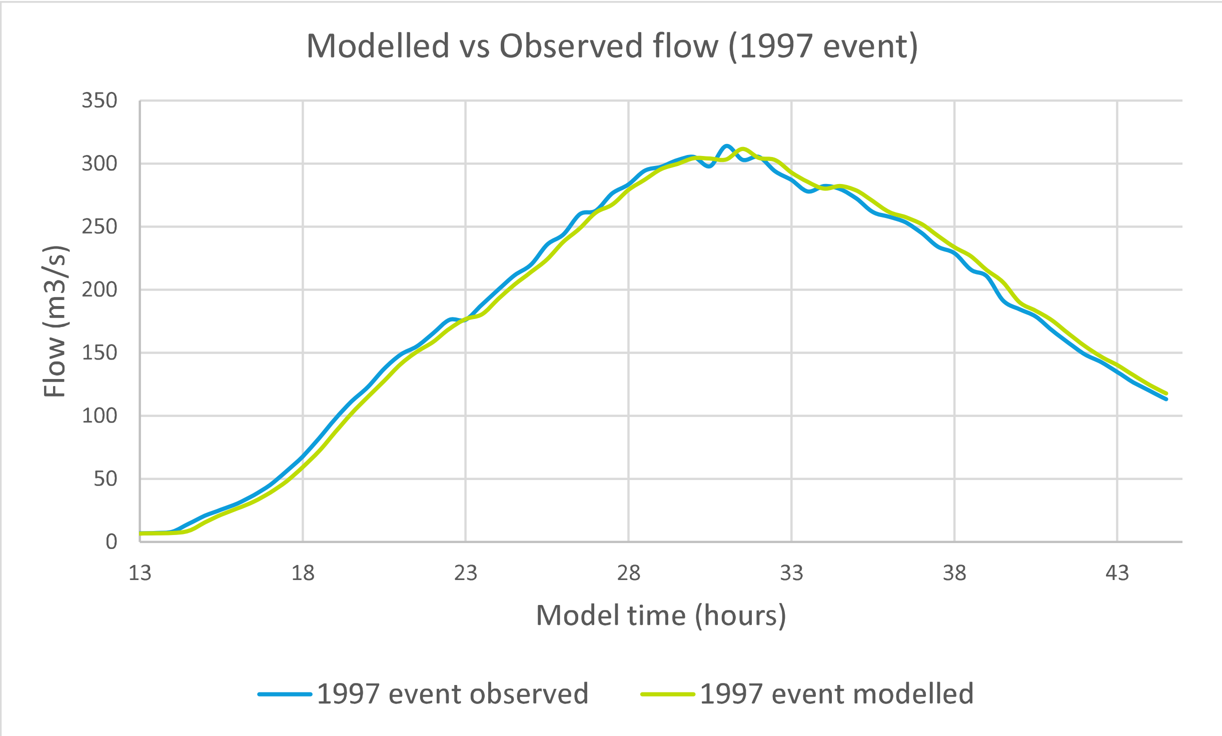

Figure 4-4: flow-time hydrograph at the gauge location (1D and 2D outputs combined)

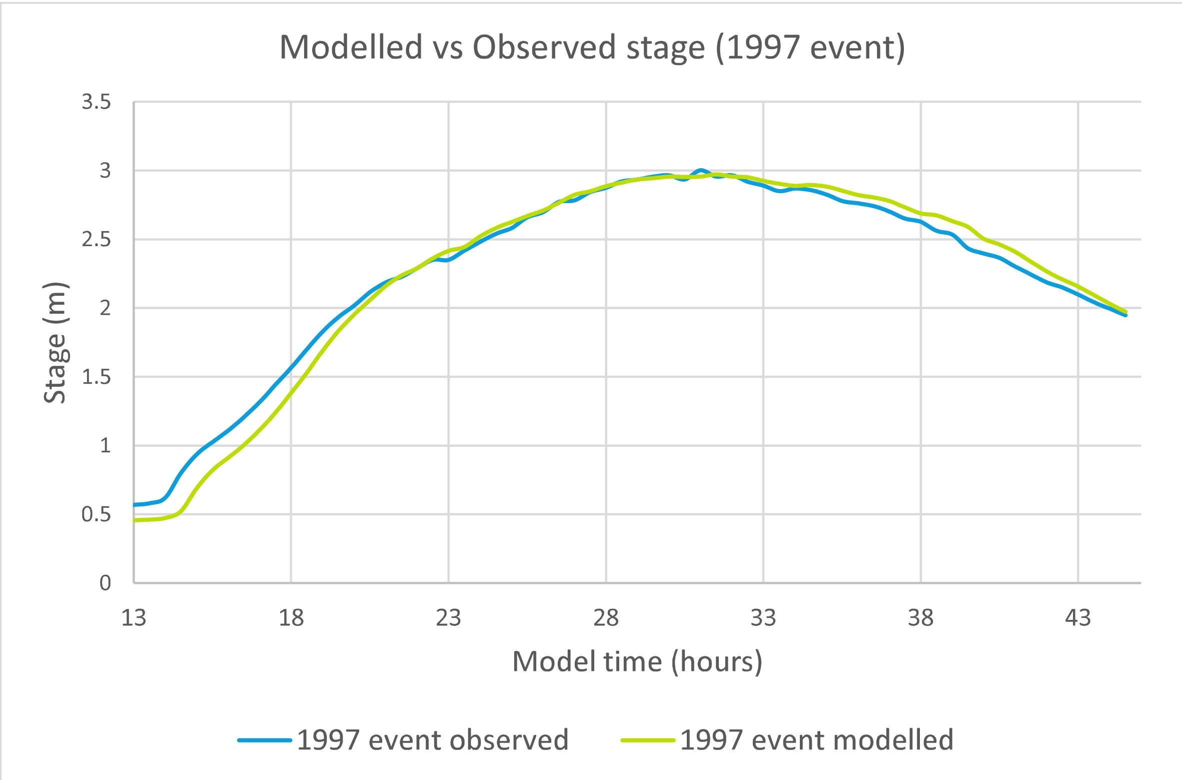

Figure 4-5: stage-time hydrograph at the gauge location (1D output only)

A plot output (PO) line was added at the gauge location, to output the flow for comparison against the observed flow from the 1997 event. The plot output line calculates the flow in the 2D domain and crosses the channel at the gauge. This flow has been added to the flow output from the cross section at the gauge, to calculate the modelled total flow at the gauge location. This has been used to compare the model rating to the observed rating as shown in Figure 4-6. This figure also includes sample gaugings, as used to derive the NRFA (observed) rating at the gauge. The modelled rating (shown in green) slightly underestimates for lower flows and slightly over estimates for larger flows, compared to the observed rating. For larger flows (i.e. 200 year flow and above), the model geometry was adjusted. The pipe crossing downstream of the gauge which is modelled as a spill unit for lower flows was replaced with a channel cross section. As the pipe is effectively another roughness feature on the channel bed, for flood risk modelling purposes, the spill was removed for the larger events as the head loss was more realistic (and shown to be drowned out) for larger events on representing the pipe as a cross section. This results in a reduction in stage for larger flows and the figure below includes the 200 year peak stage/flow point, showing a reduction in the steepness of the rising curve. It is noted that the modelled 200-year rating (not shown in figure) had a less good fit at the lower flows, up to approximately the 30-year event (estimated flow of 250 m^3/s).

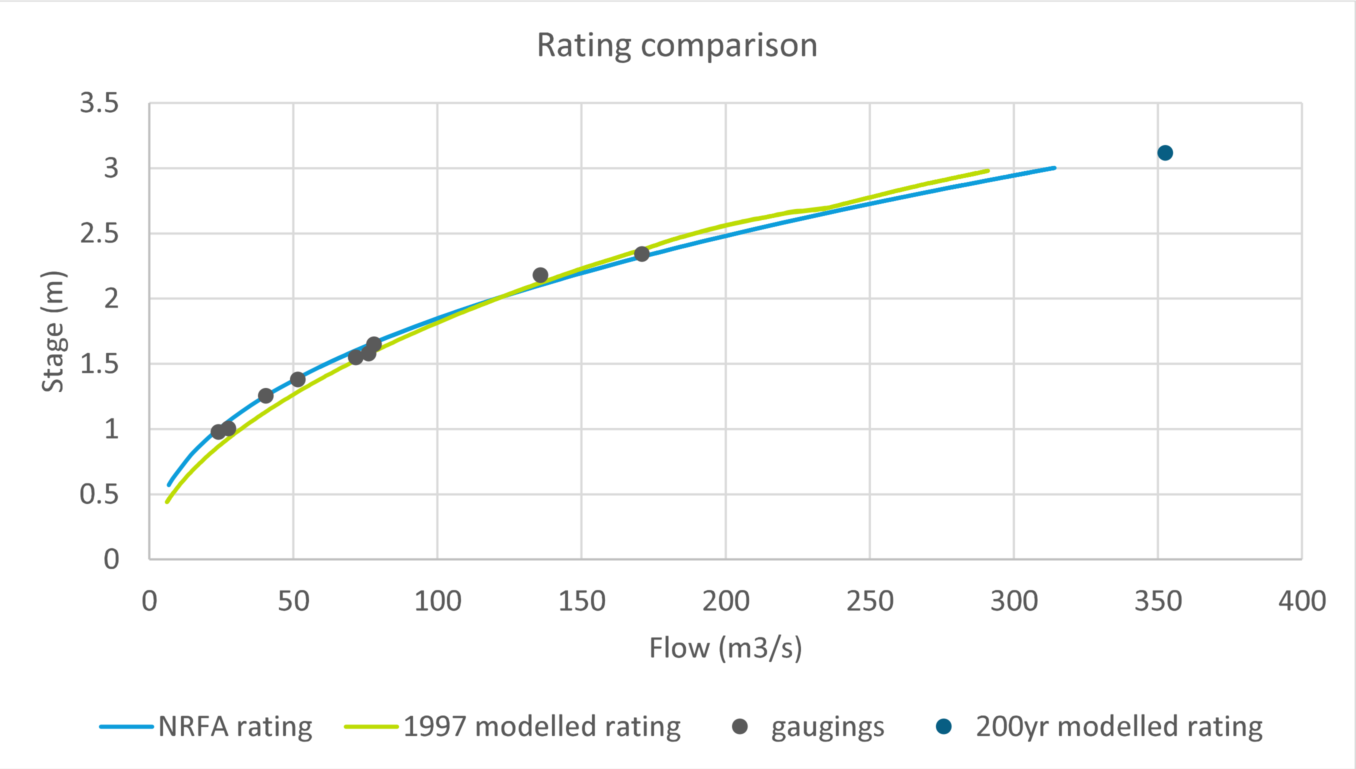

Figure 4-6: rating (1997 event: modelled vs observed)

The table below shows the modelled water level, stage and indicates whether the water is in bank or out of bank at the gauge location, for each event. The right bank at the gauge location first starts to overtop at a water level of around 10.06 mAOD (i.e. stage of 2.88 m).

Table 4-4: modelled water level and stage for key events at gauge location

Event	WL (mAOD)	Stage (m)	In or Out of bank
2	8.96	1.78	In
10	9.60	2.42	In
30	9.89	2.71	In (though considerable by-passing occurs)
1997	10.16	2.98	Out
100	10.17	2.99	Out
200	10.30	3.12	Out
1000	10.76	3.58	Out

As noted in section 2.3, the hydrology calculations suggested that the observed 1997 event at the gauge was estimated to be in the region of a 50-year to 75-year fluvial flood event. From the modelled stage at the gauge, the stage from this event is close to the 100-year event[35]. However, on comparison on flood extent outputs, the 100-year fluvial event is considerably larger than the 1997 event, suggesting that the 1997 observed event is in the region of a 50-year to 75-year event magnitude, as expected (from the hydrology calculations).

Estimating the magnitude of the observed 1997 event by comparison with the design return period events has been undertaken with caution as the design events (i.e. 100-yr event) and observed 1997 event were modelled under different scenarios i.e. Do Nothing and Do Minimum, as such the estimation of the 1997 flood event magnitude (a 50-year to 75-year event) is an approximation. A peak flow of 314.1 m^3/s was input into the model for the observed 1997 event and 363.0 m^3/s input for the 100-year estimate, as such, a relatively large difference in flow results in a small increase in modelled stage at the gauge location and a large increase in flood extent. This is understood to be due to the large floodplain in the area leading to significant out of bank flow paths. The out of bank flow path that forms upstream of the gauge location for the 100-yr flood event is significantly larger than that formed for the 1997 event (i.e. the 100-yr modelled flood extent is larger than the 1997 modelled flood extent, upstream of the gauges location).

A comparison between the flow hydrographs as input into the model were compared to the flow hydrograph extracted at the gauge location (which is 1 km downstream of

35 It's noted that the observed 1997 event was modelled as the 'Do Minimum' scenario whereas the design return period events were modelled as the 'Do Nothing' scenario. As such, the inclusion of the 1997 event in this table is for indicative purposes only.

the US model extent where the hydrographs were input). The extracted flow hydrographs from the model where slightly smaller than those input at the US extent, particularly for the larger events (Figure 4-7). This is due to out of bank flooding, that occurs upstream of the gauge location.

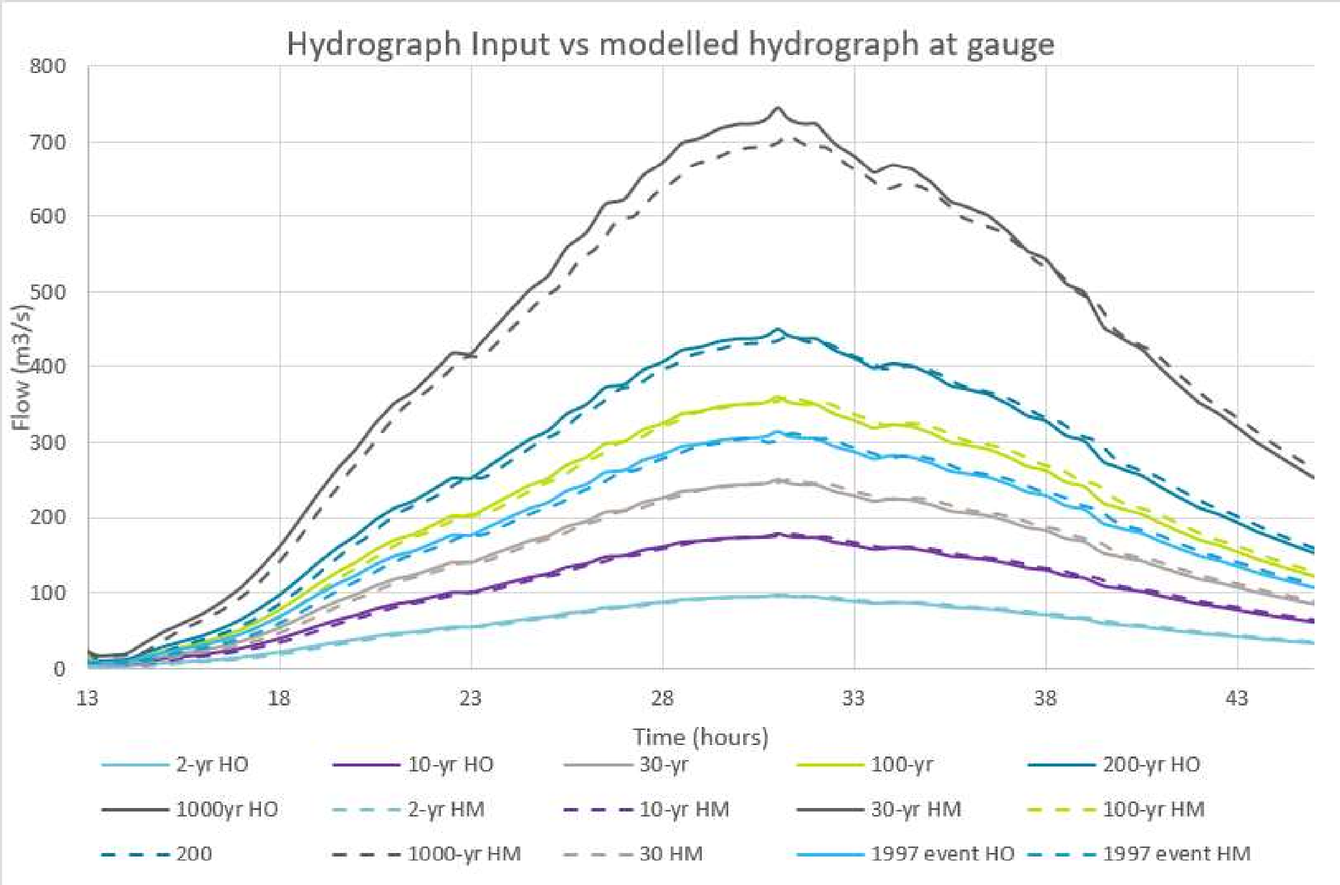

Figure 4-7: Comparison between flow hydrographs as input into the model and flow hydrographs extracted from the model at the gauge location

Model validation from photographs

Historic flood event locations (as taken from photographs) for the observed coastal event on 15/12/2012 and fluvial events on the River Nairn (08/10/2014) and Auldearn burn (11/08/2014) have been compared to model grid depth results, to consider modelled flood extent against locations where historic floods have occurred (Figure 4-8). The photographs of the flood event on the Auldearn Burn (11/08/2014) were provided by the Highland Council and the photos for the other events are available open access[36] via a webpage on Flickr as provided by GurnNurn.com. The table below (Table 4-5) describes examples of where photographs have been used to refine the model results, however due to licensing reasons, the photos from GurnNurn.com

36 https://www.flickr.com/photos/gurnnurn/sets/72157648109283349/ (Photos from December 2012 coastal event) and https://www.flickr.com/photos/gurnnurn/sets/72157632254657982/ (Photos from October 2014 fluvial event)

cannot be included in this report. Table 4-6 describes comparison between the observed photographs and modelled flood extents.

The event on 08/10/2014 is the 4th largest in the Firhall gauge AMAX series, and the event on 11/08/2014 was 10th largest in the series. Both events are the largest event on record in their respective water years (i.e. are in the AMAX series) and have flows taken from extrapolation of the rating curve (NRFA gauge no. 7004; Firhall gauge).

Photographs of a high tide and some resulting out of bank flooding that occurred on 23rd March 2023 were also provided by the Highland Council in the latter stages of the study[37]. These showed some overtopping at the walkway between the flood wall and the River Nairn (left bank at Fishertown) as well as some very shallow ponding along Harbour Street. All water is in bank at the confluence during this event, confirming that the out of bank flood water was a result of high tide levels.

Table 4-5: Description of photographs used to refine the model results.

Description	
08/10/2014: Flooding occurred at the footbridge over the Auldearn Burn, near the confluence. Flood water is higher than the soffit level and there is flood water on the path and in the woods on either side of the bridge.	
08/10/2014: Flooding at woods on the right bank near Riverside walkway, to the west of new flats at Riverside Crescent (immediately downstream of the A96 road bridge).	
08/10/2014: Flooding of path along left bank of river near churchyard at Church road.	
11/08/2014: Flooding along Balmakeith Park road (photo reference; Highland Council)	
15/12/2012: Flooding at car park on right bank near caravan park.	

37 Email from Duncan Sharp, Highland Council to Jonathan Garrett JBA Consulting on 24th March 2023.

Description	
15/12/2012: Flooding at riverbank path between Seamans hall and the moorings flats. This is where flood water is modelled to first overtop the banks in the model and is understood to be a common place of flooding. The photograph shown shows flooding at the same location that occurred from a high tide event on 23rd March 2023, as provided by the Highland Council.	
15/12/2012: Flooding at seaside walkway near Nairn Leisure Centre	
15/12/2012: Pier walls at the River Nairn estuary are overtopped by waves	

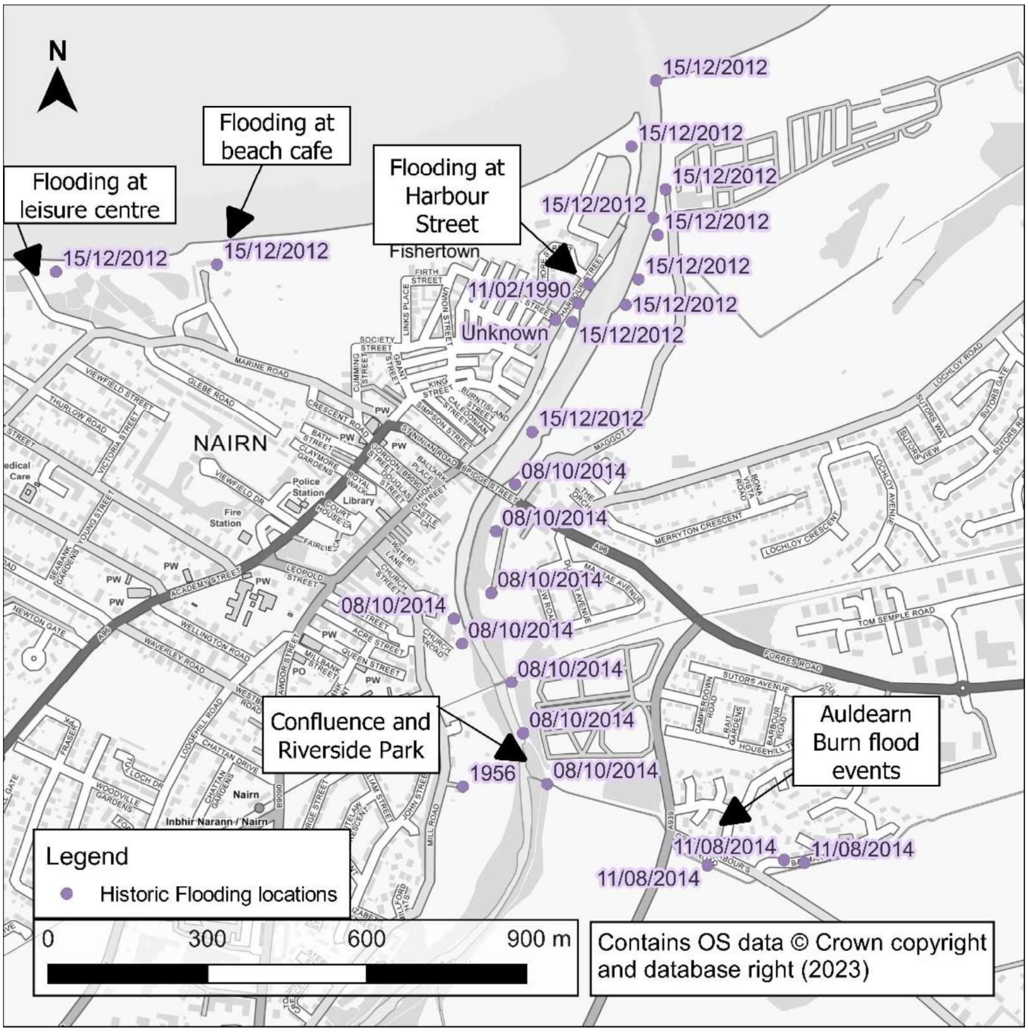

Figure 4-8: Historic Flooding Locations

Table 4-6: Estimated return period from modelled flood depth grids

Event	Stage (m) NRFA	Flow (m^3/s) NRFA	Estimated return period from hydrology calculations	Estimated return period from modelled flood depth grids
15/12/12			coastal	This event is estimated to be roughly a 10-year coastal event. However, noted that model results don't show overtopping of the Harbour walls at the estuary, as shown in the photos. The flooding at this location appears to be from wave overtopping which is not included in the model.

Event	Stage (m) NRFA	Flow (m^3/s) NRFA	Estimated return period from hydrology calculations	Estimated return period from modelled flood depth grids
08/10/14	2.41	186.8	Approx 10-20-year (at the Firhall gauge, River Nairn)	The 10-year fluvial flood extent model results show flooding at the Auldearn Burn confluence and flooding on the right bank between the road and rail bridge. This matches the photographs from this event fairly well and as such, this event is estimated to be a 10-year fluvial event. However, most photos are taken from near the river, so it's difficult to tell the flood extent in the floodplain away from the river.
11/08/14	2.157	143.9	Approx. 5-year (at the Firhall gauge, River Nairn)	Photos are mainly of the Auldearn Burn flooding. There's some flooding from model results at Balmakeith Park road for the 10-year event, though not as much as suggested from the photos. As such, from model results, this would be estimated to be a 10-year to 30-year event.

In summary, from comparison between the modelled flood extents with the flood photos, the following events were estimated to be as follows:

- Coastal flooding - December 2012 – Approximately the 10-year flood event
- River Nairn flooding – October 2014 – Approximately the 10-year flood event
- Auldearn Burn flooding – August 2014 - Somewhere between the 10-year and 30-year flood event.

4.5.1 Model assumptions

The main model assumptions are:

- The small single span road bridge over the Auldearn Burn at the confluence has been excluded from the model. The flooding at this location is dominated by the River Nairn so the bridge will not influence the extent or course of the flooding.
- The tidal boundary represents still water level only and not wave height.
- That debris pushed up against the footbridge spanning the River Nairn between the harbour and caravan park in the reach immediately downstream of

Fishertown would not be under the same hydrostatic pressure as the bridges upstream due to influence of the incoming high tide. Therefore the blockage test was applied to the footbridge upstream. The most downstream bridge was not tested.

- For the largest events i.e. the 1000 year event and the climate change events All footbridges in the model were assumed to be washed away by the force of the flood water.

4.6 Model scenarios

The initial model build represented the current watercourses condition and is referred to as the current condition (Do Minimum) scenario. This model was used to allow for model calibration against the 1997 flood event and was informed from surveyed sections, photos and the site inspection.

The baseline scenario is the Do Nothing scenario. This assumes that no maintenance on the watercourse is carried out, culverts are not cleared or restored and flood walls are allowed to deteriorate. This condition would not occur immediately but represents a feasible state after a period of inactivity associated with normal FRM maintenance. This baseline scenario has been used to determine the flood damages. To represent the Do Nothing scenario, the following changes were made to the current watercourses condition:

- The roughness of the adjacent parkland (i.e. golf course area) was increased to represent uncut grass (roughness increased from 0.035 to 0.045).
- Culverts were blocked by 50% (all culverts are over 600 mm in diameter).
- Bridge piers were assumed to cause blockage to the bridge equivalent to approximately twice their pier width.
- The pipe crossing at the Auldearn Burn cross section AUL01_00327 was assumed to be 100% blocked.
- All informal flood defence walls and embankments were excluded from the model.

The baseline scenario above was also tested for sensitivity to culvert and bridge blockage, Manning's roughness and the inclusion of the informal defences in the model. The below sensitivity tests were carried out for the 10% (10-year), 3.33% (30-year), 0.5% (200-year), 0.5% (200-year + climate change) and 0.1% (1000-year + climate change) flood event.

S_B (Sensitivity_Blockage):

The Do Nothing (baseline) Scenario already has a degree of blockage applied appropriate to the bridge or culvert opening area. When testing the sensitivity to blockage, the culvert or bridge deemed to cause the most damage/greatest flood extent in an urban area was chosen and a significant degree of blockage applied.

This involved complete blockage to the left-hand span of the footbridge (B_00809) downstream of the main road bridge on the River Nairn (Figure 4-9 show blockage of left hand span, location shown in Figure 4-2, see Table 4-1 for photo of unblocked bridge) whilst maintaining the blockage applied for the 'Do Nothing' scenario at all other bridges. As the bridge is formed from three equal spans, the bridge has been modelled as being approximately a 'third' blocked. From historic events, flooding of properties first appears to occur at Harbour Street, half-way between this bridge that was blocked and the furthest bridge downstream, B_00363. Alternatively, B_00363 could have been blocked, and this was tested for the 200-year fluvial event, however, the flood extent was smaller compared to blocking bridge B_00809.

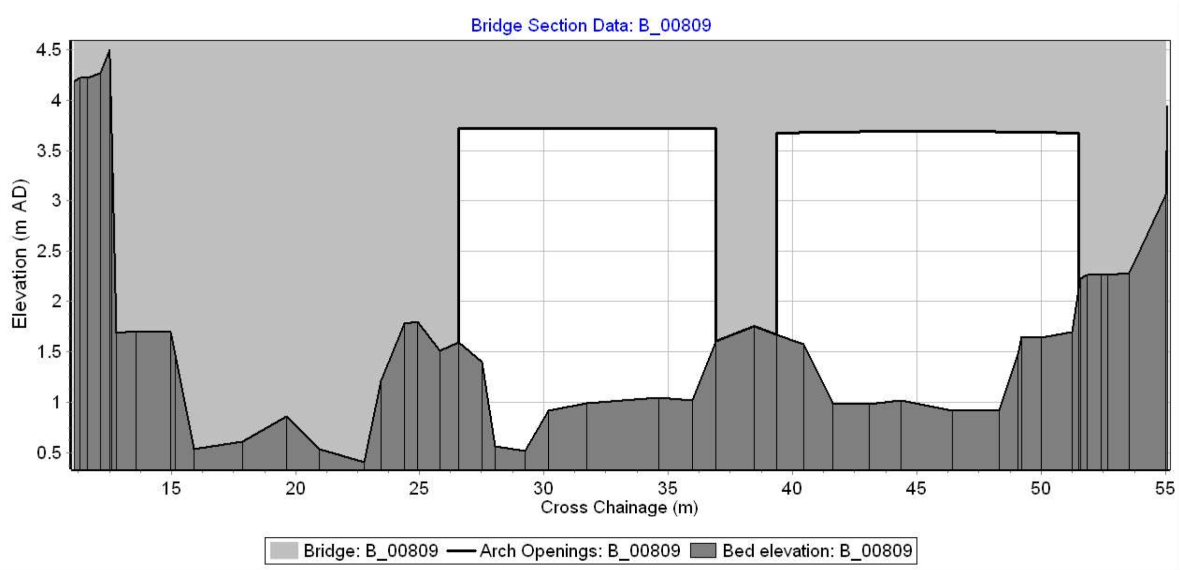

Figure 4-9: Bridge blockage modelled at footbridge B_00809

As the blockage on structures further up the reach can reduce the negative impact of the most critical structure, blockage on these structures were given the same capacity as from the Do Nothing scenario (i.e. bridge pier width doubled, to represent only a small degree of blockage). This could represent the situation where a large blockage on a bridge upstream is dislodged and migrates to the next downstream structure, dramatically increasing the degree of blockage.

On the Auldearn Burn, the Granny Barbour culvert (at the junction with Balmakeith Park) was chosen for testing the impact of blockage. This culvert has been attributed as a contributing factor to recent flood incidents along Balmakeith Park. The blockage scenario includes 92% blockage of Granny Barbour culvert (i.e. 8% capacity) for the 10-year and 30-year event and 83% blocked (17% capacity) for the 200-year and climate change events.

Blockage was only applied to fluvial dominated flood events.

N+20 and N-20 (Sensitivity_Roughness):

The roughness of both the 1D channel and 2D domain were adjusted by +/- 20%.

S_Def (Sensitivity_Defences)

The inclusion of the informal flood defences along Harbour Street and the embankments close to Househill were included in the DN (baseline) model. The wall was assumed to be able to withstand flood water held behind it for its full height and flood gate openings were assumed to be closed. The full height of the wall was used in the sensitivity test, i.e. no allowance will be made for freeboard on these defences. The wall height and position was informed from survey data. In the same scenario, the earth embankment running along the right bank beginning a short distance upstream of the Auldearn Burn confluence was included.

4.7 Joint probability

The combined flood risk from both fluvial and coastal flooding was determined. The 200-year flood event could be any combination of fluvial and tidal events, i.e. the 30-year fluvial flow with the 30-year peak tidal level, 200-year fluvial with 5-year tidal level etc. The joint probability procedure is based on a flood flow and high still water sea level dependency of 0.1[38] As such, the highest fluvial and coastal flood levels are likely to occur independently of each other. However, to ensure that the most conservative combination of fluvial and tidal events (i.e. that resulted in the largest flood level along the reach of the model) were utilised, a number of combinations for the 200 year flood event was tested in 1D. The 1D long section results showed that water levels were highest along the full length of the modelled reach using the extreme events, as opposed to the intermediate return periods (i.e. the 30-year fluvial flow with the 30-year extreme tidal level gave lower levels along the full reach when compared to both the 200-year fluvial flow with the 5-year extreme tidal level and the 5-year fluvial flow with the 200-year extreme tidal level).

The outcome of these simulations have been presented on a single map per simulation which shows the combined result of the two extreme runs, this is classed as the design flood event (as described further in Appendix A). For example, the 200-year flood event will be the maximum level of the fluvial (200-year fluvial flow with 5-year coastal tidal downstream boundary) and the maximum extent of the coastal (200-year coastal tidal downstream boundary with 5-year fluvial flow).

38 R&D Technical Report FD2308/TR1 Lists correlation between gauge 07004 Firhall (Firhall) and Wick as 0.1

The table below shows the joint probability as used to define the events to run for this flood study.

Table 4-7: Joint probability

	Fluvial dominant		Coastally dominant	
Event	FL	CO	FL	CO
2	2	2	2	2
5	5	2	2	5
10	10	2	2	10
30	30	2	2	30
100	100	2	2	100
200	200	5	5	200
1000	1000	10	10	1000
200CC1	200 CC1	5 CC1	5 CC1	200 CC1
200CC2	200 CC2	5 CC2	5 CC2	200 CC2
1000CC1	1000 CC1	10 CC1	10 CC1	1000 CC1
1000CC2	1000 CC2	10 CC2	10 CC2	1000 CC2

4.8 Simulations and running the model

In line with FM-TUFLOW best practice, the 2D calculation timestep is half the grid resolution i.e. in this case 2 seconds (4m/2). The 1D calculation timestep is half that of the 2D, i.e. 1 second. The save and output interval for the 1D and 2D are consistent with each other. All model parameters for running the model are default apart from the dflood value (the maximum allowable water depth allowed above bank top before the model crashes), which has been amended from 3 m to 10 m (as some flood depths are in the order of 8.4 m for the very large fluvial events, at the harbour).

The simulation run time is 32 hours, from 13 hour to 45 hours with regard to 1997 event hydrograph. This was reduced to 27 hours (from 13 hours to 40 hours with regard to the hydrograph) for the climate change event as ending the simulation run after the largest tidal curve helped with model stability (i.e. reduced mass balance error) and reduced non-convergence. The peak of the 1997 fluvial event occurred on 1st July 1997 at 20:00 and as such, the hydrograph as used and scaled to peak flows from the hydrology calculations begins at 01:45 on 1st July and ends at 2nd July 1997 at 09:45 (18.25 hours prior to the peak of the event and 13.75 hours after the peak of the event). The peak of the event occurs at 31.25 hours into the model run.

The model log file describes the dat (geometry) file and initial flow and water level conditions file for each event. Following rating analysis (described in section 4.5) and the need to include the Auldearn Burn in the 2D only for large events, three separate dat files were required to run the baseline (Do Nothing) model, this is outlined in the model log.

A logical and descriptive naming structure has been adopted for both model folders and scenarios names. TUFLOW has a standard folder structure which has been followed, and a similar folder structure adopted for Flood Modeller files. The folder structure sorts data depending on its intended use; for example, run files, model build files, flow files etc.

There are 71 simulations in total to cover all events and scenarios. In order to quickly identify a simulation, a logical file naming system has been used. The following naming convention has been adopted:

'Main river - Return period - 'FL or AUL' - Return period - 'CO' - scenario - version'

- Main river - All runs will be prefixed with "Nairn"
- Return period - Flood event, e.g. 200 year. 'CC1' or 'CC2' at the end indicates a climate change scenario 1 or 2 event i.e. '200CC1'
- Flood type - FL = Fluvial flow, AUL = Auldearn flow, CO = coastal. Separate River Nairn (FL) and Auldearn (AUL) simulations were required for larger fluvial events (the 1000-year and climate change events), as running these events on both the River Nairn and Auldearn Burn in one simulation caused instability. For all other fluvial events (i.e. smaller than and including the 200-year Fluvial event), the River Nairn and Auldearn Burn flows were run in the same simulation and described as 'FL' for Fluvial or 'CO' for Coastal.
- Scenario - Do Nothing (DN), Current Condition (DM), S_Def for sensitivity to defences, N+20 and N-20 for sensitivity to roughness, S_B for sensitivity to blockage.

4.9 Model stability and mass balance

Conveyance

Conveyance curves are generally appropriate and panel markers have been added at abrupt changes in elevation as well as at changes in Manning's 'n' values across the channel, to help conveyance.

Flow and stage profiles

Water levels and flows have been checked throughout the hydraulic model for the present day baseline (DN) events (2-year to 1000-year event). From Longitudinal section results, there are minimal oscillations throughout the majority of the reach and stage profiles are generally smooth. There are some oscillating (unstable) water levels at the pier end / downstream boundary during the 'climate change' fluvial events, some checks were undertaken for this following internal model review, discussed further in the appendix.

Change in volume (dVol)

The change in volume between the 1D and 2D domain (dVol) was checked and for the 200-year event, the dVol seems reasonably sensible, though there is some oscillation (as shown in the figure below). The dVol reduces towards 0 at the end of the model run, as would be expected. During the internal review of the model, some oscillations in volume (i.e. dVol value) at various reaches of the channels were identified and the HX lines adjusted to limit the oscillations, where appropriate.

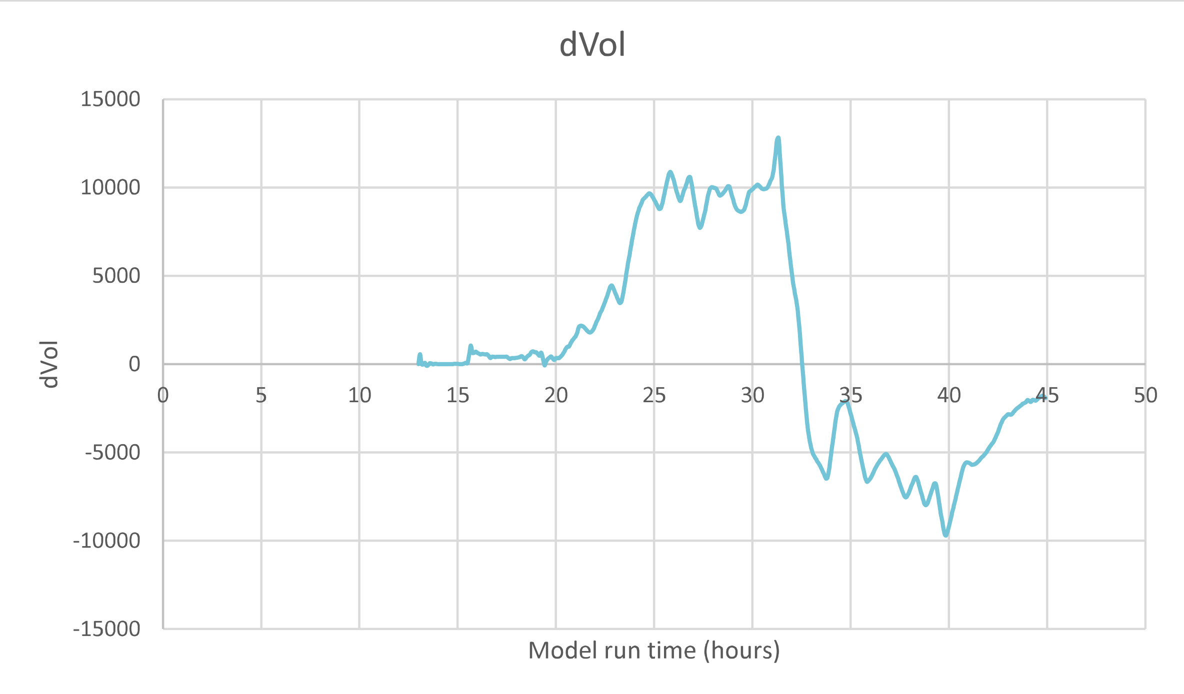

Figure 4-10: dVol for the 0.5% AEP event

Cumulative mass balance error

Another indication of model stability is cumulative mass balance error. Typically, during a stable model run the cumulative mass error will have a value of ±1%. Figure 4-11 shows the mass balance recorded during the model run for the 200-year fluvial event. For this event, the overall mass balance error is -3.60% in the 1D domain and 0.37% in the 2D domain. Mass balance tends to be smaller for the smaller events and slightly larger for the climate change events and sensitivity testing runs. The model log shows the 1D and 2D mass balance for all 71 simulation runs.

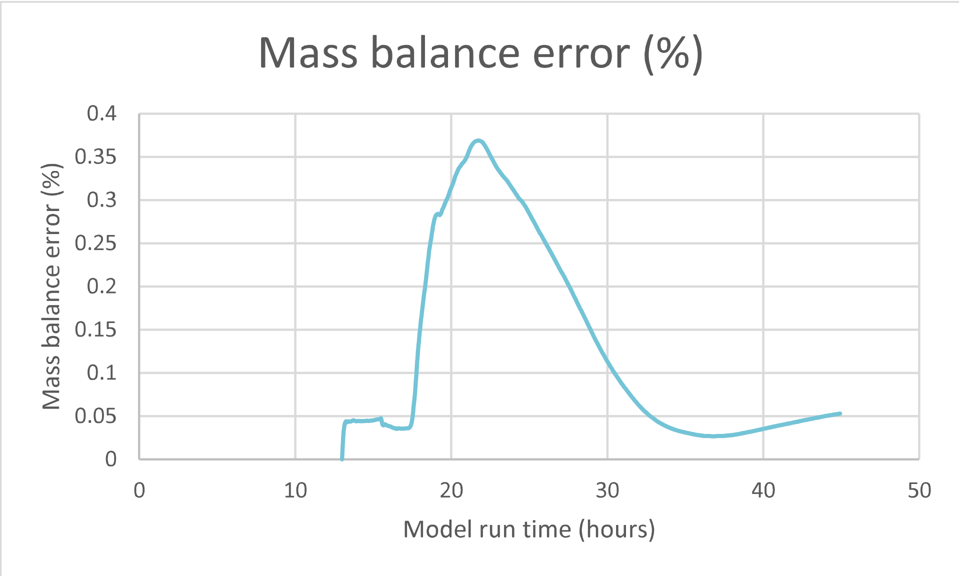

Figure 4-11: Cumulative mass balance error for the 200-year fluvial event

Tuflow warning messages

There are a number of warning messages flagged by TUFLOW outwith the model's domain, these have been reviewed and are believed to not affect the model results. There are a handful of 'check' messages within the model's domain and one warning message for larger events which have been run, regarding water level lines not being snapped to the Auldearn Burn channel. The larger fluvial events have been run with the Auldearn Burn in the 2D grid only, and as water level lines are used for visual purposes regarding the 1D channel, this warning message does not affect results.

4.10 Model review

The model was reviewed internally and documented in a model technical review (included in the appendix). The corrections were addressed and additional modelling/checks carried out as necessary to the satisfaction of the internal reviewer. Once all corrections were made, the modeller ran the rest of the simulations and produced the requested deliverables.

4.11 Model recommendations

A number of improvements to the modelling, which are not considered to have a quantifiable impact on the results, were identified. These improvements should be incorporated into future model simulations:

- Enlargement to the 2D downstream boundary to high ground and alignment with coast for the large climate change events.
- The confluence of the Auldearn Burn with the River Nairn was responsible for numerous hours of modelling time working through model instabilities and for larger events it had to be removed altogether, instead the Auldearn Burn was

modelled in the 2D domain or alternatively it was applied as a direct inflow into the River Nairn. For future model runs consideration should be given to representing the Auldearn Burn in Estry (the 1D component of TUFLOW) or if keeping in the 2D, to apply a geometry modification to remove false blockages on the channel. The maximum flow through the culverts in the 1D domain for the events up to the 200-year event was 4.8 m^3/s at Granny Barbour Road culvert and 3.5 m^3/s at the A939 culvert (for the Do Nothing scenario) and given the excessive out of bank flooding around the Auldearn Burn as shown in the 2D domain for the 1000-year and climate change scenario events (section 5.3), the false blockages are not thought to have a profound effect on model results given the large magnitude of these events.

- There are three culverts on the Auldearn Burn within the model extents. Inlet and outlet losses were removed from the culvert to prevent crashing of the model. If the 1D component of the Auldearn Burn is kept then the roughness of the culvert should be increased to a suitable level to represent the expected head loss.
- As noted in Appendix section D-4, some water level instability near the downstream boundary of the fluvial climate change model runs was flagged in the internal model review. This occurs around the peak of the event and causes oscillation of water levels between NAI01_00596 and NAI01_00182 (approximately a 400 m long reach). A conservative approach has been used for the fluvial climate change flood mapping regarding these oscillations (as described in the appendix), but if a detailed design of flood defences were undertaken in future (to incorporate a fluvial climate change allowance), the oscillations should be looked at to give greater confidence.

5 Hydraulic model results

5.1 Introduction

The model produced estimates of the flood extent, water levels, depths and velocities within Nairn for the various events and scenarios. The full set of flood map outputs are provided in the appendix and the number of properties impacted is discussed in section 6. The largest (1000-year Climate Change Scenario 2) and smallest (2-year) flood extent outline are shown in Figure 5-1. This results section presents:

- The flow paths, flood extents and mechanism of flooding at Nairn (i.e. with discussion on dominant flood risk and onset of flooding).
- Maximum and mean depths and velocities at key receptor areas i.e. Fishertown, the caravan park, residential area along the Auldearn Burn and at Househill.

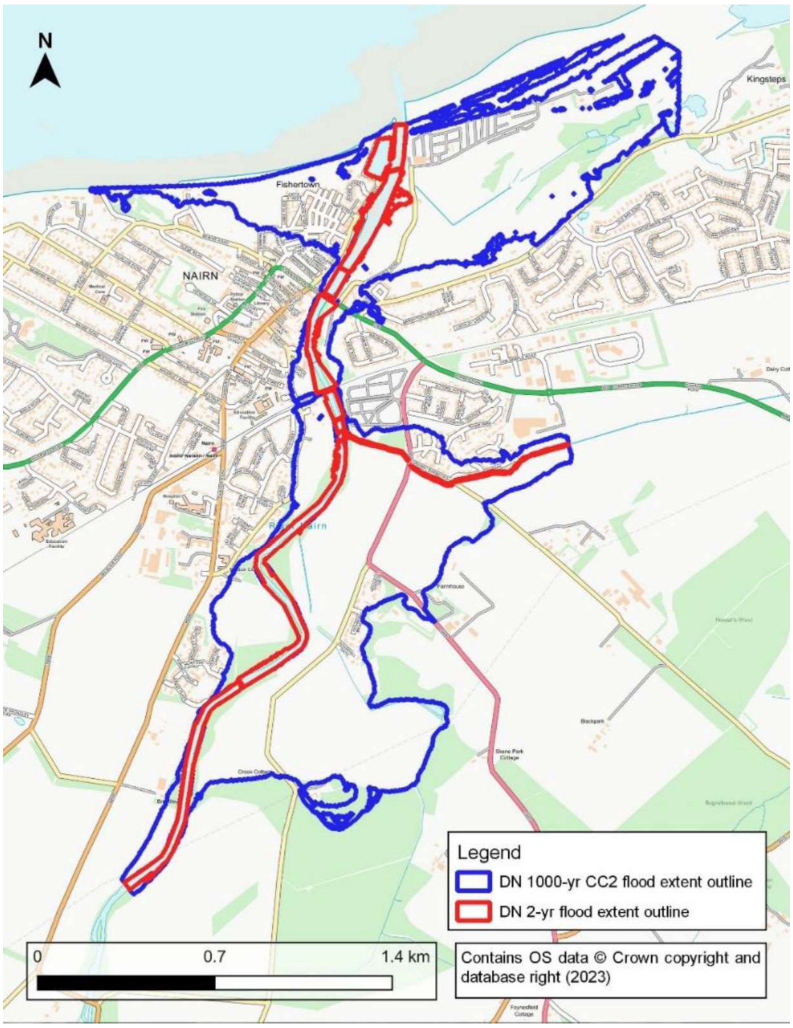

Figure 5-1: Combined flood outline extent for the largest and smallest 'Do Nothing' (baseline) events.

5.2 Dominant flood risk

The model results show that for most of the events, the fluvial events give larger flood extents and greater depths, compared to the tidal events, for a given return period, including at the area downstream of the A96 road bridge. However, the tidal flood outputs result in higher water levels downstream of the A96 road bridge for the 5-year and 10-year events. The same is also true for both the climate change scenario 2 events (200-year CC2 and 1000-year CC2).

Form analysis of longitudinal sections, the influence of tidal flooding for 'present day' scenarios (up to the 1000-year event) extends up to the Merryton footbridge between swan island and the A96 road bridge (B_00809 in model). As such, Fishertown (at all streets north of and including Grant Street, King Street and Society Street) and the Caravan Park are affected by both tidal and fluvial flooding. Properties along Riverside Crescent (to the north of the A96) are shown to be affected by fluvial flooding, but not tidal flooding, regarding present day scenarios.

Onset of flooding

Key locations and areas in Nairn are shown in Figure 5-2. The 2-year (fluvial and coastal) event is largely in bank along the full reach of the watercourses, with the exception of some overtopping of the right banks (at 3.0 mAOD) at the open grassland area between the caravan park and the grass athletics track, and overtopping of the left banks in the same vicinity (at the footpath along the River Nairn next to the flood wall, 2.9 mAOD). From the 5-year event and greater (regarding both a fluvial or a tidal flood event), the properties along Harbour Street (next to the flood wall) are shown to be within the flood extents. From the 30-year event there is a large increase in flood extent for both the fluvially and tidally dominant flood events, particularly at Fishertown.

At Balmakeith Park (right bank of Auldearn Burn), flooding is shown to start occurring from the 10-year fluvial event, and it is this same event where flooding to warehouses along Church Road would be expected (next to the cemetery near Riverside Park, left bank of River Nairn, Figure 5-2). It is noted that there is considerable out of bank flooding between the railway and the road bridge during this event (on both banks of the River Nairn) however there are no buildings in this area. The model results show that one property at the bottom of Alder Bank and the property off Mill Street at Riverside Park would be expected to flood from approximately the 30-year fluvial event (locations shown in Figure 5-2).

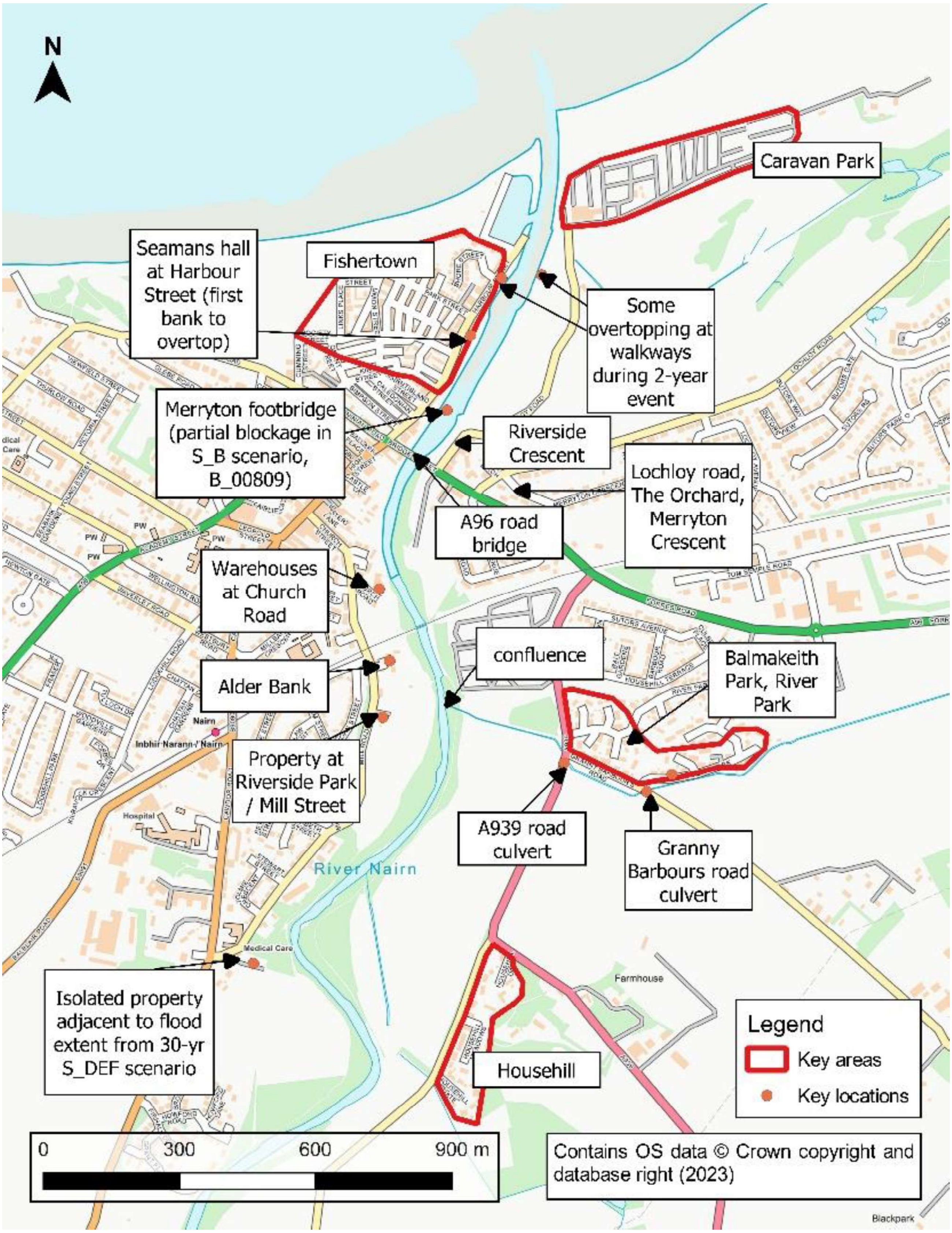

Figure 5-2: Key locations and areas as discussed in the results outputs.

5.3 Discussion of flooding at key receptor areas

Fishertown:

Fluvial flood risk

During the Do Nothing (baseline) fluvial flood event, flow paths at Fishertown are expected to form from overtopping of the left bank near Seamans Hall and flowing along Harbour Street. Overtopping of the left bank is expected to occur from the 5-year event with water flowing westward down Park Street and Shore Street into Fishertown from the 30-year event. From the 100-year event and greater, water would also be expected to flow down Firth Street and Links Place and southward along the parallel ‘Park Streets’ through the middle of Fishertown. From the 200-year event, flow paths would also form along Society Street. The flow paths are somewhat controlled by the road network and residential nature of the area. Flood depths for the 200-year event are expected to reach 1.75 m, and velocities for the same event in the order of 1.67 m/s, as shown in Figure 5-3, Table 5-2 and Table 5-3. Velocity is generally considered alongside depth to inform a Hazard rating. A combination of 1.75 m water depth and 1.67 m/s velocity would result in a hazard rating of 'danger to all'[39] (though it is noted that this is at the location of maximum flood risk in Fishertown, and velocity and water depths are generally lower throughout Fishertown for this event (average velocity of 0.16 m/s and average depth of 0.77m).

39 Defra/Environment Agency Flood and Coastal Defence R&D Programme: R&D Outputs: Flood Risks to People, FD2321/TR2 Guidance Document, 2006. Page 16. https://assets.publishing.service.gov.uk/media/602bbc3de90e07055f646148/Flood_risks_to_people_-_Phase_2_Guidance_Document_Technical_report.pdf

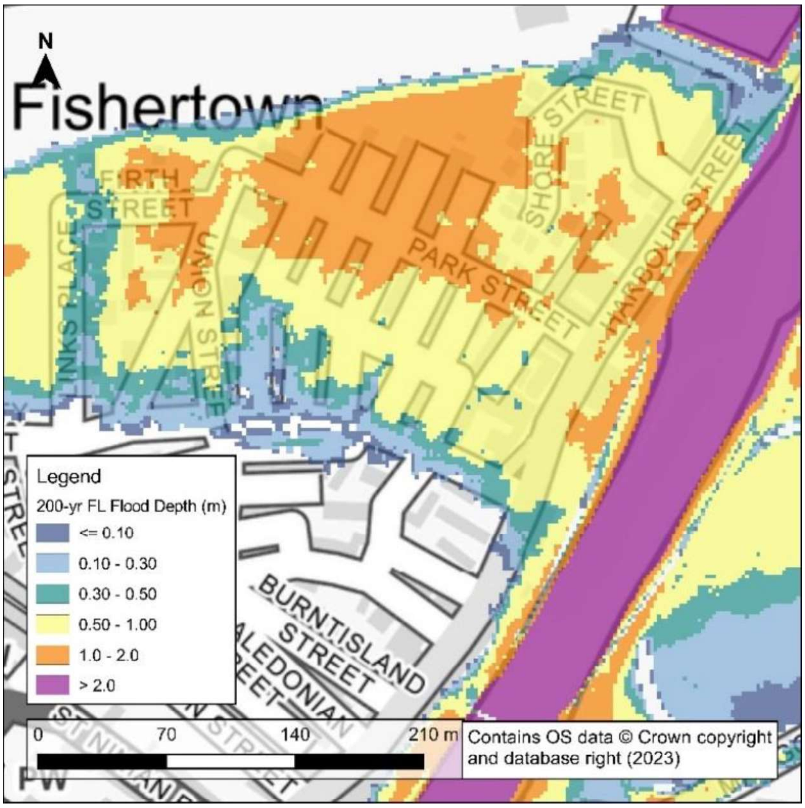

Figure 5-3: Flood depths at Fishertown for 200-year Do Nothing (baseline) fluvial event

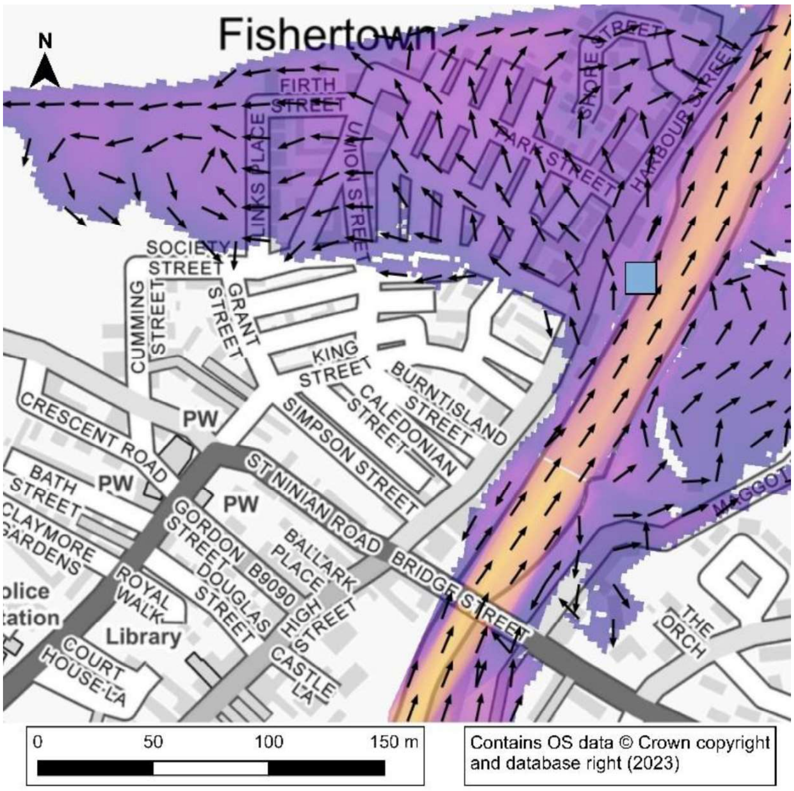

Figure 5-4: Flow direction at Fishertown for 200-year Do Nothing fluvial event. Blue square denotes location of first out of bank flooding at Seamans hall.

Fishertown:

Tidal flood risk

During a tidal flood event, flow paths at Fishertown are also expected to form from overtopping of the left bank near Seamans Hall at Harbour Street (similar to the fluvial event). This would occur from the 5-year event. For the 200-year event, flow paths form along Park Street, Shore Street, Firth Street and Union Street, mainly flooding the northern area of Fishertown. Flood depths for the 200-year event are expected to reach 1.19 m, and velocities for the same event 1.26 m/s (though are largely <1.0 m/s), as shown in Figure 5-5, Table 5-2 and Table 5-3.

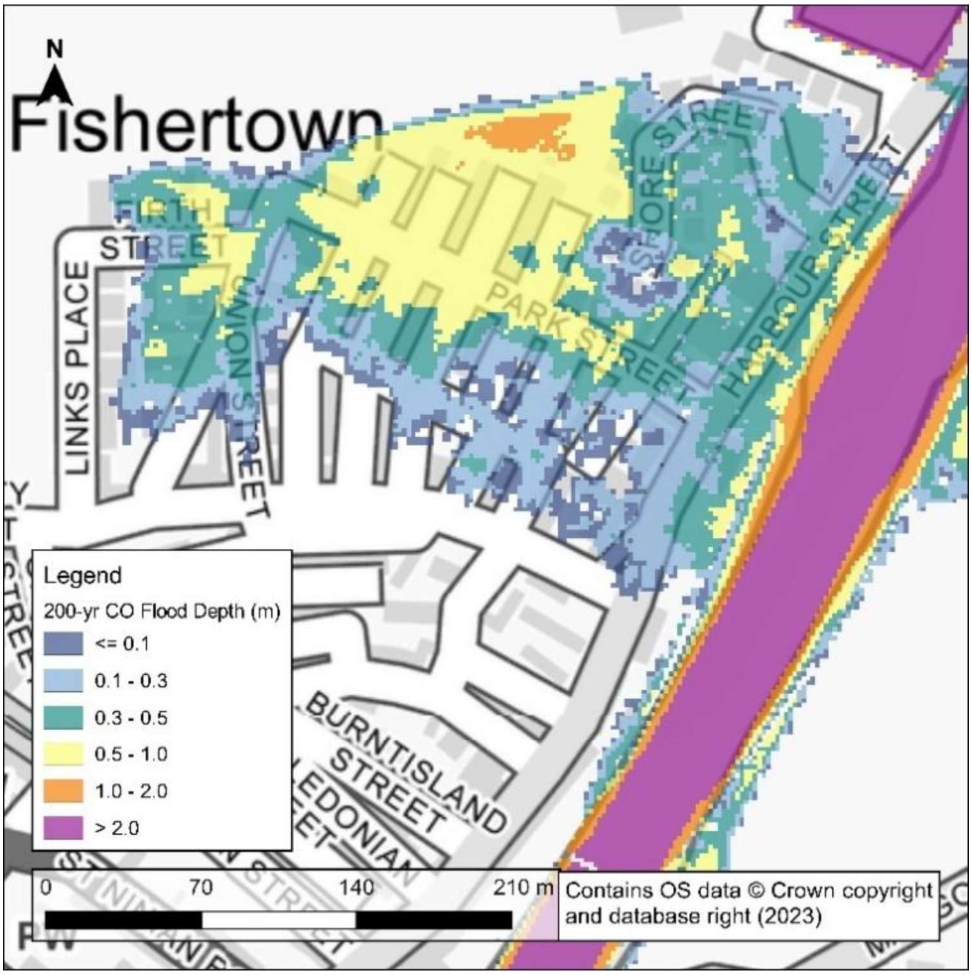

Figure 5-5: Flood depths at Fishertown for 200-year Do Nothing tidal event

Caravan Park:

During the baseline fluvial and tidal event, flow paths at the caravan park are expected to form from the right bank at the car park near Riverside Crescent, and flow northward and eastward through the caravan park. This would occur from the 100-year event for both the fluvial and tidal events, though flood extents are generally greater at the caravan park for the fluvial events.

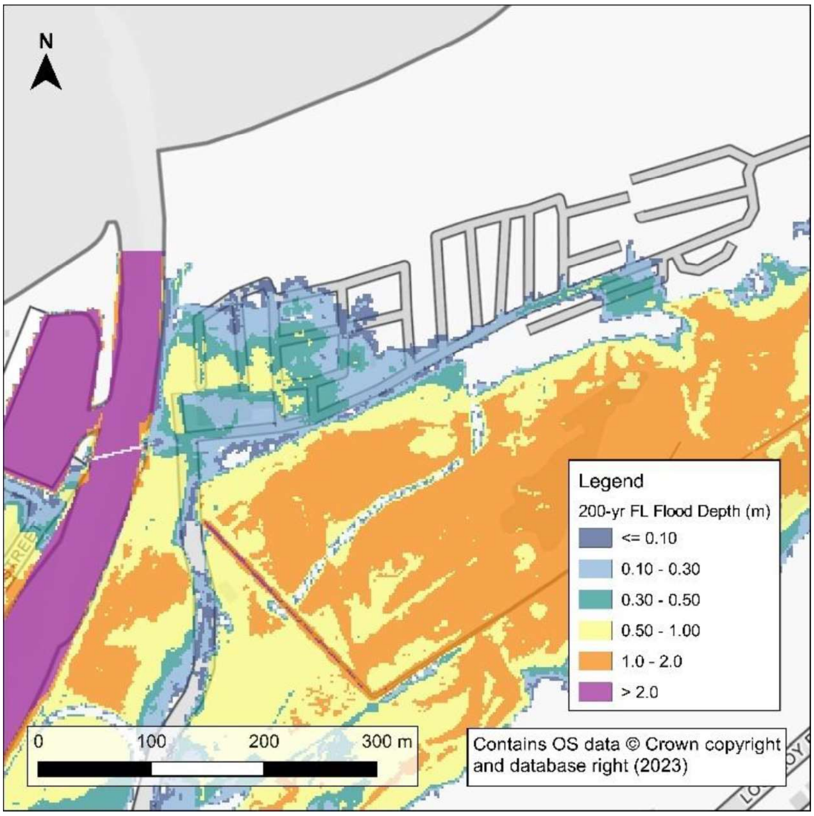

Figure 5-6:Flood depths at caravan park for 200-year Do Nothing fluvial event

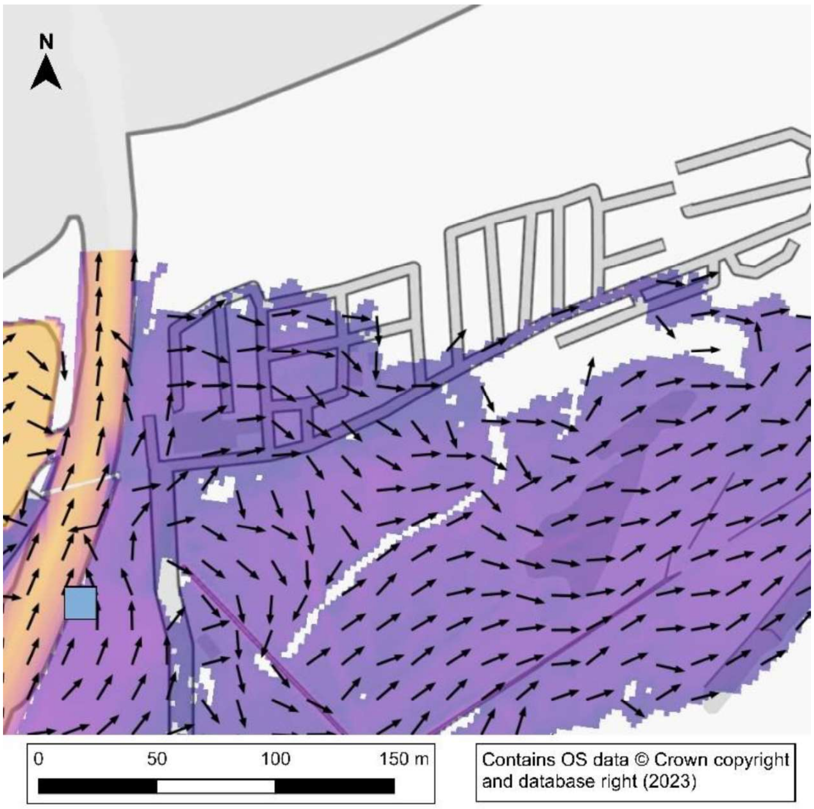

Figure 5-7: Flow direction at caravan park for 200-year Do Nothing fluvial event. Blue square denotes location of first out of bank flooding south of caravan park.

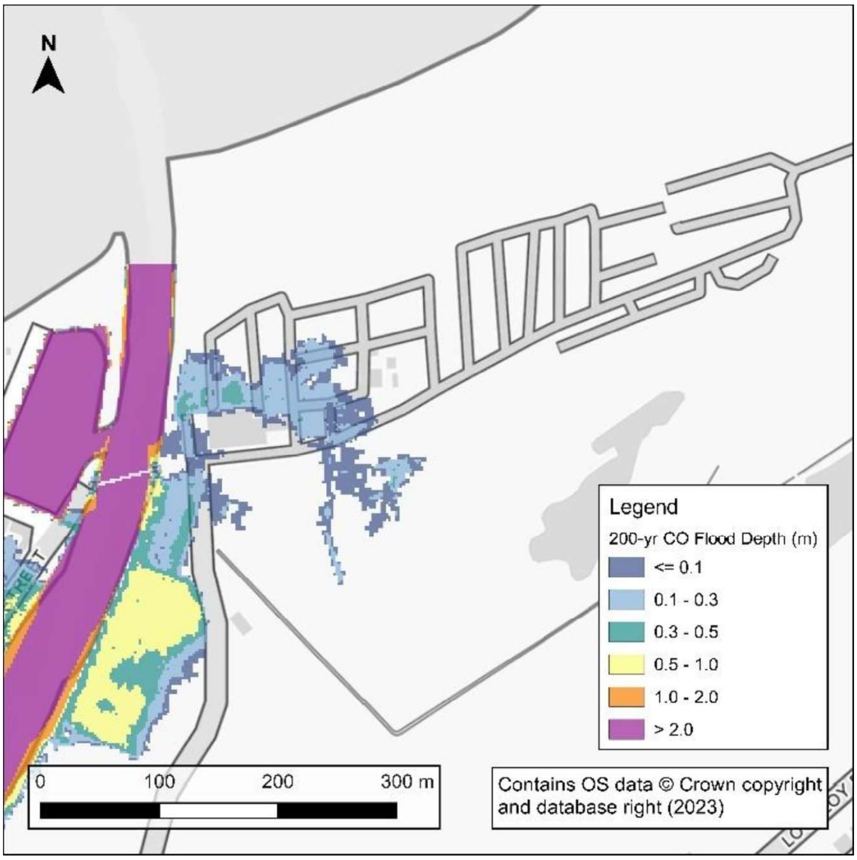

Figure 5-8: Flood depths at caravan park for 200-year Do Nothing tidal event

Auldearn Burn:

During a fluvial flood event on the Auldearn Burn, flow paths are expected to form from overtopping of the right bank at Balmakeith Park (from the 10-year event) and flow down Granny Barbours Road. Flood water would be expected to flow down River Park from the 200-year event, with flood depths expected to reach 1.04m, and velocities for the same event of 0.84 m/s.

During fluvial flood events greater than and including the 30-year event, the model results show that water levels from the River Nairn would affect water levels on the Auldearn Burn up to where the Granny Barbour Road crosses the burn. As such, overtopping of the A939 road would be expected from the River Nairn (location shown in Figure 5-2). In addition, out of bank flooding from the River Nairn during very large events (1000-year and fluvial climate change events) would be expected to flow over the floodplain between the River Nairn and Auldearn Burn, including in the upper reaches of the modelled area of the Auldearn Burn (i.e. at Balmakeith Park). Flood depths for the 1000-year event are expected to reach 2.33 m along Granny Barbours Road, and velocities for the same event 1.15 m/s.

All three culverts along the Auldearn Burn are surcharged during the 2-year event (as modelled from the Do Nothing scenario; where the capacity of the culverts are reduced to 50% of their full capacity). The maximum water level and flow at the peak of this event, as well as the water level and flow when the culvert soffit level is reached, is shown in Table 5-1. Although the culverts are surcharged during the 2-year event, the roads are not overtopped at the culvert locations until events larger than the 30-year event at both Granny Barbours road culvert and the A939 culvert. The maximum flow at the culverts from the 30-year event, prior to the roads overtopping (that occurs between the 30-year and 100-year event) is 4.78 m^3/s at Granny Barbours road culvert (downstream of Balmakeith Park) and 3.49 m^3/s at the culvert under the A939. The most upstream culvert (CUL_00857, immediately upstream of Balmakeith Park) overtops at the 10-year event.

Table 5-1 2 year water level and flow on Auldearn Burn culverts.

Culvert	Water Level (mAOD)		Flow (mAOD)		Road overtopped at 2 year event?
	Maximum water level	Culvert surcharge level	Peak flow during 2-yr event	flow at which culvert is surcharged	
Most US culvert (CUL_00 857)	6.12	5.50	2.43	1.00	No
Granny Barbour Road culvert (CUL_00 518)	5.92	5.74	2.43	1.55	No
A939 culvert (CUL_00 319)	5.23	5.10	2.43	2.18	No

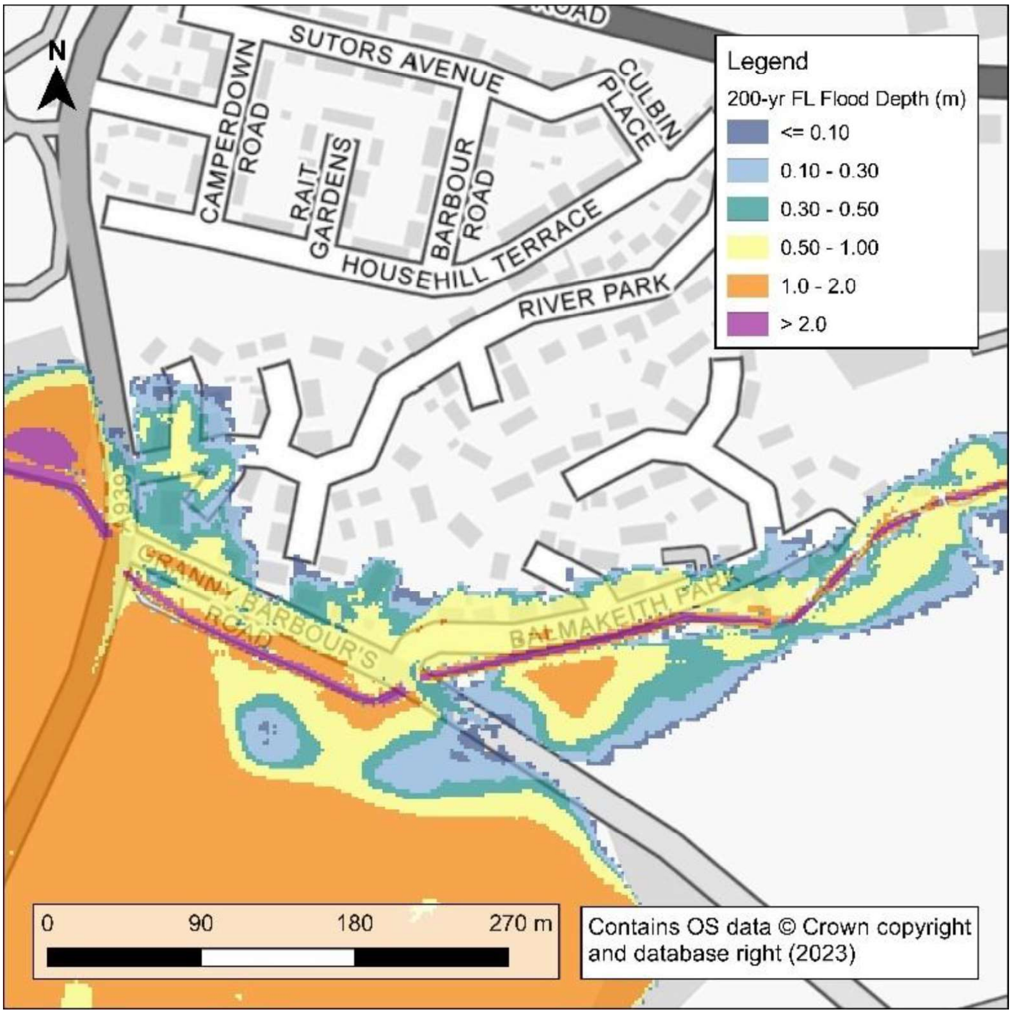

Figure 5-9: Flood depths at Balmakeith Park for 200-year Do Nothing fluvial event

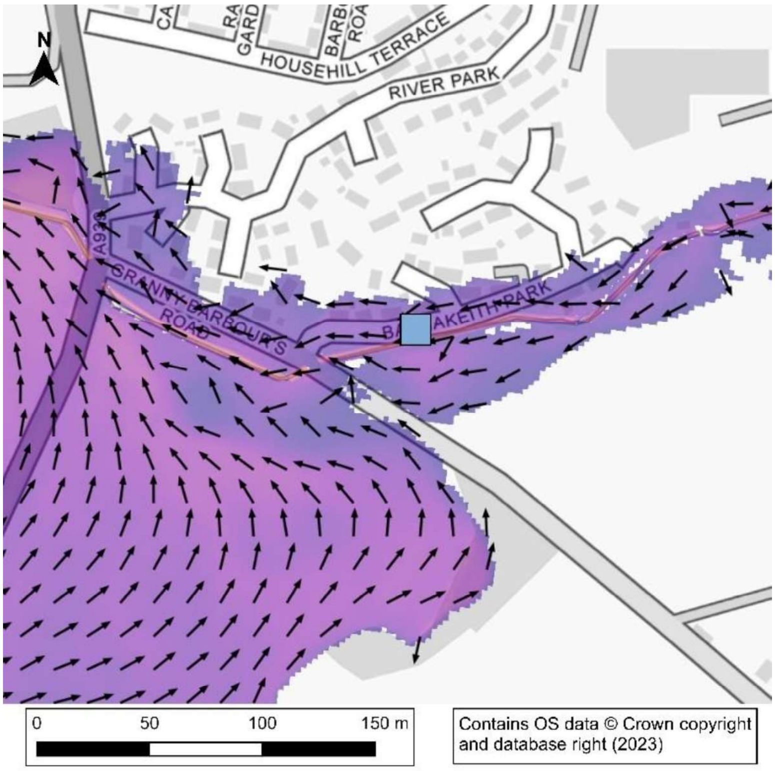

Figure 5-10: Flow direction at Balmakeith Park for 200-year Do Nothing fluvial event. Blue square denotes location of first out of bank flooding at Balmakeith Park.

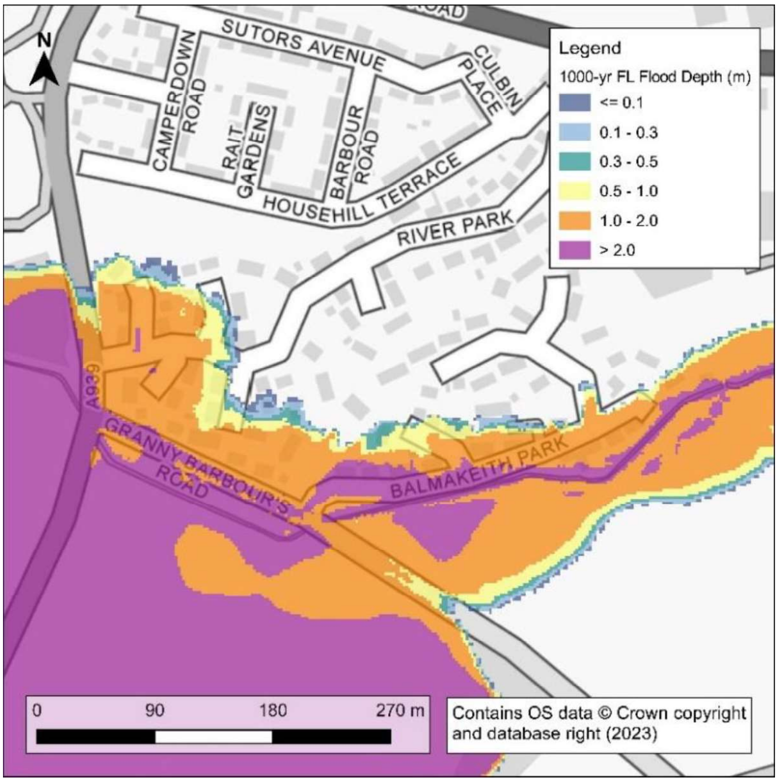

Figure 5-11: Flood depths at Balmakeith Park for 1000-year Do Nothing fluvial event

Househill:

During a fluvial flood event, flow paths at Househill are expected to form from overtopping of the right bank of the Nairn upstream of the informal embankment (on the right bank) and flowing along the minor road towards Househill, as well as a separate flow path that overtops the right bank of the Nairn downstream of Househill and reaches the A939 road. These flow paths converge at Househill from the 30-year fluvial event (and prior to the peak of the 200-year event, hence why flow paths in Figure 5-13 show flow going northward). Flood depths for the 200-year event are expected to reach 1.43 m, and velocities for the same event 2.08 m/s, as shown in Figure 5-12. This combination of water depth and velocity would result in a hazard rating of 'danger to all'[40] (at the location where these maximum values occur).

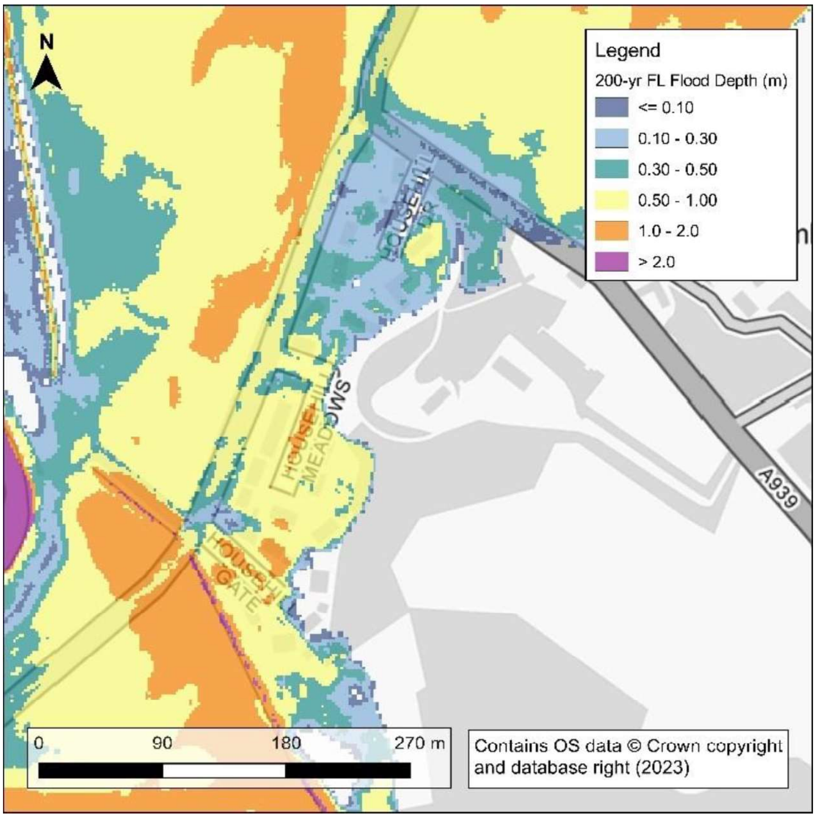

Figure 5-12: Flood depth at Househill for 200-year Do Nothing (baseline) fluvial event

40 Defra/Environment Agency Flood and Coastal Defence R&D Programme: R&D Outputs: Flood Risks to People, FD2321/TR2 Guidance Document, 2006. Page 16. https://assets.publishing.service.gov.uk/media/602bbc3de90e07055f646148/Flood_risks_to_people_-_Phase_2_Guidance_Document_Technical_report.pdf

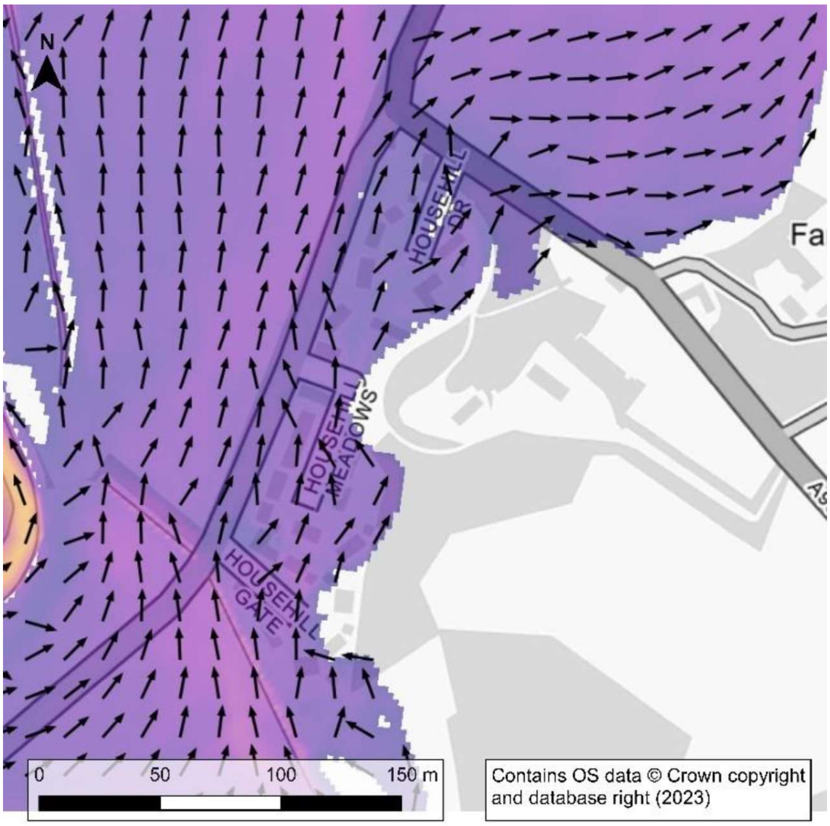

Figure 5-13: Flow direction at Househill for 200-year Do Nothing fluvial event

Flood depth and velocities at key locations.

Table 5-2 and Table 5-3 shows the maximum and average flood depths and velocities in the floodplain (i.e. area surrounding the River Nairn and Auldearn Burn) for key return periods at the locations above. The maximum and average water depths were generally largest at Fishertown, from all the four receptor areas, although velocities were largest at Househill. For reference, guidance regarding calculating a Hazard Classification from velocity and depth suggests that at velocities of greater than 1 m/s, and relatively shallow depths (<0.5m) some people would be unable to stand and at velocities greater than 2 m/s and depths around 0.6m, most people would be unable to stand[41].

Table 5-2: Flood depths (m) at key receptor areas. Note FL = Fluvial, CO = Coastal

Return Period	30 years		200 years		1000 years	
	Max (m)	Average (m)	Max (m)	Average (m)	Max (m)	Average (m)
Fishertown (FL)	0.73	0.20	1.75	0.77	2.45	1.32
Fishertown (CO)	0.44	0.13	1.19	0.40	1.37	0.50
Caravan Park (FL)	No Flooding	No Flooding	0.83	0.30	2.20	1.24
Caravan Park (CO)	No Flooding	No Flooding	0.45	0.14	0.78	0.26
Auldearn Burn (FL)	0.48	0.18	1.04	0.44	2.33	1.28
Househill (FL)	0.75	0.20	1.43	0.53	1.87	1.14

Table 5-3: Velocities (m/s) at key receptor areas. Note FL = Fluvial, CO = Coastal

Return Period	30 years		200 years		1000 years	
	Max (m)	Average (m)	Max (m)	Average (m)	Max (m)	Average (m)
Fishertown (FL)	1.09	0.13	1.67	0.16	1.73	0.18

41 Defra/Environment Agency Flood and Coastal Defence R&D Programme: R&D Outputs: Flood Risks to People, FD2321/TR2 Guidance Document, 2006. Page 16. https://assets.publishing.service.gov.uk/media/602bbc3de90e07055f646148/Flood_risks_to_people_-_Phase_2_Guidance_Document_Technical_report.pdf

Return Period	30 years		200 years		1000 years	
Fishertown (CO)	1.22	0.11	1.26	0.12	1.28	0.16
Caravan Park (FL)	No Floodi ng	No Flooding	1.46	0.24	1.64	0.25
Caravan Park (CO)	No Floodi ng	No Flooding	0.93	0.07	1.47	0.23
Auldearn Burn (FL)	0.39	0.07	0.84	0.85	1.15	0.08
Househill (FL)	1.56	0.25	2.08	0.51	2.53	0.67

5.4 Longitudinal section mapping change against baseline

The 200-year fluvial and tidal baseline scenarios are shown in the longitudinal section below for the River Nairn, the results demonstrated that the fluvial outputs are higher up to the footbridge near the caravan park (NAI01_00363). Water backs up against the road bridge (NAI01_00942), and two footbridges at NAI01_00809 and NAI01_00363 during the fluvial event, causing raised water levels at these locations.

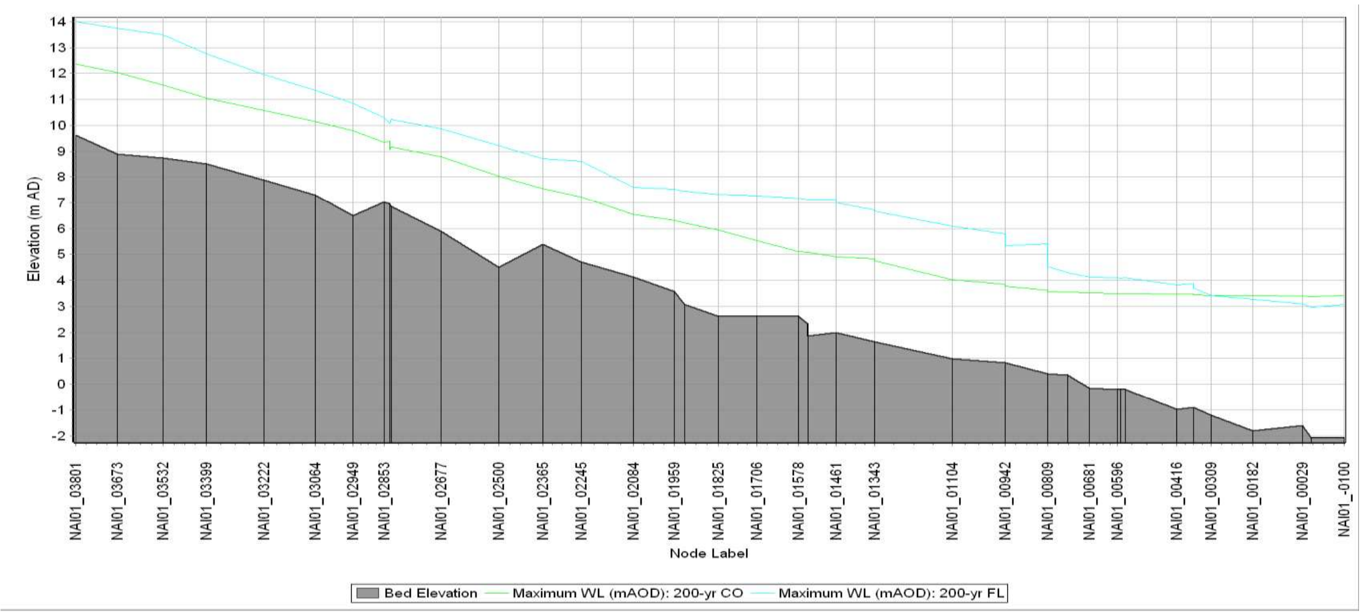

Figure 5-14: Comparison between 200-year fluvial (blue) and tidal (green) Do Nothing scenarios. Firhall gauge is located at NAI01_02853, railway bridge at NAI01_01343 and road bridge at NAI01_00942

The 30-year, 100-year and 200-year baseline water levels along the River Nairn are shown below. The 'backwater effect' at bridges is much more prevalent from the 100-year and 200-year event, compared to the 30-year event.

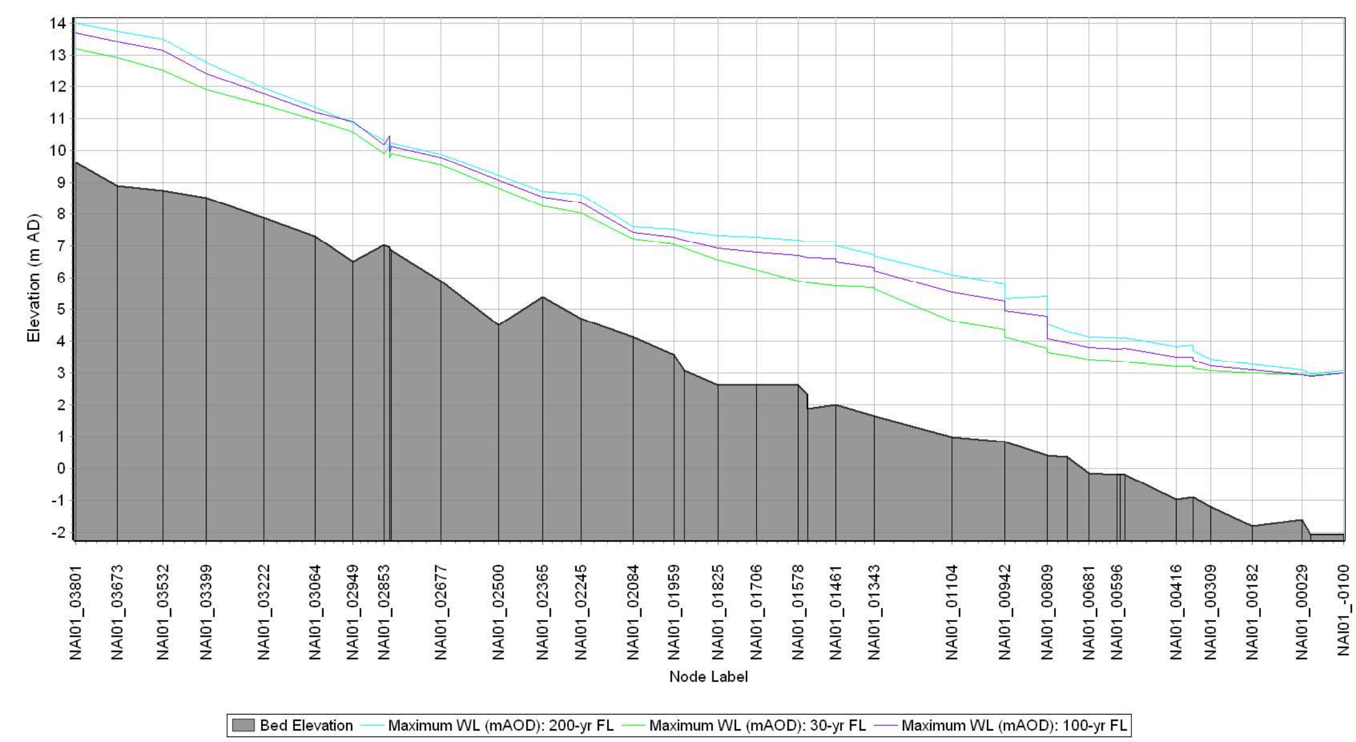

Figure 5-15: Comparison between 30-year (green), 100-year (purple) and 200-year (blue) Do Nothing water levels along River Nairn

The 30-year, 100-year and 200-year baseline water levels along the Auldearn Burn are shown below. Backing up of water from the Nairn on to the Auldearn occurs between the 30-year and 100-year events. The culvert at Granny Barbours Road (CUL_00518) becomes drowned out between the 100-year and 200-year event though overtopping of the road at this location occurs during both events. There is considerable difference in water level downstream of Granny Barbours Road between the events (approximately 0.5 m). Downstream of the A939 road (AUL01_00327) the water level difference between the 30-year and 100-year event is approximately 0.8 m in the channel. This large increase in flood level described is controlled by flood water from the River Nairn backing up the Auldearn Burn, rather than from flood water flowing down the Auldearn Burn.

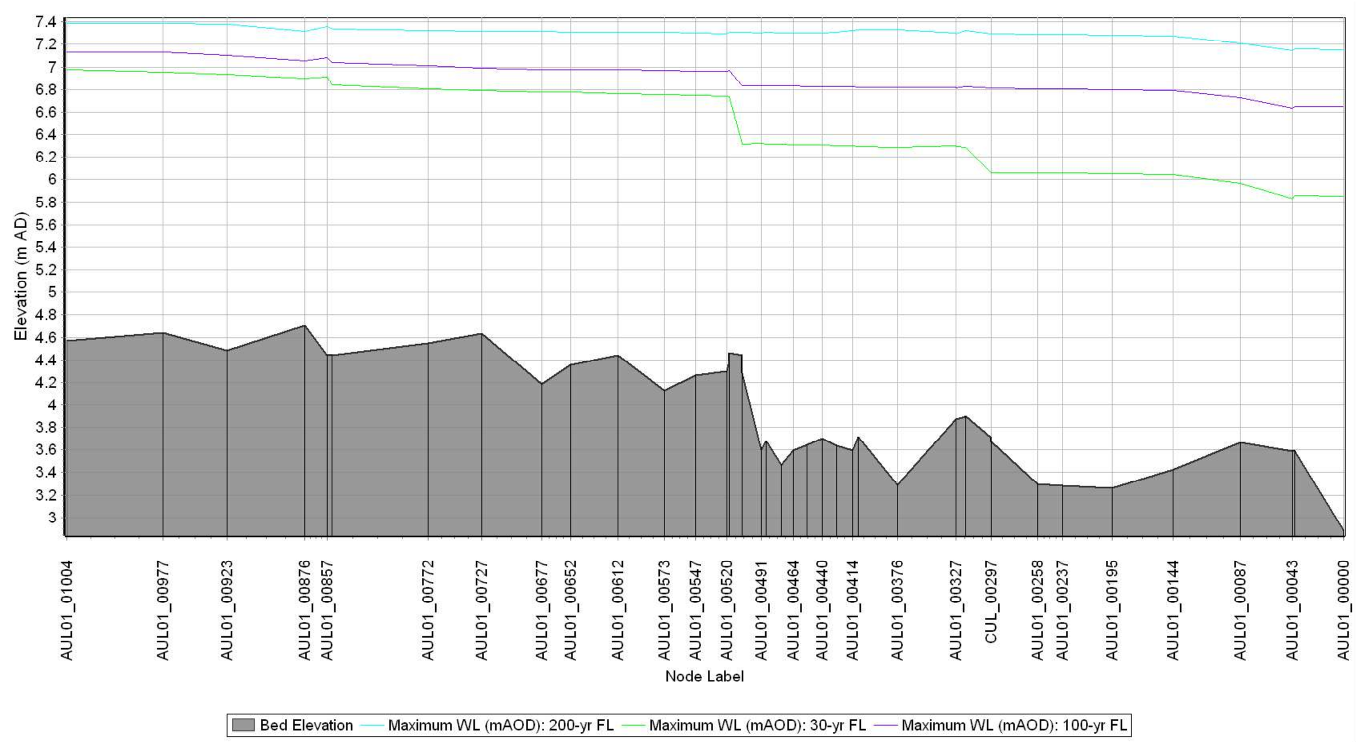

Figure 5-16: Comparison between 30-year (green), 100-year (purple) and 200-year (blue) Do Nothing water levels along Auldearn Burn

5.5 Sensitivity Testing results

Four sensitivity test scenarios were undertaken in addition to the baseline (Do Nothing) scenario, these were increase and decrease in Manning's roughness (N+20 and N-20), sensitivity to blockage (S_B) and sensitivity to defences (S_DEF). The sensitivity test scenarios are described further in section 4.6. Five events were used in the sensitivity testing: 10-year, 30-year, 200-year, 200-year Climate Change scenario 1 and 1000-year Climate Change scenario 1. The sensitivity test present day results, in relation to the baseline, are described below. Analysis of the climate change sensitivity runs are included in the appendix.

Roughness (N+20 and N-20)

To test the hydraulic model's sensitivity to changes in roughness, Manning's 'n' coefficients in both the 1D and 2D domains (both channels and structures) have been adjusted uniformly by +20% and -20% over the entire domains for the five events (section 4.6). The average change in flood depth at Fishertown for the 200-year event between using the original roughness values and those derived from a +20% and -20% adjustment are +0.12 m and -0.16 m, as outlined in Table 5-5. From focusing on Key areas, the caravan park shows the largest change in water depth for the N+20 scenario (maximum change +0.36m and average change +0.21 m, Figure 5-17) and for the N-20 scenario, the area of greatest change was at Balmakeith Park (maximum change -0.34m and average change -0.17 m, Figure 5-18).

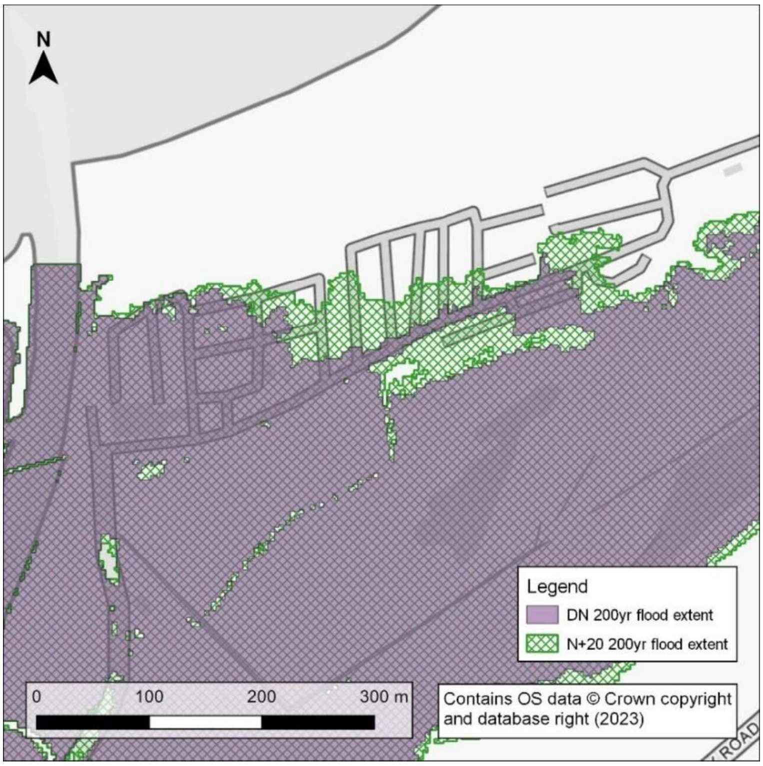

Figure 5-17: Increase in flood extent at Caravan Park for 200-year event (N+20)

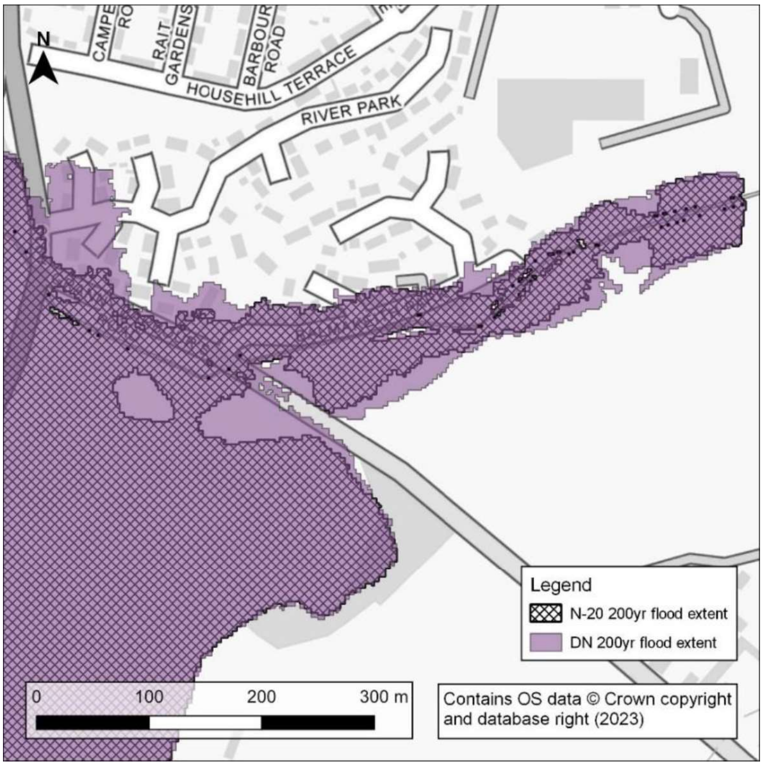

Figure 5-18: Decrease in flood extent at Balmakeith Park for 200-year event (N-20)

Defences (S_DEF)

The defended scenario included adding the informal flood wall (left bank at Fishertown) and informal embankment (right bank near Househill) into the baseline (DN) scenario, further description included in section 4.6.

Local knowledge supplied by THC confirmed that the informal flood wall running parallel to Harbour Street has not been overtopped since the wall was constructed in the early 2000s; flooding has reached about half-way up the wall.

The hydraulic model shows that the wall (without a reduction in height to account for model freeboard) is high enough to prevent overtopping from flood events up to the 1 in 30 year flood. For the 200-year fluvial flood event, the wall is overtopped and the flood extent is almost the same with and without the wall. However, it also shows that the wall is sufficiently high enough to hold back the 200-year tidal event. An approximate freeboard level between the peak water level and the top of the wall, for these events, is provided in the table below. It is noted that in the undefended (DN) scenario, all of the events in the table below overtop the location of the flood wall (when the flood wall is not included in the model).

A sensitivity analysis was undertaken for the 10-year, 30-year and 200-year events (as well as two climate change events), an interpolation calculation was undertaken to estimate the flow and thereby, the return period to which it is expected that the flood wall would overtop for the fluvial event (by using the equation of a straight line for interpolation, with 'X' and 'Y' points representing flow and level respectively). From this, it was estimated that the flow when the wall would be overtopped (3.65 mAOD) was of the order of 363 m^3/s. The 100-year flood event is approximately 13 m^3/s greater than this flow so it can be assumed that the wall has a capacity a bit less than the 100 year flood event. This does not leave any allowance for model or hydrology uncertainty i.e. no freeboard is provided.

Table 5-4: Approximate freeboard level on flood wall at cross section NAI01_00586 for various events.

Event	Top of flood wall (mAOD)	Peak water level (mAOD) for S_DEF	Freeboard (m)
200-year FL	3.65	4.08	-0.43 (overtopped)
200-year CO	3.65	3.51	0.14
30-year FL	3.65	3.38	0.27
30-year CO	3.65	3.30	0.35
10-year FL	3.65	3.20	0.45
10-year CO	3.65	3.21	0.44

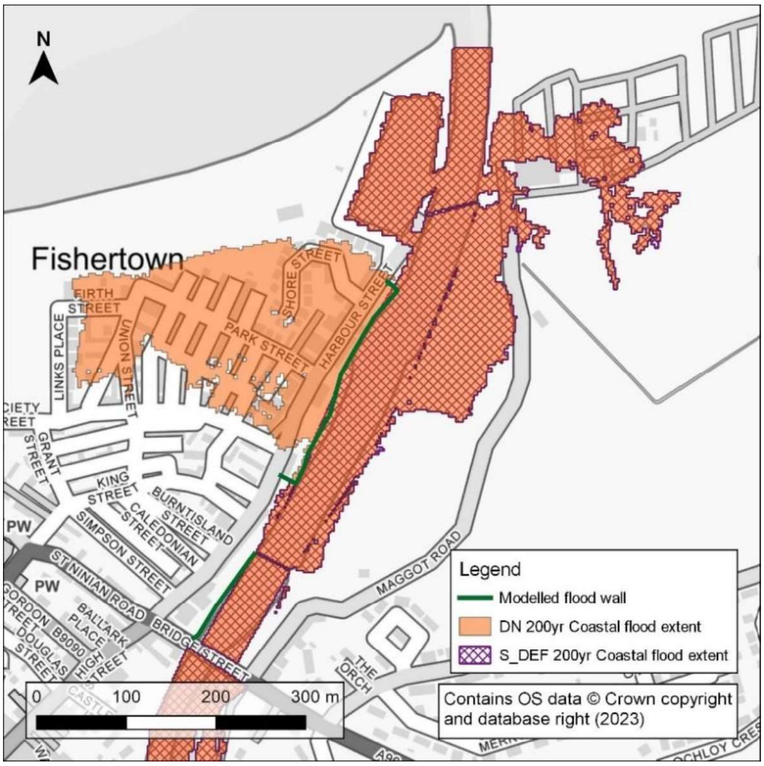

Figure 5-19: Difference in flood extent for the 200-year tidal event at Fishertown in vicinity of flood wall

It is noted that regarding the defended scenarios, the absence of the informal embankment in the DN scenario causes significant out of bank flooding during the 30-year event at Househill, and the presence of it causes less flooding in this area but more flooding on the left bank (Figure 5-20). Consequently, there is considerable decrease in flood depths and velocities at Househill between the scenarios (as noted in Table 5-8). It is noted that the greater flood extent on the left bank comes close to one property at Mill Road for the 30-year event. This property (shown in Figure 5-2) is overlain by both the 200-year defended scenario (flood depth approximately 0.5m) and baseline scenario (flood depth approximately 0.3m), though no other properties in the area are shown to be at increased risk of flooding, from comparing the baseline (DN) to the defended outputs. Flood extents and depths appear similar around the confluence and between the road and rail bridge.

The defended scenario showed that flood depth would be decreased very slightly at Balmakeith Park, understood to be a result of the embankment near Househill preventing less water from flowing over the floodplain between Househill and the Auldearn Burn.

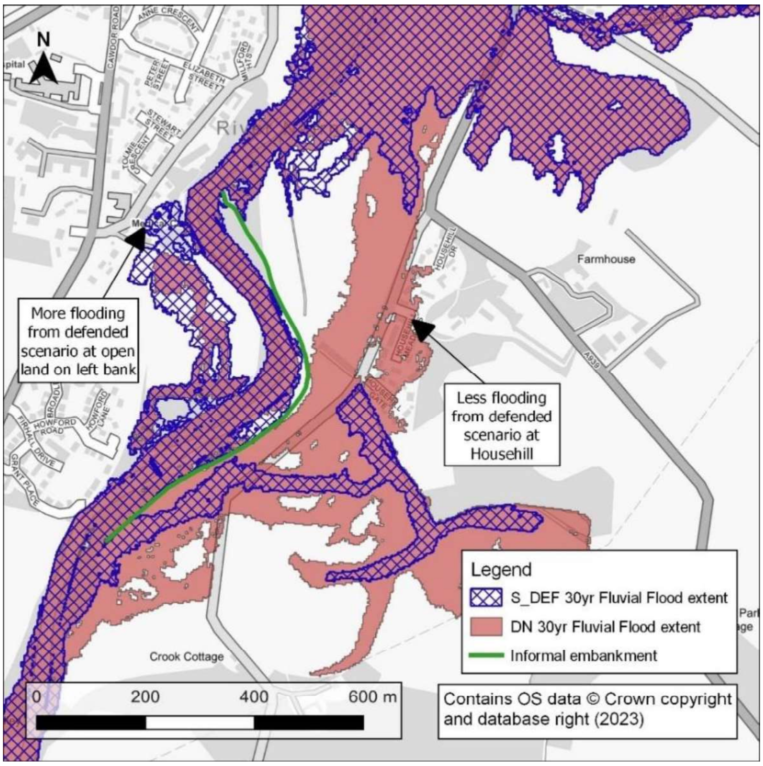

Figure 5-20: Difference in flood extent for the 30-year fluvial event at Househill in vicinity of embankment.

Bridge Blockage (S_B)

It was found that, for the bridge blockage scenario (choice of structure blockage described in section 4.6), partially blocking the footbridge at B_00809 on the River Nairn has the largest flood impact. The caravan park experienced the greatest increase in flood risk, only a small increase in flood extent is noted at the southern end of Harbour Street (location of the footbridge, in Fishertown). It is understood this is because the southern portion of Fishertown is on relatively higher ground than the northern portion, that constrains the flood extent, whereas the caravan park is at flatter, lower topography.

On the Auldearn Burn, blocking the Granny Barbour road culvert caused only a slight increase in flood extent and depths in the surrounding vicinity for the 200-year event (i.e. +0.03m in depth at properties at Balmakeith Park, Table 5-7), and little difference in velocity. This is likely because flood risk along the Auldearn Burn is mainly from the River Nairn during this event. The difference in flood extent was relatively more significant for the smaller events, such as for the 30-year event (Figure 5-22), though the largest increase in flood extent is along the left bank (rough open land), upstream of the culvert. The model results generally showed that there is at an increased risk of flooding regarding blockage of bridges and culverts, though not a significant increase in risk, regarding the 200-year event.

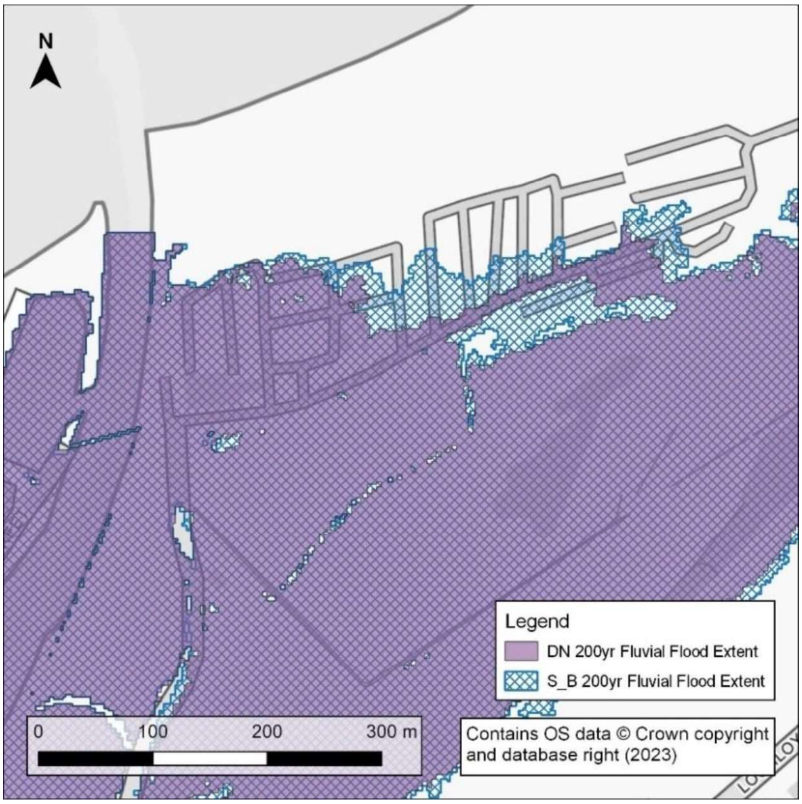

Figure 5-21: Difference in flood extent at Caravan Park for the 200-year event (bridge blockage at B_00809)

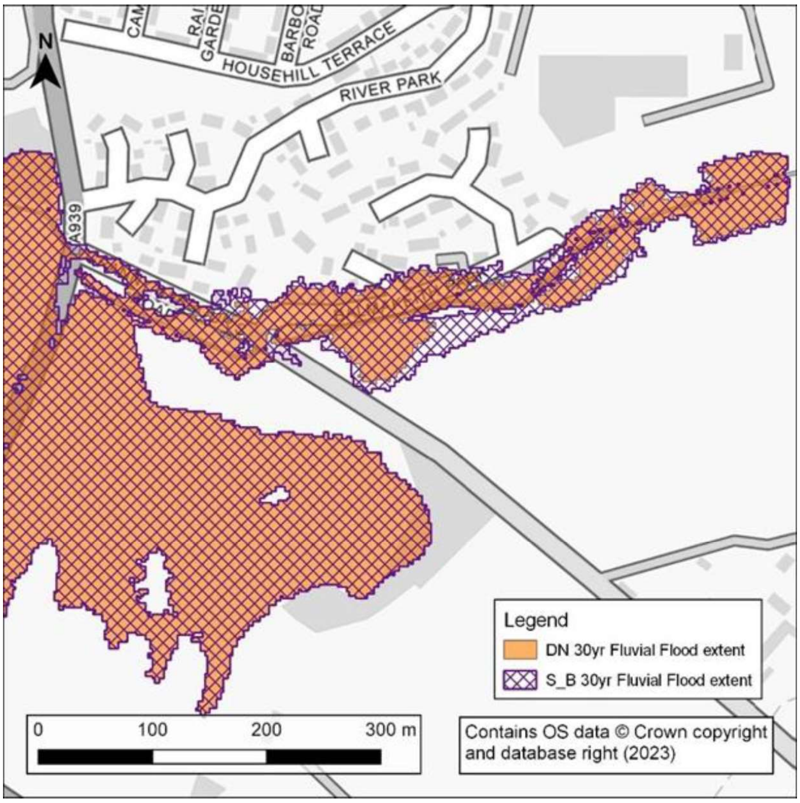

Figure 5-22: Difference in flood extent at Balmakeith Park for the 30-year event

The tables below show the maximum and mean (average) difference for water depth between each sensitivity test scenario and the baseline scenario, at key receptor areas in Nairn for the 200-year event. This identifies the areas that demonstrated greatest difference between the results and as such, the areas that are most sensitive to each scenario (as described in the figures above). The results tables generally show that the roughness testing had greater impact on the fluvial events compared to the tidal events, at Fishertown and the caravan park. The results for the other events are included in the Appendix C.

Table 5-5: Fishertown - sensitivity test water depth (m) comparison with baseline (DN) for 200-year event

ST	N+20		N-20		S_DEF		S_B	
	Max (m)	Mean (m)	Max (m)	Mean (m)	Max (m)	Mean (m)	Max (m)	Mean (m)
Fluvial	1.89	0.89	1.53	0.61	1.75	0.77	1.72	0.75
Tidal	1.22	0.42	1.16	0.38	0.08	0.03	N/A	N/A
Fluvial - change (m)	0.14	0.12	-0.22	-0.16	0	0	-0.03	-0.02
Tidal - change (m)	0.03	0.02	-0.03	-0.02	-1.11	-0.37	N/A	N/A

Table 5-6: Caravan Park - sensitivity test water depth (m) comparison with baseline (DN) for 200-year event

ST	N+20		N-20		S_DEF		S_B	
	Max (m)	Mean (m)	Max (m)	Mean (m)	Max (m)	Mean (m)	Max (m)	Mean (m)
Fluvial	1.19	0.51	0.68	0.22	0.83	0.3	1.09	0.44
Tidal	0.49	0.15	0.42	0.13	0.45	0.15	N/A	N/A
Fluvial - change (m)	0.36	0.21	-0.15	-0.08	0	0	0.26	0.14
Tidal - change (m)	0.04	0.01	-0.03	-0.32	0	0.01	N/A	N/A

Table 5-7: Auldearn Burn, Balmakeith Park - sensitivity test water depth (m) comparison with baseline (DN) for 200-year event

Sens Test	N+20		N-20		S_DEF		S_B	
	Max (m)	Mean (m)	Max (m)	Mean (m)	Max (m)	Mean (m)	Max (m)	Mean (m)
Fluvial	1.35	0.63	0.7	0.27	0.99	0.42	1.08	0.47
Fluvial - Difference	0.31	0.19	-0.34	-0.17	-0.05	-0.02	0.04	0.03

Table 5-8: Househill - sensitivity test water depth (m) comparison with baseline (DN) for 200-year event

Sens Test	N+20		N-20		S_DEF		S_B	
	Max (m)	Mean (m)	Max (m)	Mean (m)	Max (m)	Mean (m)	Max (m)	Mean (m)
Fluvial	1.60	0.67	1.18	0.36	1.27	0.41	1.43	0.53
Fluvial - Difference	0.17	0.14	-0.25	-0.17	-0.16	-0.12	0.00	0.00

Longitudinal sections from sensitivity tests

The longitudinal section below shows the 200-year baseline scenario (blue) against the roughness sensitivity testing outputs for the same event (increase in roughness represented in orange, and decrease represented in green), along the River Nairn. The largest change in results in the channel is at the Auldearn Burn confluence (NAI01_01507, Figure 5-24), this is thought to be due to more floodwater being 'held back' at the floodplain between the River Nairn and Auldearn Burn before flowing to the confluence and accumulating in this area. The floodplain at this location is agricultural land and hence given relatively high roughness value to represent this land cover type. In addition, there are areas of high roughness (i.e. woodland) in the vicinity of the confluence, that could slow the flow and increase water level. Both these land cover types have a high starting roughness value so a percentage increase has a larger physical difference on these areas.

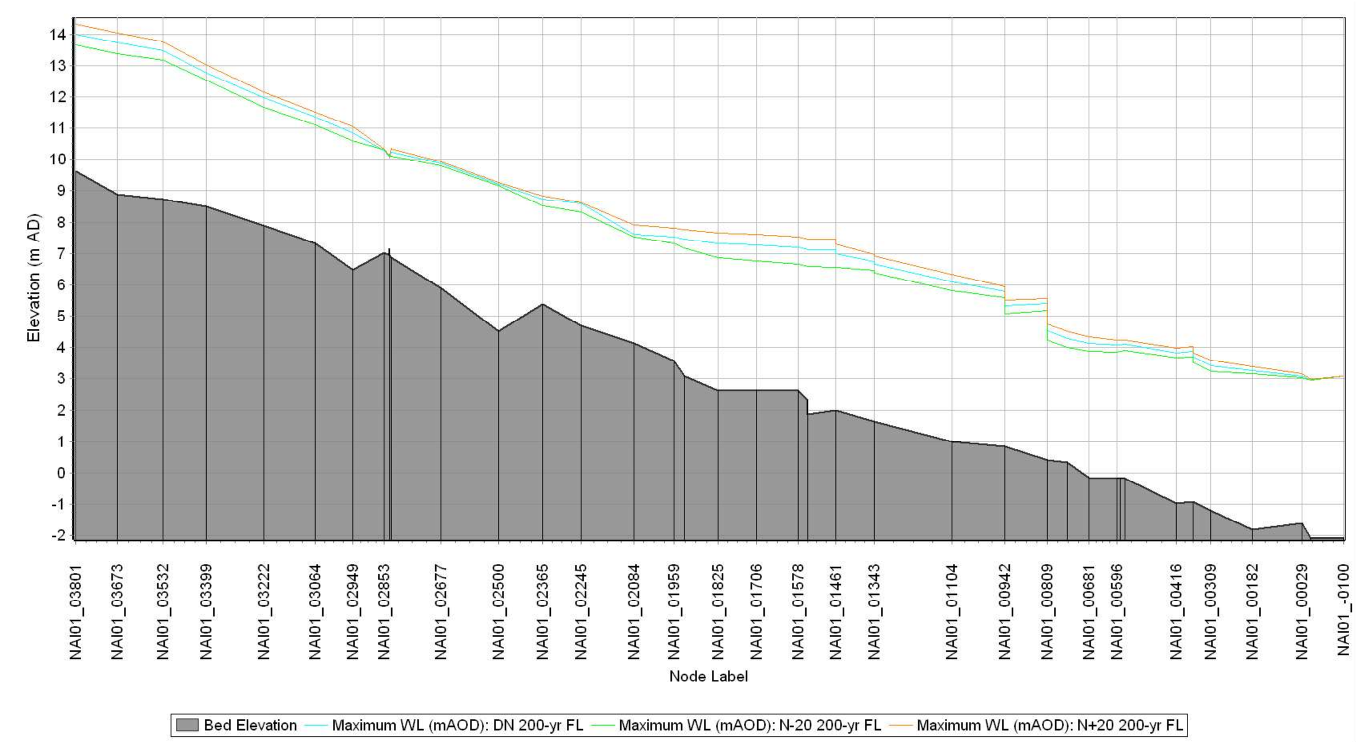

Figure 5-23: Comparison between roughness and baseline scenario, 200-year fluvial event- Light blue-baseline, green N-20, Orange N+20.

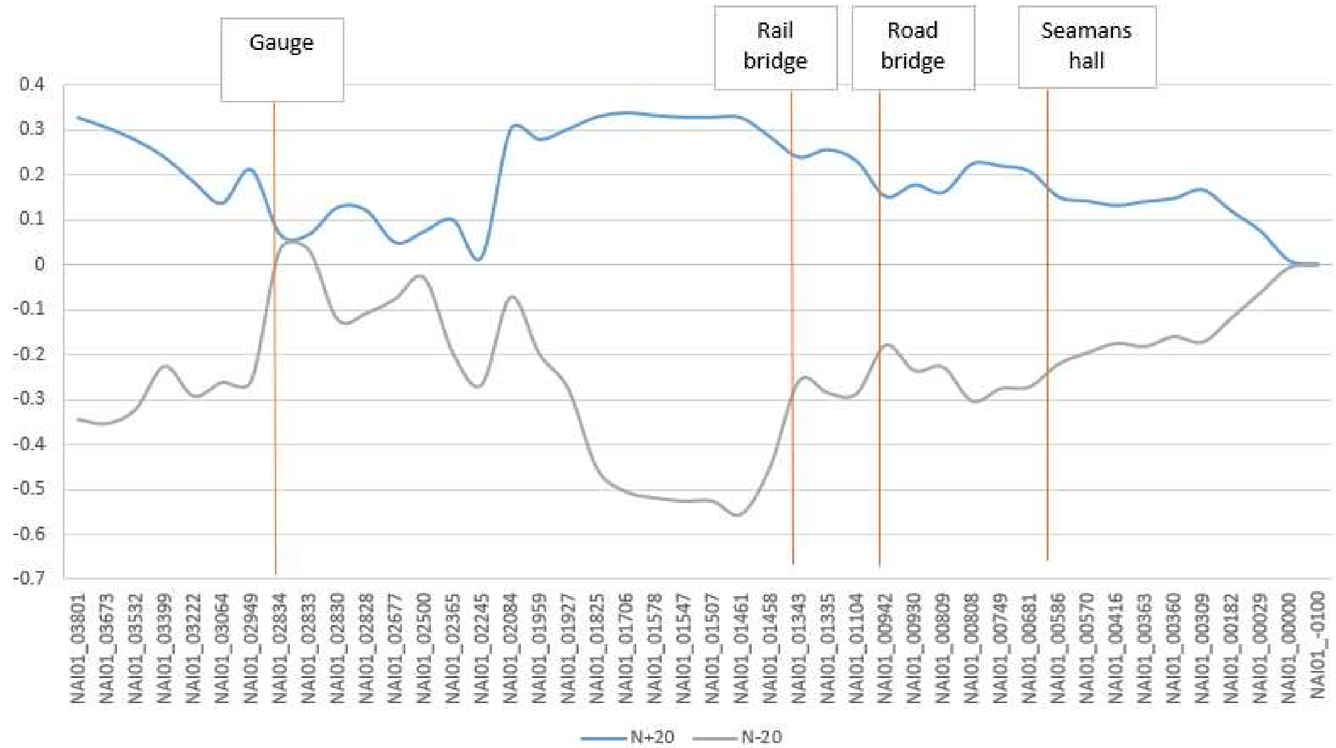

Figure 5-24: Comparison between roughness and baseline scenario, 200-year fluvial event (relative difference in water level, m)

The longitudinal section below shows the 200-year Defended scenario (red) and Bridge Blockage scenario (purple, blockage included at NAI01_00809) along the River Nairn. The DN scenario is very similar to the Defended scenario for this event, so has been omitted for clarity. The water level difference at NAI01_00809 between the Bridge Blockage scenario and baseline is +0.41m.

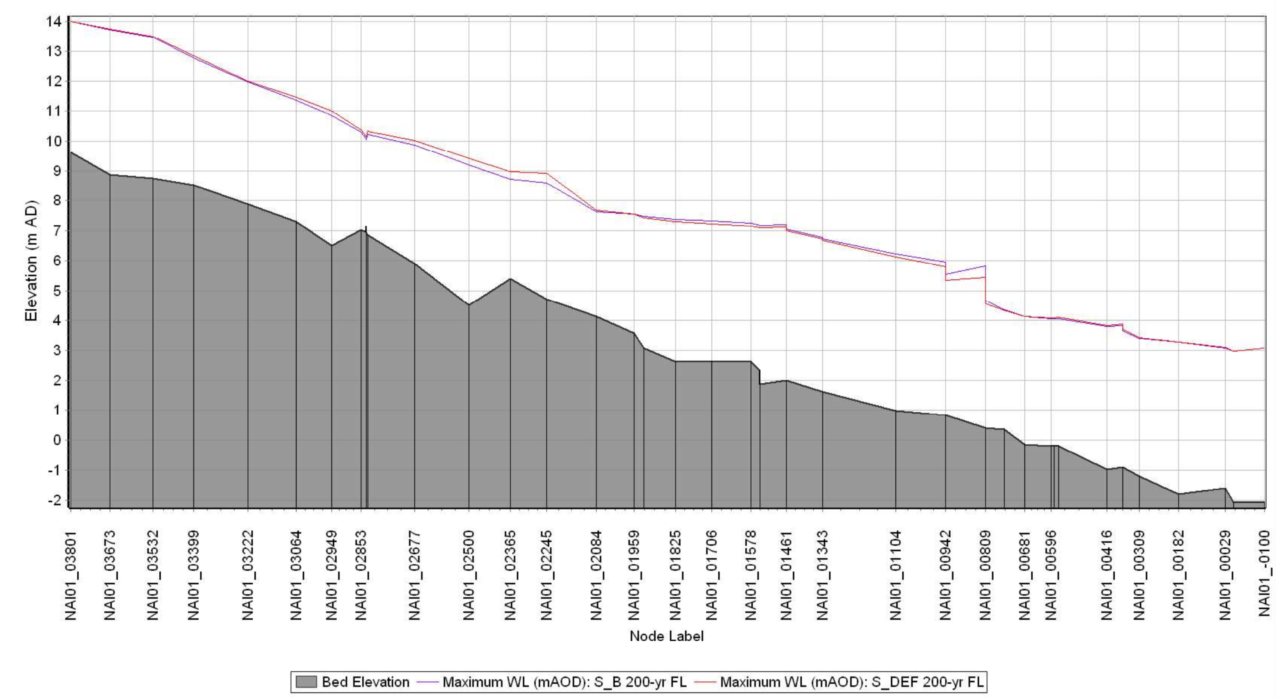

Figure 5-25: Comparison between defended(red) and bridge blockage scenario (purple), 200-year fluvial event

Auldearn Burn

The longitudinal section below shows the 200-year baseline (blue), Defended scenario (red), Bridge Blockage scenario (purple) and N-20 roughness (green) scenarios along the Auldearn Burn. The N+20 outputs are not shown in this figure as they were represented in the 2D domain only. These 2D outputs (for the N+20 test) show that water level at the channel location upstream of the A939 road (AUL01_00327) is approximately 7.51 mAOD, and downstream of the road, 7.43 mAOD, an increase of approximately 0.20 m and 0.13 m respectively above the baseline.

For the S_B scenario, the culvert downstream of AUL01_00520 was blocked by 83% (compared to 50% in the baseline run) and this has raised water level by +0.06m at the culvert outlet (CUL_00518). It is noted that the defended scenario water levels are slightly lower than the baseline along the Auldearn, this is thought to be due to less water from the River Nairn reaching the Auldearn Burn due to the presence of the informal embankment. There is a considerable difference between the N-20 and baseline (DN) run, about -0.5 m difference downstream of the culvert at Granny Barbours road (AUL01_00520) and -0.3 m difference upstream of the culvert.

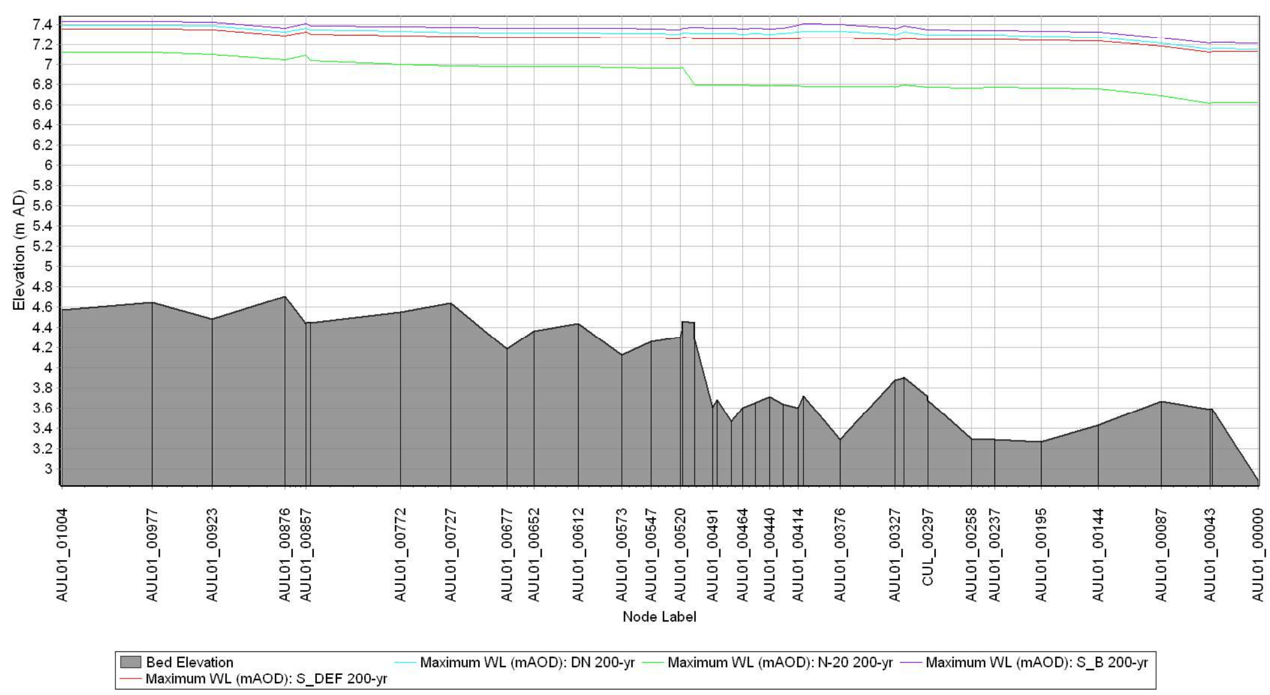

Figure 5-26: Comparison between sensitivity tests along Auldearn Burn (200-year)

5.6 Climate change runs

As described in section 2.8, two climate change scenarios have been run for the 200-year and 1000-year events. The 200-year climate change scenario 1 and 1000-year climate change scenario 1 has been included in the sensitivity testing (see Appendix E), however this section focuses on the Climate Change Do Nothing (baseline) outputs. As described in section 4.8, the climate change results grid outputs have been created from the maximum outputs from three separate runs, the Fluvial (Nairn), Fluvial (Auldearn) and Coastal runs.

The 1000-year climate change scenario 2 is the largest flood extent output, this was used to derive the largest extent for undertaking property counts. Figure 5-27 shows the longitudinal section from this event compared to the 200-year event for the fluvially dominated flood flows on the Nairn) Although there is significant backwater effect at the road bridge (NAI01_00942), overtopping does not occur (the road bridge deck is at approximately 8.76 mAOD to 9.55 mAOD, at the channel location). Figure 5-28 shows the same flood events but for the tidally dominated flood event.

Figure 5-29 and Figure 5-30 show the 1000-year flood event for climate change scenario 1 and 2 respectively. They have been coloured coded based the flood source giving the highest level. In climate change scenario 1 fluvial flooding results in the highest flood levels, whereas in climate change scenario 2 tidal flooding gives the highest flood levels up to the Merryton footbridge.

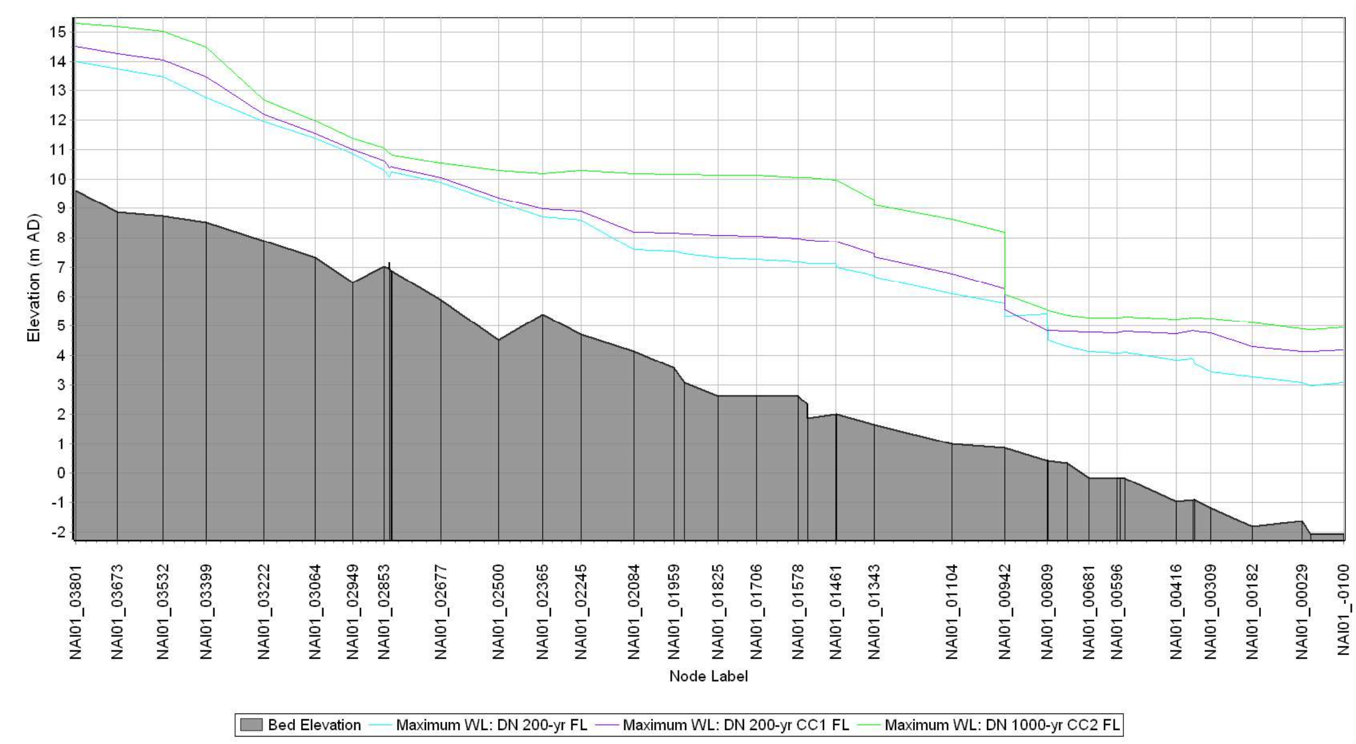

Figure 5-27: Longitudinal section from the 1000-year CC2 Fluvial event (green) and 200-year CC1 Fluvial event (purple) compared to the 200-year Fluvial event (blue). Note bridge at chainage 809 removed for climate change runs.

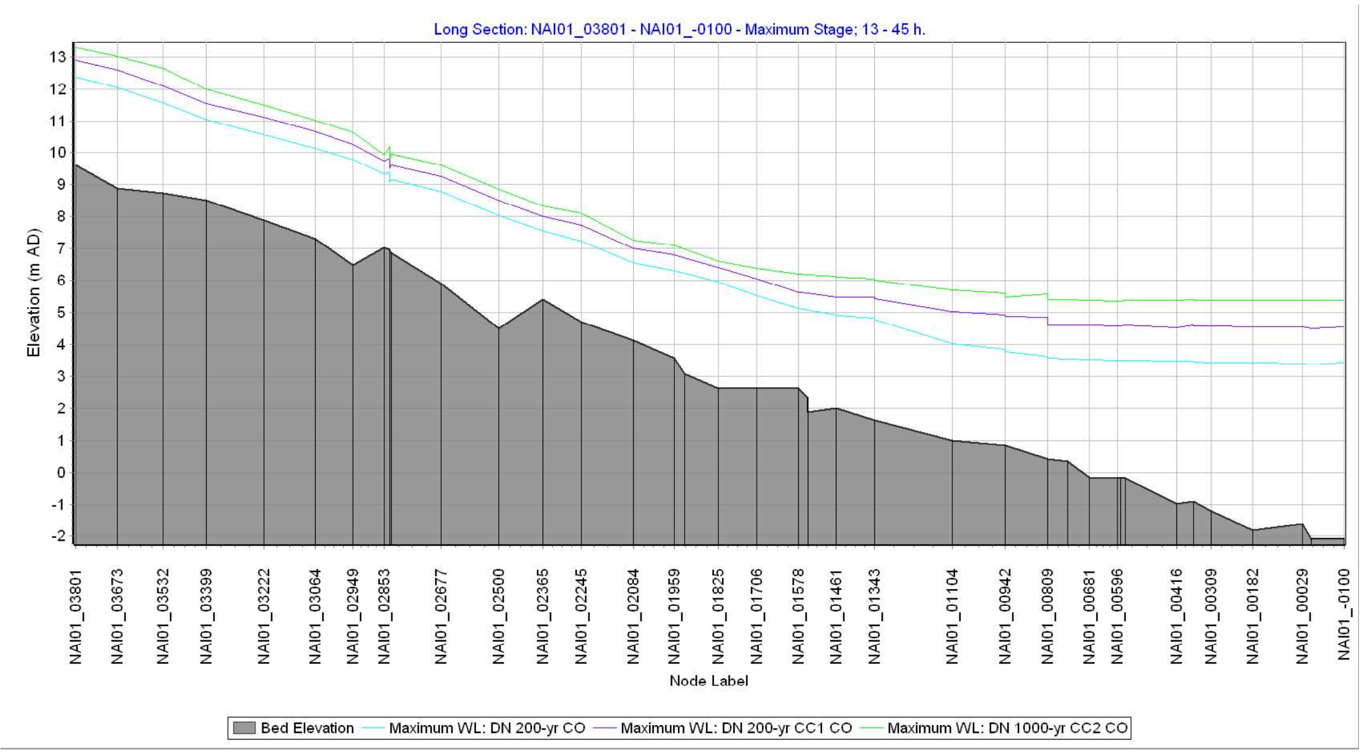

Figure 5-28: Longitudinal section from the 1000-year CC2 (green) and 200-year CC1 (purple) compared to the 200-year event (blue), for the tidal events.

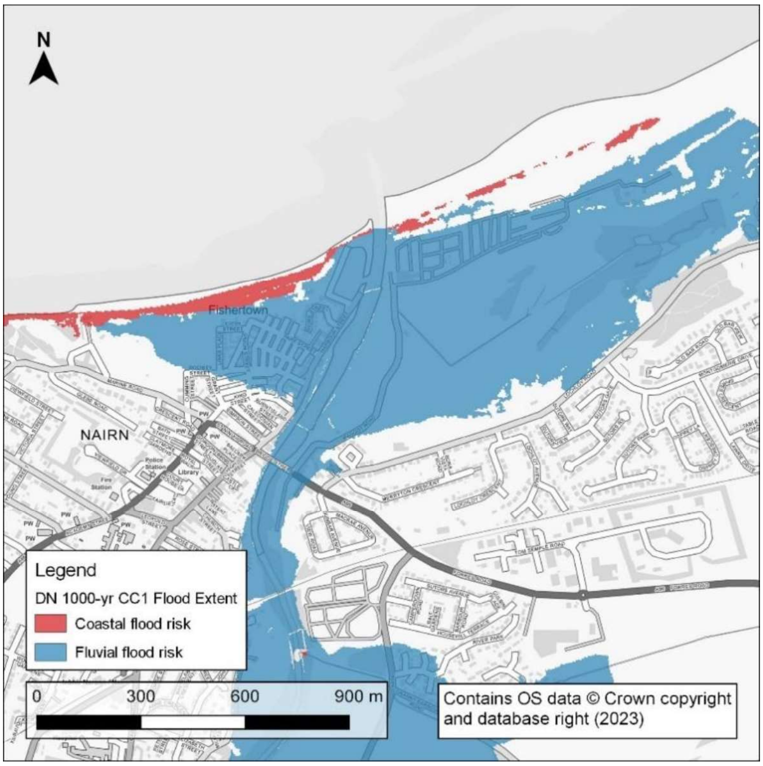

Figure 5-29: 1000-year climate change scenario 1 and DN 200-year

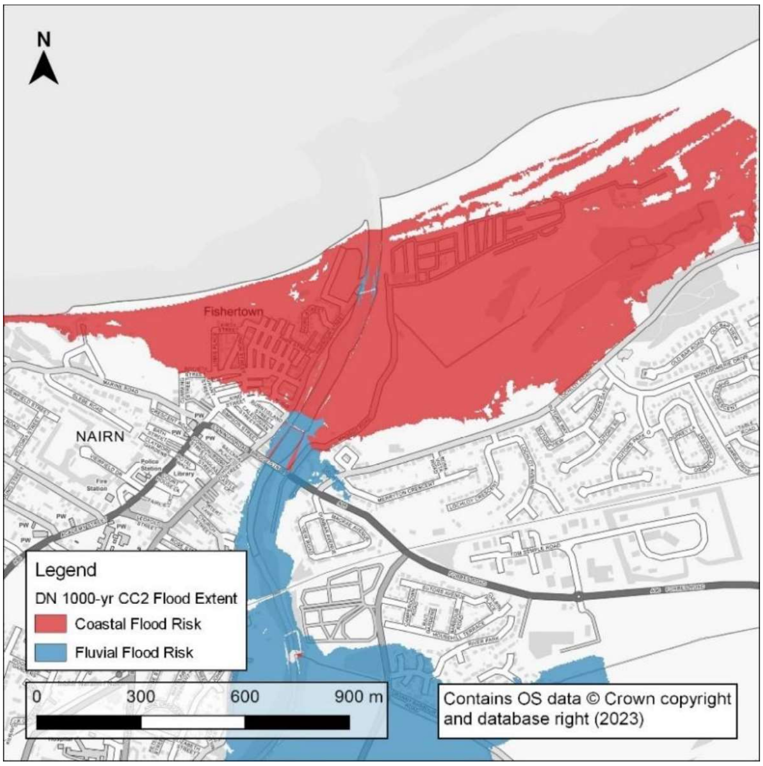

Figure 5-30: 1000-year climate change scenario 2 and DN 200-year

5.6.1 Impact of climate change at key locations

Figure 5-31 to Figure 5-33 shows the flood extent from the 1000-year climate change scenario 2 event compared to the baseline 200-year event, where considerable difference in extents were evident. In Fishertown the properties on Marine Road near the Strathnairn beach café, the links car park and streets south of Society Street (such as Grant Street, Union Street and King Street) all become engulfed by the increased flood extent.

Along the right bank, downstream of the A96, the entire caravan park, golf course and many properties at Merryton Crescent, The Orchard and Lochloy Road and Riverside Crescent are overlain by the flood extent (location shown in Figure 5-2). As are properties at Church Street, Church Road, Mill Road as well as the entirety of Alder Bank.

In the vicinity of the Auldearn Burn, the flood extent at Balmakeith Park and River Park also increase. However, at Househill and the surrounding agricultural fields, the model extents are relatively similar. It is noted that the suburb of Firhall is outside of the climate change flood extents.

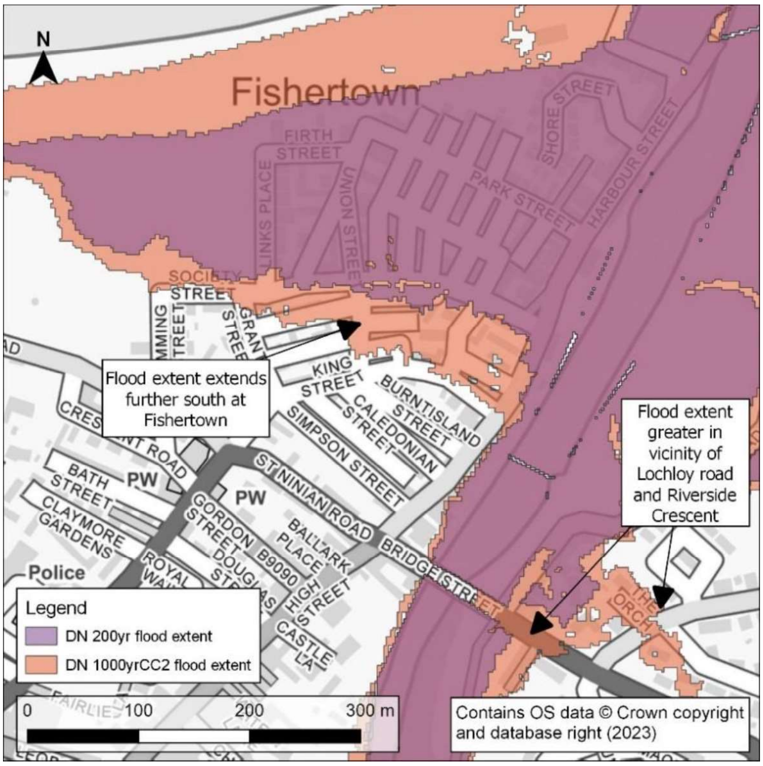

Figure 5-31: Comparison between the 1000 year climate change scenario 2 event and 200-year event at Fishertown

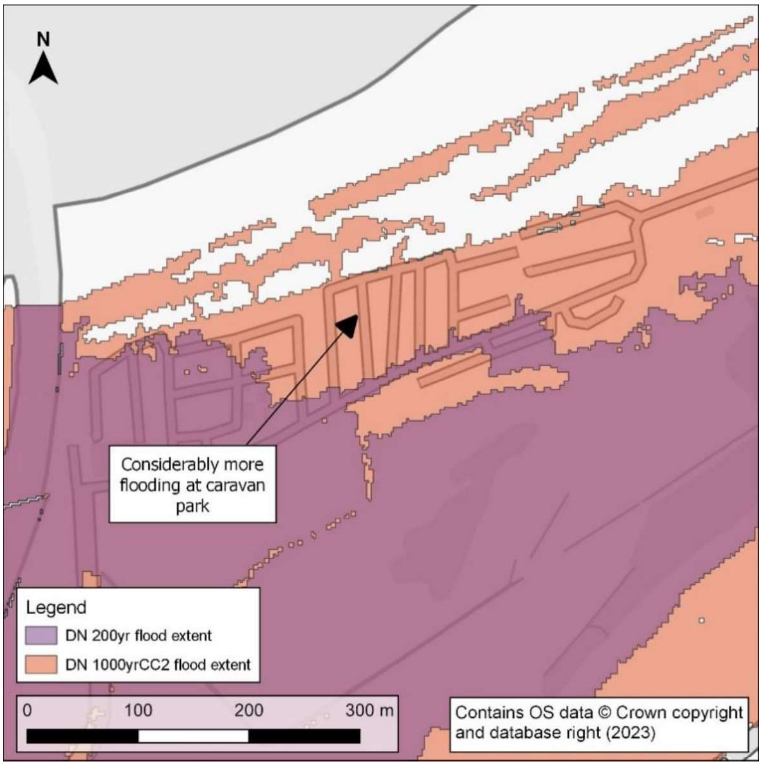

Figure 5-32: Comparison between the flood extent from the climate change scenario 2 event and 200-year event at the Caravan Park.

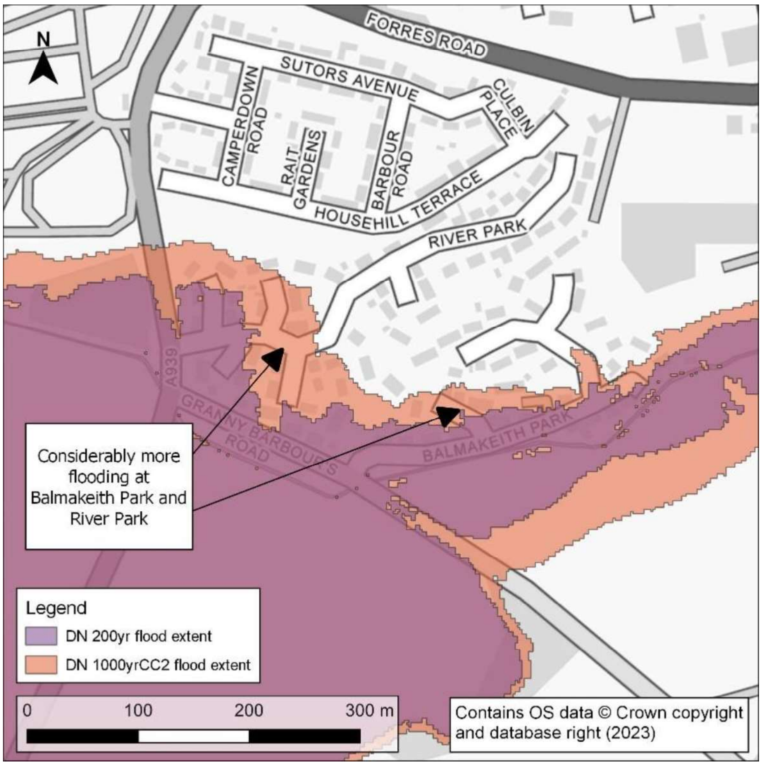

Figure 5-33: Comparison between the flood extent from the climate change scenario 2 event and 200-year event at Balmakeith Park.

6 Damage assessment

6.1 Introduction

A damage assessment, based on best practice guidance[42], has been undertaken to estimate the damage associated with fluvial and tidal flood damage. The higher the damages the higher the benefits of a potential flood defence scheme would be. This chapter describes the datasets and the methodology used and presents the damage results.

6.2 Flood damage methodology

Flood Hazard Research Centre's (FHRC) Multi-Coloured Manual[43] (MCM) provides standard flood depth/direct damage datasets for a range of property types, both residential and commercial. This standard depth/damage data for direct and indirect damages has been utilised in this study to assess the potential damages that could occur under for each flood event. Flood depths within each property have been calculated from the hydraulic modelling by comparing predicted water levels at each property to the surveyed or estimated threshold levels.

Flood damage assessment can include direct, indirect, tangible and intangible impacts of flooding. Direct damages to property are the most significant in monetary terms.

The following flood damages have been appraised for this study:

Direct Damages – to residential, commercial and industrial properties. This includes base damages to building fabric, inventory and clean-up costs, as well as vehicle damages.

Indirect damages – this accounts for costs incurred by the emergency services, temporary accommodation/evacuation costs and mental health impacts. A cost factor is also applied for non-residential properties associated with the cost of responding to the threat of disruption.

The flood damage associated with each of the flood events was determined. The return periods used in this assessment are the 5-year, 10-year, 30-year, 100-year, 200-year and 1000-year events. Based on the probability of each event the event damages were converted into an average annual damages (AAD) for each property. Treasury discount rates as recommended by the Green Book, have been used to convert damage occurring over the life of the appraisal period to present value (PV) damages using discounting rates. Damages are discounted at 3.5% for the first 30

42 Scottish Government 'Flood protection schemes - assessment of economic, environmental and social impacts: guidance'. Available at: https://www.gov.scot/publications/flood-risk-management-scotland-act-2009-flood-protection-schemes-guidance/pages/5/ (accessed April 2023)

43 The benefits of flood and coastal risk management: A Manual of Assessment Techniques – 2013 edition

years, 3% for years 31 to 75 and 2.5% thereafter, giving a present value factor of 29.813.

The following assumptions presented in Table 6-1 were used to generate direct flood damage estimates.

Table 6-1: Damage assessment assumptions and justifications

Aspect	Values used	Justification
Flood duration	<12hrs	Flood water is not anticipated to inundate properties for prolonged periods
Residential property type	MCM codes broken down by property type with the addition of caravans	Appropriate for this level of analysis.
Non-residential property type	Standard 2022 MCM codes applied	Best available date used
Upper floor flats	Upper floor flats have been removed from the flood damage estimates	Whilst homeowners may be affected it is assumed that no direct flood damages are applicable
MCM damage type	MCM 2022 fluvial depth damages for combined fluvial tidal scenario.	Best available date used
Threshold level	Thresholds surveyed by surveyor for the majority of properties in area of interest. Properties not surveyed are given the nearest surveyed threshold level or surveyed manually using Google Streetview	Best available date used. Some properties without surveyed threshold level require threshold analysis using Google Streetview if an accurate threshold cannot be obtained from the original survey.

Aspect	Values used	Justification
Sub-floor level damages	Sub-floor level damages are included in the damage calculations to account for water intrusion though air vents etc.	Site survey identified a number of properties with air vents
Property areas	SEPA's property dataset supplied majority of property areas. Satellite data has been used in some instances to estimate building area where area data was not available or inaccurate	Best available date used
Residential capping value	Residential properties based on Registers of Scotland Quarterly House Price Statistics for different property types in quarter 4 of 2022 for the Highland Council area.	Best available date used
Static caravan capping value	Caravans capped at half their value as per Scottish Government guidelines for damages to static caravans. Average value of £86,145 taken from information provided by Parkdean resorts	Best available data used
Non-residential capping value	Non-residential property values calculated using MCM guidance. No regional	Best available date used. Some Non-residential properties, such as electrical

Aspect	Values used	Justification
	MCM data available or Scotland, so North East England rateable values used along with prime yield multipliers for each industry type. These factors are multiplied by the area to estimate NRP market value	substations are not capped to reflect the impact of disruption from damages to these properties

6.3 Appraisal period

A 100-year appraisal period has been used in the damage calculations. A 100-year appraisal aligns with guidance from the Environment Agency's Flood and Coastal Erosion Risk Management Appraisal Guidance[44] (FCERM-AG). A long term appraisal period of 100 years is assumed as this aligns with current guidance and represents the long term benefits that would be gained from a future scheme in the town. This may need to be reviewed as the scheme develops and at the next stage of analysis.

6.4 Multiple sources of flooding

Both fluvial and tidal flooding damages are included in this assessment. Where there is an overlap of the flood extents the maximum flood depth for each property was applied. The fluvial depth damage MCM curve without warning has been used to estimate damages for the combined sources of flooding.

6.5 Property data set

The property dataset was compiled for all residential and commercial properties. This was informed by SEPA's property dataset. The property dataset provides information on property type, coordinates, area, MCM code and floor level used in the damage calculations. The property dataset was manually reviewed to assess any incorrect or out of date data. Where this was found, the data was updated to reflect the most recent available information. The manual review was undertaking using a combination of Google Streetview, satellite data and web searches.

In total, 489 residential and 65 non-residential properties were identified as being at risk for the 1 in 1000-year flood event.

44 Flood and Coastal Erosion Risk Management Appraisal Guidance (Environment Agency, March 2010)

Property threshold and ground levels were surveyed for a number of properties in the assessment area. These are given in mAOD, showing the height of the survey point relative to sea level. This survey data was then used to estimate the height of the threshold above ground level for the properties at risk.

35 threshold levels and 31 ground levels were recorded in the survey. Each of the threshold levels has an associated ground level. From this the height of the threshold above ground level can be found. Properties are assigned a threshold level according to the nearest average threshold survey points (in many cases it was based on a single survey point). The application of these threshold heights to groups of properties are shown in Figure 3-6. Where a property does not have a nearby surveyed point, the threshold levels have been estimated from observed threshold levels using Google Streetview or have been assigned an assumed 300mm height above ground level.

In addition to the residential and non-residential properties included in the property dataset, the Parkdean Nairn Lochloy Holiday Park is included in the damage calculations for this assessment due to the site's risk of flooding over the return periods. The property dataset records one non-residential retail property at the site. 280 static caravans at the site not recorded in the property dataset were spatially recorded using satellite imagery and mapped along with the other properties in the flood depth damage calculations for each return period. Threshold and ground levels for a sample of these caravans were provided in the threshold survey.

It is assumed that due to the scale and size of the caravan park in question that relocation prior to flooding is not possible. It is also assumed that if the threshold level of the caravan is breached then the value of the caravan is written off.

As per Scottish Government guidance on the assessment of flood protection schemes[45], caravans are considered depreciating assets and are valued in the damage calculations as being half of their replacement costs.

6.6 Capping

The FHRC and appraisal guidance suggests that care should be exercised for properties with high total (Present Value) damages which might exceed the market value of the property. In most cases it is prudent to assume that the long-term economic losses cannot exceed the capital value of the property. The present value flood damages for each property were capped at the market value using average property values obtained from Registers of Scotland Quarterly House Price Statistics for the Highland Council Area[46]. These house prices are broken down by detached,

45 Scottish Government 'Flood protection schemes - assessment of economic, environmental and social impacts: guidance'. Available at: https://www.gov.scot/publications/flood-risk-management-scotland-act-2009-flood-protection-schemes-guidance/pages/5/ (accessed April 2023)

46 Registers of Scotland Quarterly House Price Statistics. Available at: https://www.ros.gov.uk/data-and-statistics/house-price-statistics (accessed April 2023)

semi-detached, terrace and flat property types. These property types can be determined for properties at risk in this assessment using MCM codes provided by the property dataset. An overview of the Highland Council Area house price statistics is shown in Table 6-2.

Table 6-2: Mean residential property market value for Highland Council Area (Q3 2022)

Property Type	MCM Code	Value (£)
Detached	11	317,705
Semi-detached	12	186,841
Terrace	13	157,331
Flat	15	151,848
All house types		229,402

Market values for non-residential properties were estimated from a properties rateable value per metre squared of floor space and the prime yield multiplier, informed from the MCM Table 5.4 and Table 3.4 respectively. The MCM does not supply rateable value and equivalent yield figures for Scotland. Instead, the rateable values for the North-East of England are used as they are determined to be the most equivalent to figures for Scotland. Prime yield values are given for certain categories of non-residential properties, and associated multipliers are calculated by dividing 100 by the prime yield percentage. A non-residential property market value per metre square can be calculated by multiplying the mean rateable value per m^2 by the prime yield multiplier. These values are shown for retail, offices, industrial and other non-residential properties in Table 6-3. The 'Other' value, which is applied to non-residential properties that do not have an associated property type in the prime yield Table 3.4 of the MCM, is calculated by taking an average of the values for every property type.

Table 6-3: Non-residential property mean rateable value per m2 of floor space, prime yield, multiplier and market value per m2

NRP type	Mean rateable value per m2	Prime yield (%)	Multiplier (100/prime yield)	Market value per m2 (£)
Retail	150.07	6.5	15.38	2,308
Offices	99.65	4.75	21.05	2,097
Industrial	29.31	3.25	31.06	901
Other	50.41	4.89	20.45	1030

The non-residential property market value was based on the following equation:

Capital Valuation = (100/Prime Yield) x Rateable Value x Area

6.7 Updating of Damage Values

The MCM data used is based on April 2022 values and therefore do not need to be brought up to date to compare the costs and benefits. Given the current inflationary environment, it may be worth uplifting the damage values in due course or for follow-on scheme appraisal.

6.8 Property Counts

A breakdown of the cumulative number of residential and non-residential properties which are flooded above the property threshold (i.e. ground floor level) in the Do Nothing option is presented in Table 6-4 at each return period in the present day. Table 6-5 shows the number of (cumulative) residential and non-residential properties impacted by flooding when property threshold levels are not taken into account. This was included due to the uncertainty around some of the threshold levels that were not surveyed. It shows that the property count is very sensitive to threshold levels, at the 1 in 30 year event the number of properties affected more than doubles. Many of these are thought to be from the Fishertown and Househill area.

Table 6-4: Cumulative number of properties flooded above threshold level in each return period

	5year	10year	30year	100year	200year	1000year
Residential properties	0	0	44	182	253	489
Non-residential properties	0	0	8	29	41	65
Total	0	0	52	211	294	554

Table 6-5: Cumulative number of properties flooded with no threshold level in each return period

	5year	10year	30year	100year	200year	1000year
Residential properties	9	18	93	264	372	584
Non-residential properties	0	0	20	45	57	70
Total	9	18	113	309	429	654

Table 6-6: Cumulative number of properties flooded above threshold level in each return period for the Fishertown, Househill and Auldearn Burn areas

	5year	10year	30year	100year	200year	1000year
Fishertown						
Residential properties	0	0	37	157	213	241
Non-residential properties	0	0	5	21	30	32
Househill						
Residential properties	0	0	4	16	19	26
Non-residential properties	0	0	2	5	5	12
Auldearn Burn						
Residential properties	0	0	0	0	7	31
Non-residential properties	0	0	0	0	2	10

Table 6-7: Cumulative number of properties flooded with no threshold level in each return period for the Fishertown, Househill and Auldearn Burn areas

	5year	10year	30year	100year	200year	1000year
Fishertown						
Residential properties	7	10	64	181	219	243
Non-residential properties	0	3	7	22	31	36
Househill						
Residential properties	0	0	15	24	24	28
Non-residential properties	0	0	5	8	9	12
Auldearn Burn						
Residential properties	0	0	10	11	22	40
Non-residential properties	0	0	3	3	4	10

6.9 Direct damages to residential and non-residential properties

The calculated direct property damages at each return period and a summary of the annual average property damages and uncapped and capped Present Value flood damages (PVd) to property for the 'Do Nothing' scenario are presented in Table 6-8 and Table 6-9. The split of flood damages between residential and non-residential properties is provided. PVd are the cumulative discounted flood damages over the 100-year appraisal period.

Property damage is first recorded at the 10-year return period. Despite the fact that no properties have their recorded threshold level breached, as shown in Table 6-4, damages are still incurred from sub-floor level damages.

No single property accounts for over 3% of the total property damages, indicating that the damages are relatively spread out across the area so that there is no key beneficiary. Early return period flooding largely impacts properties in the Fishertown and Househill areas. Significant damages are observed in these areas beginning at the 30-year period. In the 1000-year return period the majority of the properties within both these areas are impacted by flood damages. Properties along the Auldearn Burn are also impacted at the later return periods, with the majority of properties directly alongside the burn impacted at the 100-year. It should be noted that the impacts of climate change will increase the frequency and extent of flooding in the area, however this has not been considered in the calculations.

Table 6-8: Direct property damages at each return period (£k)

Property type	5year	10year	30year	100year	200year	1000year
Residential properties	0	33	1,018	5,861	9,547	23,446
Non-residential properties	0	0	82	465	1,183	3,674
Total	0	33	1,100	6,326	10,730	27,119

Table 6-9: Average annual property damage and Present Value property damage (£k)

Property type	AAD (£k)	PVd (£k)	Capped PVd (£k)
Residential	246	7,353	7,333
Non-residential	27	803	803
Total	273	8,156	8,136

6.10 Direct damages to vehicles

Vehicle damages are calculated using MCM (2022) guidance. This guidance recommends that the average loss associated with vehicle damages during flood events should be determined using a value of £6,944 assigned to residential properties at risk above 0.39m. This is applied to all residential properties (above threshold level) for each return period to find the AAD which is converted to Present Value damage (PVd) using the normal discounting process. The present value vehicle damages are shown for each return period in Table 6-10.

Table 6-10: Vehicle damages (£k)

	30year	100year	200year	1000year	AAD	PVd
Vehicle damages	0	597	1,062	2,923	22	663

6.11 Total direct damages

Total direct damages to residential properties, non-residential properties and vehicles are shown in Table 6-11.

Table 6-11: Total direct damages (£k)

	5yr	10yr	30yr	100yr	200yr	1000yr	AAD	PVd
Residential	0	33	1,018	5,861	9,547	23,446	247	7,353
Non-residential	0	0	82	465	1,183	3,674	27	803
Vehicle	0	0	0	597	1,062	2,923	22	663
Total	0	33	1,100	6,923	11,792	30,034	296	8,819

6.12 Indirect damages

A number of indirect damages are typically included within damage assessments. Whilst some are only appropriate at the most detailed level of assessment, JBA have adapted our spreadsheet analysis tools to allow appropriate common methods to be incorporated. These include:

- Evacuation and temporary accommodation costs
- Indirect commercial damages
- Mental health damages
- Emergency service costs

6.12.1 Evacuation and temporary accommodation costs

The MCM provides guidance on the losses associated with evacuation (getting people safely out of homes during an event and temporary accommodation costs whilst properties are repaired). Costs recommended are based on flood depths and property type as shown in Table 6-12. Total property counts per return period for each depth classification have been extracted and used to total evacuation losses based on the 'Mid' values in Table 6-12 (MCM 2022 data).

Table 6-12: MCM recommended evacuation costs by property type

MAXIMUM DEPTH INSIDE PROPERTY (CM)	EVACUATION COSTS BY PROPERTY TYPE (£)											
	DETACHED			SEMI-DETACHED			TERRACED			FLAT		
	Low	Mid	High	Low	Mid	High	Low	Mid	High	Low	Mid	High
0-1	681	1,007	1,631	609	865	1,419	588	838	1,387	532	782	1,330
1-10	1,308	1,928	3,126	1,169	1,653	2,714	1,126	1,600	2,652	1,018	1,491	2,540
10-20	2,511	3,662	5,954	2,232	3,108	5,126	2,146	3,002	5,001	1,928	2,781	4,776
20-30	2,694	3,928	6,387	2,394	3,334	5,499	2,302	3,221	5,364	2,069	2,984	5,123
30-60	3,625	5,269	8,575	3,216	4,458	7,363	3,090	4,303	7,179	2,772	3,980	6,850
60-100	4,342	6,299	10,256	3,848	5,320	8,793	3,696	5,134	8,572	3,312	4,744	8,175
100+	6,965	10,045	16,383	6,154	8,438	13,981	5,905	8,132	13,617	5,275	7,491	12,965

Total indirect evacuation costs calculated using this information are shown in Table 6-13

Table 6-13: Evacuation costs (£k)

	5yr	10yr	30yr	100yr	200yr	1000yr	AAD	PVd
Evacuation costs	0	0	104	718	1,199	1,892	26	775

6.12.2 Indirect commercial damages

Indirect losses to commercial properties consist of loss of business to overseas competitors, the disruption to business which impacts firms when flooded and the additional costs of responding to the threat of disruption. Chapter 5, Section 5.7 of the MCM recommends estimating and including potential indirect costs where these are the additional costs associated with trying to minimise indirect losses. This is assessed by calculating total indirect losses as an uplift factor of 3% of estimated total direct NRP losses at each return period included within the damage estimation process. The total indirect commercial damages are shown in Table 6-14.

Table 6-14: Indirect commercial damages (£k)

	5yr	10yr	30yr	100yr	200yr	1000yr	AAD	PVd
Evacuation costs	0	0	2	14	35	110	0.81	24

6.12.3 Mental health damages

Mental health costs associated with flooding are included in this assessment. Mental health impacts of flooding are calculated using EA guidance. Mental health losses per adult per flood event are provided for flood depths between 0-30cm, 30-100cm and more than 100cm. For each property for each flood event mental health costs per property per flood is equal to the loss per adult per flood multiplied by the number of adults per property. The number of adults in each property is estimated using averages for different residential property types provided by the MCM. Property types are identified in the damage calculations using the associated MCM code. Total mental health damages are shown in Table 6-15.

Table 6-15: Mental health damages (£k)

	5yr	10yr	30yr	100yr	200yr	1000yr	AAD	PVd
Mental health damages	0	0	212	1,103	1,754	4,008	83	2,466

6.12.4 Emergency service costs

The MCM provides guidance on the assessment of indirect damages for emergency services and other third-party costs. It recommends that a value between 5.6% and 10.7% of the direct property damages is used to represent emergency service costs. These include the response and recovery costs incurred by organisations such as the emergency services, the local authority and SEPA. The lower value of 5.6% value has been used for the purposes of this assessment as the properties affected are located close together and relatively easy to access. Total emergency service costs are shown in Table 6-16.

Table 6-16: Emergency service costs (£k)

	5yr	10yr	30yr	100yr	200yr	1000yr	AAD	PVd
Evacuation costs	0	2	57	328	535	1,313	13.8	24

6.13 Total indirect damages

Total indirect damages consisting of evacuation and temporary accommodation costs, indirect commercial damages, mental health damages and emergency service costs are shown in Table 6-17.

Table 6-17: Total indirect damages (£k)

	5yr	10yr	30yr	100yr	200yr	1000yr	AAD	PVd
Evacuation and temporary accommodation	0	0	104	718	1,199	1,892	26	775
Indirect commercial	0	0	2	14	35	110	1	24
Mental health	0	0	212	1,103	1,754	4,008	83	2,466
Emergency service	0	2	57	328	535	1,313	14	751
Total	0	2	375	2,164	3,523	7,323	124	4,016

6.14 Damage summary

Table 6-18 provides an overview of the total Present Value flood damages for Nairn. The total capped flood damages are £12,815,000. A more comprehensive breakdown of the damages, along with the associated depth damage curve can be found in Appendix B.

Table 6-18: Present value damage summary

	PVd (£k)	PVd (£k) (capped)
Residential property	7,353	7,333
Non-residential property	803	803
Vehicle	663	663
Evacuation and temporary accommodation	775	775
Indirect commercial	24	24
Mental health	2,466	2,466
Emergency service	751	751
Total	12,835	12,815
AAD	382	382

7 Conclusion

A baseline fluvial and tidal flood appraisal study has been carried out for the town of Nairn. The assessment confirmed the 'at risk' areas identified by SEPA's Flood Risk Management Maps. A little less flooding is predicted for the 10-year event fluvial around the Auldearn and River Nairn confluence but slightly more flooding in the lower reach of the River Nairn. Compared to SEPA's Flood Risk Management Maps the modelled 200-year fluvial show much more extensive flooding to Fishertown and the lower reach, the flood extent at Househill appears similar. For the coastal comparison the 200-year event appears similar on the left bank but is much smaller on the right bank at the golf course. This assessment has refined the flood extent areas and flood depths and has combined the tidal and fluvial maps into a single output. This assessment predicts for the combined mapping that out of bank flooding begins at the 2-year event, with onset of flooding to Harbour Street (the first street to flood) from the 5-year event. The first property will be reached by flood water from the 5-year event and first property threshold will be exceeded from the 30-year event flood event. A significant jump in flood extent is seen at the 30-year event flood event where the number of properties flooded is estimated to be 52. At the 200-year event, 294 properties are at flood risk.

Flooding to Fishertown first emerges close to the Seamans Hall from the 5-year event before flowing north-west through Harbour Street and Park Street. The centre of Fishertown is approximately 0.4 metres lower than the point at which water first over tops the river bank and flows towards and then pools in Fishertown. The 200-year flood depth in Fishertown is up to 1.75m deep.

The flood defence benefit of the informal wall running parallel to Harbour Street was assessed and showed it significantly reduced the risk of flooding. The wall was tested without the application of freeboard. It showed it could hold back tidal flooding up to 200-year event (the dune system was assumed to be stable and impassable up to its crest level) and fluvial flooding up to 30-year event. An unmodelled estimate determined that the wall would almost be able to hold back the 100-year fluvial flood event (without freeboard). Flooding due to a back flow of water through the urban drainage network has not been considered, this could result in water effectively bypassing the wall.

Househill is affected from a large arching flow path beginning upstream of the gauge, with flooding first affecting properties from between the 10-year and 30-year event in the baseline scenario. The informal agricultural embankment has been shown to provide a flood defence benefit to the properties of Househill for the more frequent flood events, at least up to (and including) the 30-year event. The model showed that no properties would be affected by flooding during the 30-year event, but the flood extent does come close to some properties at the southern side of Househill, suggesting that flooding may occur at a flood event only slightly larger than the 30-year event (assuming the that the informal embankment does not breach).

The model results show that the properties along the Auldearn Burn first experience flooding at the 30-year event with water emerging from the right bank at Balmakeith Park. Flood depths do not breach the surveyed property thresholds in this area until the 200-year event, however, damages are recorded at the 30-year event due to the inclusion of sub-floor level damages (air bricks were noted on some properties during the site visit). It's noted that as no properties at Balmakeith park are shown to receive flooding from the 10-year event model results, but are shown to be affected from the 30-year event, the flooding to properties occurs between the 10-year and 30-year event. Out of bank flooding between the 10 year and 30 year is in keeping with observations on the modelled flood extents and photographs from an observed flood event on the Auldearn Burn (August 2014). During the Do Nothing scenario, the road at the Granny Barbour culvert is overtopped for a flow of 4.8 m^3/s and the culvert begins to surcharge from a flow of 1.6 m^3/s. At the A939 road, the flow when the culvert is surcharged is around 2.2 m^3/s and the capacity of the channel at the culvert location before the road is overtopped is approximately 3.5 m^3/s. Both culverts surcharge at the 2-year flood event on the Auldearn Burn and cause flood water levels to rise and back up the channel. However, for larger flood events this effect is drowned out by flooding from the River Nairn inundating the Auldearn Burn.

The model was tested to its sensitivity to blockage and roughness. The model is sensitive to both. Water level differences of +0.34 m and -0.56 m were noted in the 20% increase and decrease roughness test (in the vicinity of the confluence) and +0.41 m in the blockage increase (at bridge B_00809) respectively, regarding the 200-yr event.

The resulting damage from the Do Nothing Scenario is estimated to have a present value damage of £12.82, million. This is a large number and even if a proportion of this damage avoided could be realised then it is likely that a flood defence scheme would be viable. There are several properties close to the river Nairn that contribute to this damage, however, the majority of properties affected are from Fishertown and Househill. Any proposed flood scheme should first focus efforts to these two areas.

8 Recommendations

A damage assessment has been carried out for the town as a whole. For the purpose of defence optioneering, it would be useful to split the study areas into distinct areas so that the defence can be proportional to the level of damage anticipated.

Depending on the ambition of the flood defence options and the life of the scheme it would be useful to run climate change simulations for the design event. It would also be beneficial to carry out a damage assessment accounting for the impact of climate change, this would also align with the revised planning policy, NPF 4.

The modelling has been carried out to represent the worst case flood scenario, which has meant that the flood peaks of the River Nairn and the Auldearn Burn have been aligned. This has shown that the influence of the River Nairn on the Auldearn Burn is considerable. It may be beneficial to model the Auldearn Burn in isolation so that if it proves too costly to protect properties from the River Nairn, it may be possible to protect them from the Auldearn Burn.

The presence of the Firhall gauge provides the benefit of allowing for model calibration and estimation of the magnitudes of historic flood events. The rating at the Firhall gauge was compared to the modelled rating and as such, used to calibrate the model in the gauge's vicinity. The model results showed that the gauge, upon which the hydrology estimates were heavily dependent, is bypassed from the 30-year event. A rating review was outside the scope of this Flood Risk Appraisal however, further checks on the rating could be beneficial.

Dredging of the channel by the harbour has only been carried out twice in 20 years. Details on the timing, quantity and relocation of the material was not available. It has been assumed that the sediment in the channel at this location has returned to a state of equilibrium and that it is not artificially low. If this assumption is incorrect it could mean that the modelled flood risk in the lower reach is underestimated.

Now that the area of flood risk is better defined and it is known that the applied building threshold has a considerable impact on the number of properties affected, a targeted building threshold level could be undertaken to better inform property flood counts and damage. The damage assessment has been set up to facilitate a future update of threshold levels.