Ballater Flood Protection Study

Hydraulic Analysis Chapter

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Ballater Flood Protection Study - Hydraulic Analysis Chapter

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1 INTRODUCTION

1.1 BACKGROUND

Ballater is located within the Cairngorms National Park in West Aberdeenshire, Scotland. The River Dee, which is a Special Area of Conservation for salmon, trout, otters and freshwater pearl mussels, flows through Ballater. The confluences of the River Gairn and the River Muick with the Dee are located within the town (Figure 1.1).

The hydraulic analysis for the Ballater Flood Protection Study (FPS) focuses on the main source of flood risk from the River Dee and its two significant tributaries - the Rivers Gairn and Muick. The FPS is being undertaken as part of the current cycle of the Flood Risk Management Plan.

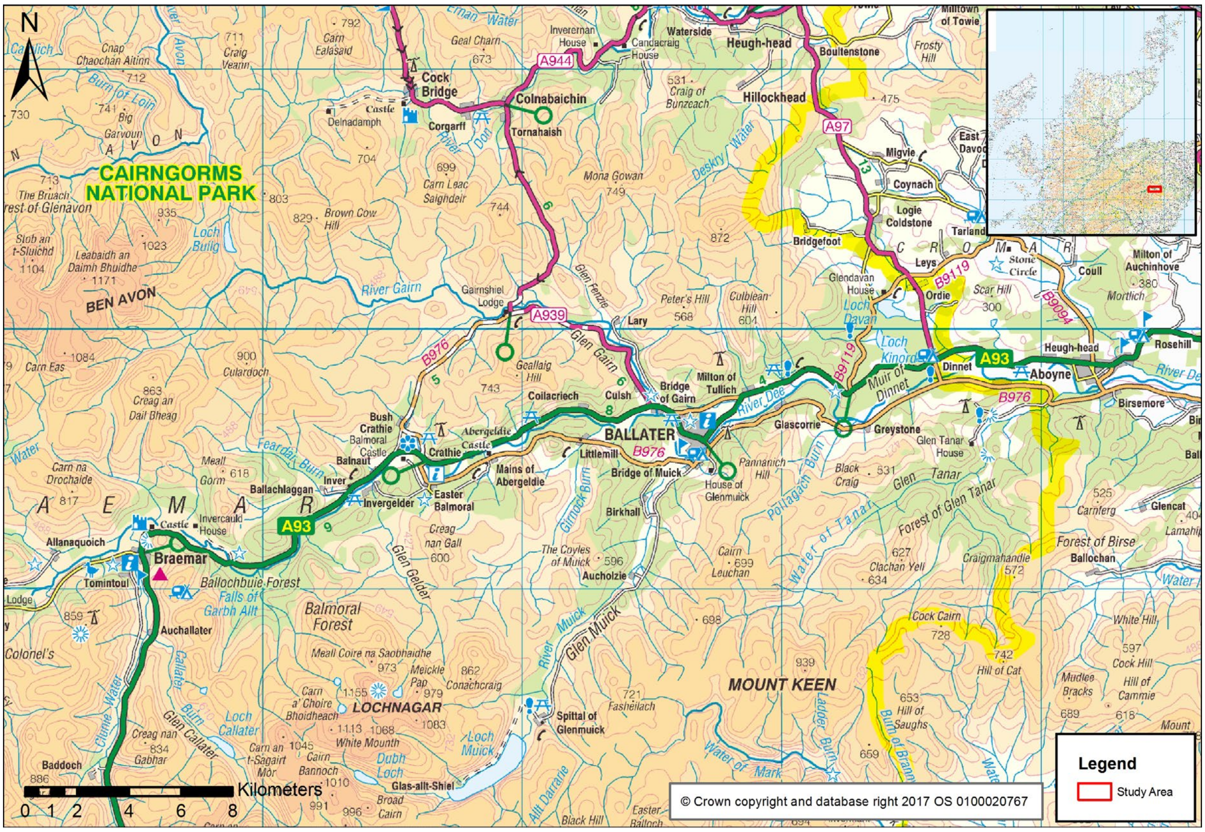


Figure 1.1 Location of Ballater, West Aberdeenshire

1.2 OBJECTIVES OF THE STUDY

The aims of the study are summarised below:

- Undertake a site visit and topographical surveys of the reach of the upper River Dee, including the associated tributaries the River Gairn and River Muick to understand the local flood flow pathways and flood history.
- Hydrological assessment to include and update of the hydrology for the three watercourses and incorporation of the available river gauges and completion of hydrological analysis to determine the design flows at Ballater. Also to derive inflows for 50%, 20%, 10%, 3.33%, 2%, 1%, 0.5%, 0.1%, 3.33% plus climate change and 0.5% plus climate change fluvial annual exceedance probabilities (AEP).
- Construct and deliver a new hydraulic model extending over all River reaches.
- Environmental considerations including completion of an environmental walk-over of the site, scoping of environmental impacts and completion of an environmental survey.
- Calibration of the Ballater model through simulation of at least three events and verify performance through simulation of at least one event. Likely events include: December 2015.
- Sensitivity analysis to be completed for the 0.5% AEP (1 in 200 year return period) event and/or the AEP closest to bank top level.
- Produce flood mapping for a number of design events with and without defences for 50%, 20%, 10%, 3.33%, 2%, 1%, 0.5%, 0.1%, 3.33% plus climate change and 0.5% plus climate change fluvial AEPs.
- Develop options to manage flood risk and provide recommendations for the most sustainable option.

The purpose of this report is to provide details on the hydraulic analysis and flood mapping, with details of the work undertaken to fulfil the other objectives located in separate reports.

2 DATA COLLECTION

2.1 HISTORIC FLOOD EVENTS

2.1.1 Overview

RPS has reviewed historic flood records related to fluvial flooding in the Ballater area. Sources of information on events include internet searches, community magazines and newspapers, consideration of the hydrometric data and a review of the Chronology of British Hydrological Events. A summary of the historic event records is shown in Table 2.1 with the location of the streets identified in Figure 2.1.

Table 2.1 - Summary of historic flood records in the Ballater Area

Date	Waterbody	Scale or Magnitude	Source
Aug 1829	River Dee	The Muckle Spate was a great flood in August 1829. The River Dee rose rapidly above its normal level; many bridges were washed away including the bridge at Ballater. The river was said to have risen one foot every ten minutes with flood depths of 5 feet 6 inches recorded.	Chronology of British Hydrological Events website, 'The great floods of August 1829' by Sir Thomas Dick Lauder.
1877	River Dee	Reports of cellars in the lower part of Ballater were flooded.	SEPA
1920	River Dee	Ballater town and roads infrastructure were flooded. Reports mention the main cause was heavy runoff from bare field's post clear felling. The flood of 1920 was also reported to have drove the river into its old course at Inch of Culter.	SEPA / The Ballater & Crathie Eagle, Winter 2014, Issue 76, Dee Catchment Partnership
Jan 1929	River Dee	Ballater town and roads infrastructure were flooded.	SEPA
1937	River Dee	The River Dee burst its bank and caused significant flooding.	Aberdeen Journals
1990	River Dee	Local reports are Deebank Road, Bridge Street Richmond Place and Braichlie Road were all badly flooded with water coming up through drains.	Aberdeenshire .gov.uk
Jan 1993	River Dee	Basement of Montaltrie Hotel, Deebank House and two houses on Anderson Road were flooded. Water was reported to be six feet deep on the golf course.	Deeside Piper
Aug 2014	River Dee	The caravan park was closed and 150 people were evacuated from the site as well as a number of roads being closed as a result of the River Dee Flooding.	Newspaper/ Youtube/ SEPA
30th Dec 2015	River Dee	Footage available on Youtube indicates the River Dee burst its banks – this caused flooding to over 300 residential and commercial properties resulting in 100 residents having to be evacuated and substantial damage occurring to the Cambus O'May Bridge, a section of the A93 between Ballater and Balmoral Castle as well as the police station. An article in The Telegraph stated that it was estimated to "be the highest river level on the Dee since 1928"	Newspaper/ Youtube/ SEPA

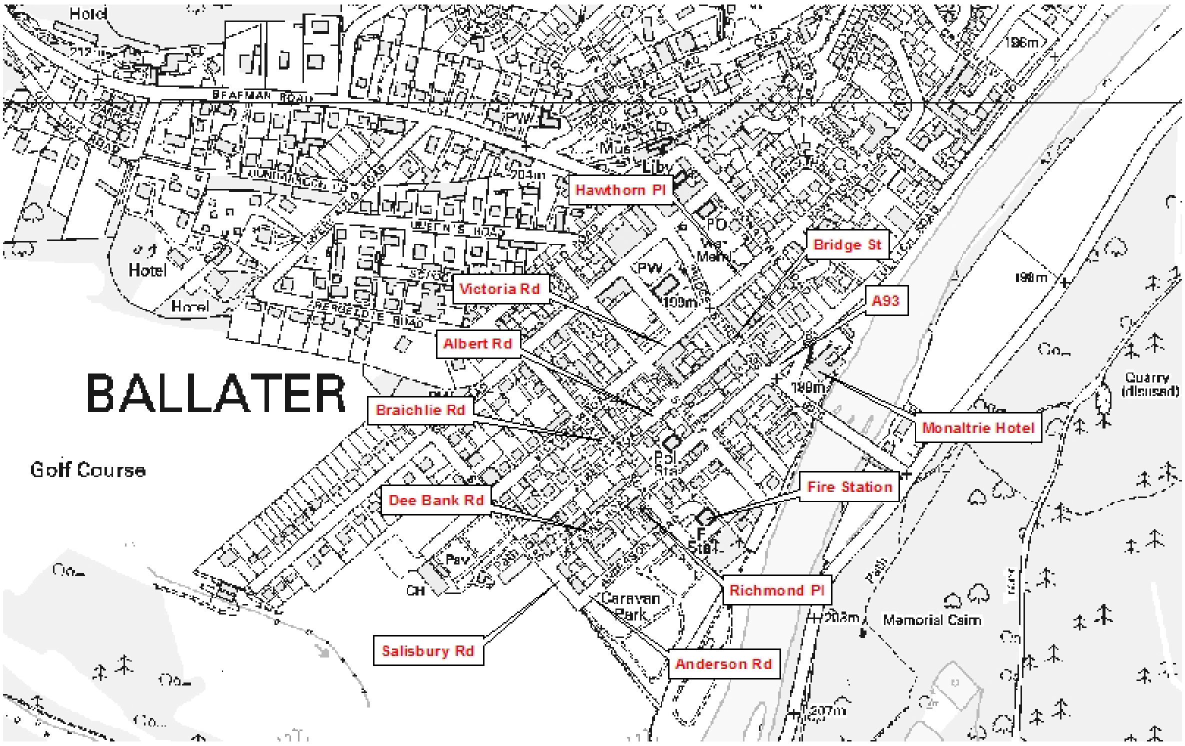


Figure 2.1 Street locations within Ballater.

2.1.2 19th and 20th Century Flood Events

Flooding occurred on the River Dee in 1829, known as the 'Muckle Spate' destroying the Ballater Bridge and in 1839, the bridge at Tullich was damaged. In 1877, cellars in the lower part of Ballater were flooded, and in 1920 and 1929 the town and roads were flooded. Local reports stated that in the late 1980s the bottom part of the village was badly flooded with water coming up through the drains. Deebank Road, Bridge Street Richmond Place, Braichlie Road were all affected during this event.

The River Dee burst its banks on 16th January 1993 when the basement of Montaltrie Hotel, Deebank House and two houses on Anderson Road were flooded. Newspaper reports (Deeside Piper) indicate that the depth of flood water on the golf course peaked at six feet during this flood event.

2.1.3 August 2014 Flood Event

During the 10th and 11th August 2014, the north-east of Scotland experienced unseasonably high winds and rain in the wake of ex-hurricane Bertha. Weather warnings, issued by the Met Office, and flood warnings, issued by SEPA, were in place across Aberdeenshire.

The River Dee achieved the second highest level on record at the Polhollick gauge on the Dee and the highest on record at the upper catchment gauging station at Mar Lodge and also at the Invergairn station on the Gairn, just upstream of Ballater. During this event the caravan park was evacuated and a number of roads were closed due to flooding from the River Dee, following hurricane Bertha. As a result, 150 people were evacuated from the caravan site. The flooding along the River Dee destroyed a bridge at Mar Lodge Estate and the A93 between Braemar and Ballater was closed because of flooding across the road.

Aberdeenshire Council provided photographs taken between 45 minutes and 1 hour and 15 minutes of the peak flow being recorded at the Polhollick gauging station (1:00 pm). Figure 2.2 to Figure 2.6 show the extent of flooding along Dee Street, at the caravan park and at the Fire Station.

Figure 2.2 Photo taken from Dee Bank Road (at 2:02 pm) showing flooding on Dee Street to the junction with Richmond Place on 11/08/14.

Figure 2.3 Photo taken (between 1:42pm and 2:16pm) from the upstream side of the Royal Bridge in Ballater on 11/08/14.

Figure 2.4 Photo taken along the pathway from Salisbury Road past the caravan park in Ballater at 12:03 pm on 11/08/14.

Figure 2.5 Photo taken from Fire Station looking across green area in Ballater at 12:08 pm on 11/08/14.

Figure 2.6 Photo taken within the caravan park in Ballater on 11/08/14 (time unknown).

2.1.4 December 2015 Flood Event (Storm Frank)

The most recent significant flood event in Ballater occurred on 30th December 2015. This event is the largest on record at the Dee gauging station just upstream of Ballater at Polhollick.

On 28th December 2015, rain gauges were approaching record rainfall totals for a calendar month, and had recorded the wettest December in 20 years. Temperatures, which had been around freezing for a few days, rose on the morning of 28th to around 7°C which resulted in snow melt on higher ground in the Cairngorms. On the 29th December 2015, there was 12 hours of intense rainfall (accompanied by a further temperature rise to 10°C and high winds).

On the 30th December 2015, Ballater experienced flooding, with more than 100 residents having to be evacuated from the Anderson Road, Deebank Road and Albert Road areas and some 300 properties suffering inundation. The Dee overtopped its banks and breached an informal flood defence embankment adjacent to Ballater Golf Course. Aberdeenshire Council provided photographs and videos of the area both during and after the flood event, in addition to anecdotal evidence contained within flood briefing notes and a diagram (Figure 2.7) showing the location of flood markers from this event. The markers consisted of black tape on lamp posts. During the topographical survey undertaken in July/August 2017 (Section 2.5), Aspect Surveys attempted to locate and subsequently record the level of each marker.

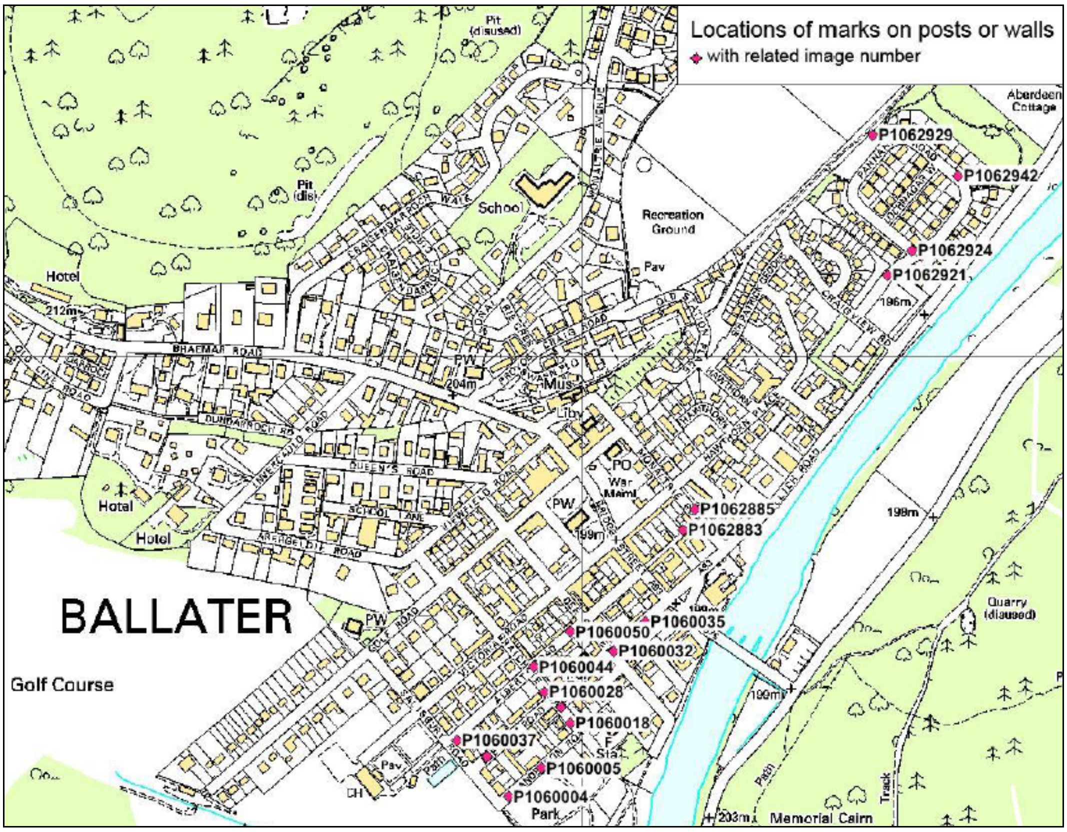


Figure 2.7 Location of Flood Markers

SEPA provided a photograph (Figure 2.8) of a map annotated by Aberdeenshire Council, showing the reported flow mechanisms and identifying the areas affected by flooding (classifying these by Major, Minor and Low). Aberdeenshire Council provided photographs taken within two hours and thirty minutes of the peak flow being recorded at the Polhollick gauging station (11:45 am). Figure 2.9 to Figure 2.12 show the extent of flooding along Bridge Street, and of the river levels looking from the south bank of the River Dee.

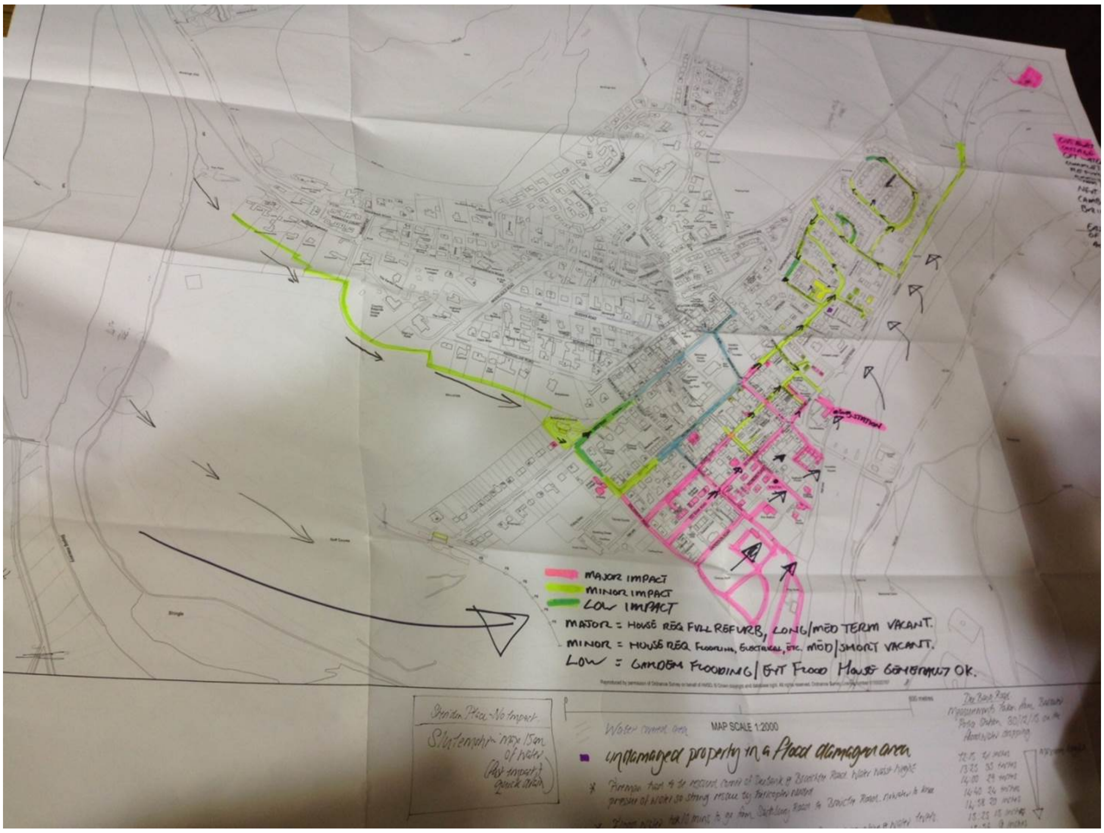


Figure 2.8 Photograph of a map annotated by Aberdeenshire Council (provided by SEPA)

Figure 2.9 Photograph of Ballater on 30th December 2015 (at 12.14pm) from the south side of the River Dee

Figure 2.10 Photograph of Ballater on 30th December 2015 (at 2.02pm) from the south side of Royal Bridge

Figure 2.11 Photo taken (at 10:25am) from the north side of the River Dee, downstream of the Royal Bridge in Ballater , with caravan debris visible on the upstream side of the nearest abutment.

Figure 2.12 Photograph of Ballater on 30th December 2015 (at 10:07am) looking south at junction of Bridge Street and Victoria Road & Hawthorn Place

2.2 EXISTING SURVEY INFORMATION

2.2.1 Topographical Surveys

Aberdeenshire Council supplied RPS with the existing cross-section surveys and a SEPA bank top survey from September/October 2016. The cross-section and structure information includes photographs, AutoCAD drawings, GIS files and formatted files for application into the modelling software, for the River Dee, River Gairn and River Muick. Top of bank levels were surveyed where it was deemed that out of bank flow could exist. Where ground was markedly higher, levels were not surveyed. Figure 2.13 and Figure 2.14 below show the extent of the existing cross-sections and top of bank levels survey data.

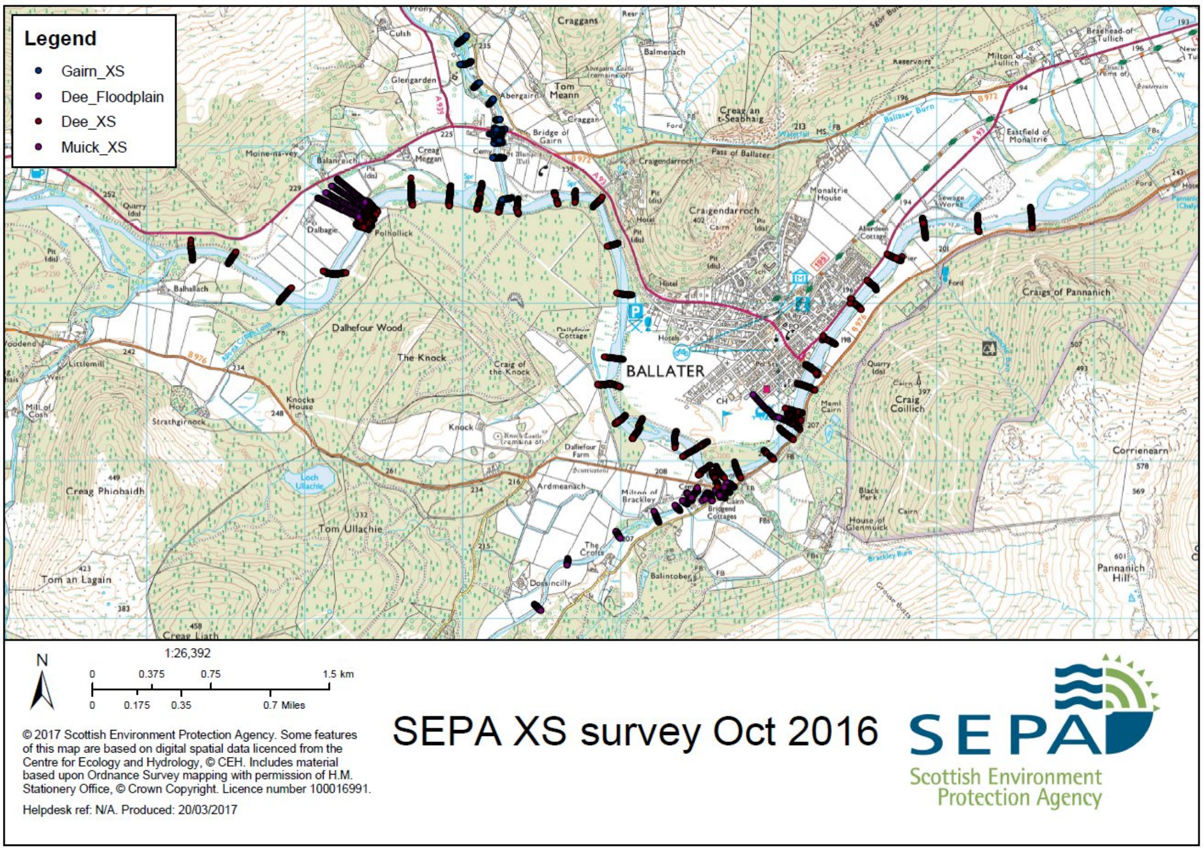


Figure 2.13 SEPA Existing Cross-Sections Survey Extent

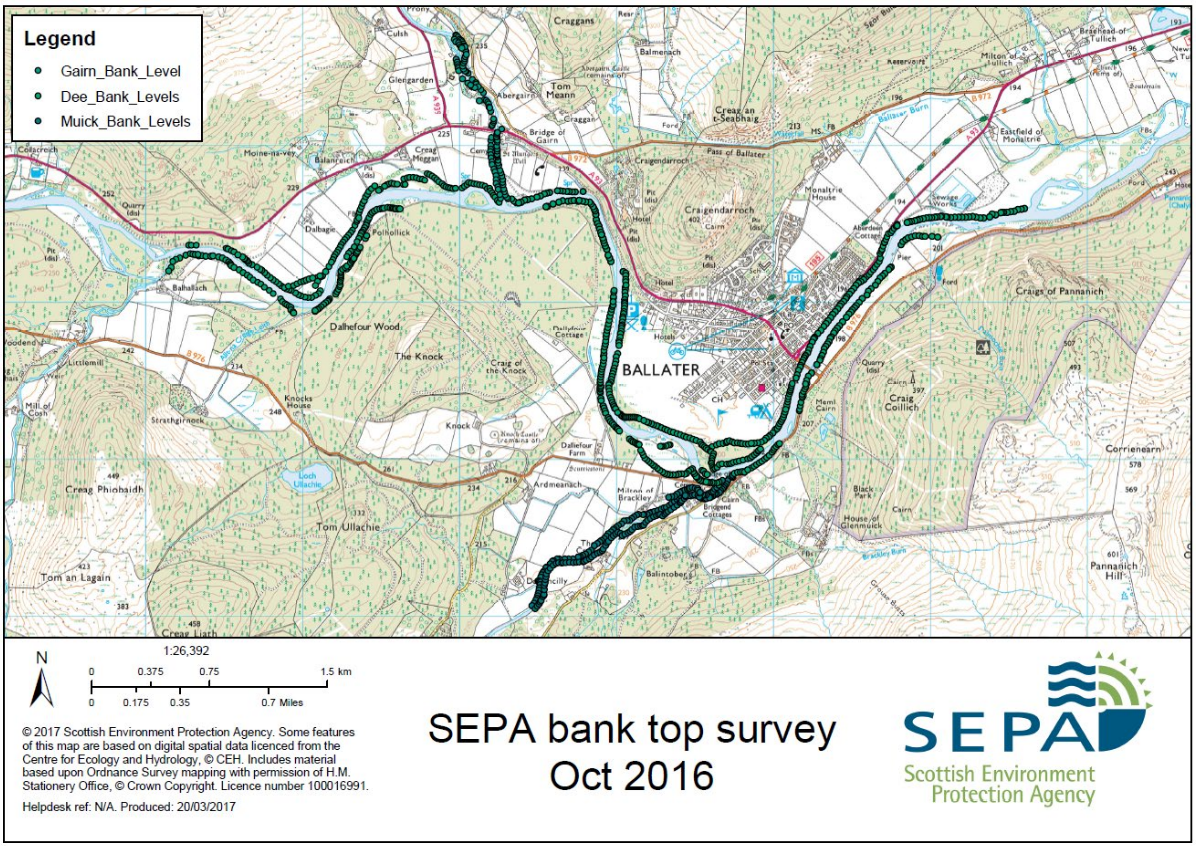


Figure 2.14 SEPA Existing Top of Bank Survey Extent

2.2.2 Surface and Terrain Models

Aberdeenshire Council provided RPS with two LiDAR datasets in October 2017. The LiDAR, dated from 2011/2012 and 2016, covers the area shown in Figure 2.15 and Figure 2.16 respectively. The 2011/2012 data is at 1 metre horizontal resolution and the stated vertical accuracy is +/- 150 millimetres (mm) (root mean square error). The 2016 data, which was supplied to Aberdeenshire Council by the Hutton Institute, is at 250mm horizontal resolution with an average difference in elevation between the LiDAR and ground control points of -190 millimetres. The 2016 LiDAR area is less than the area covered by the 2011/2012 LiDAR, and excludes the majority of the River Gairn and River Muick.

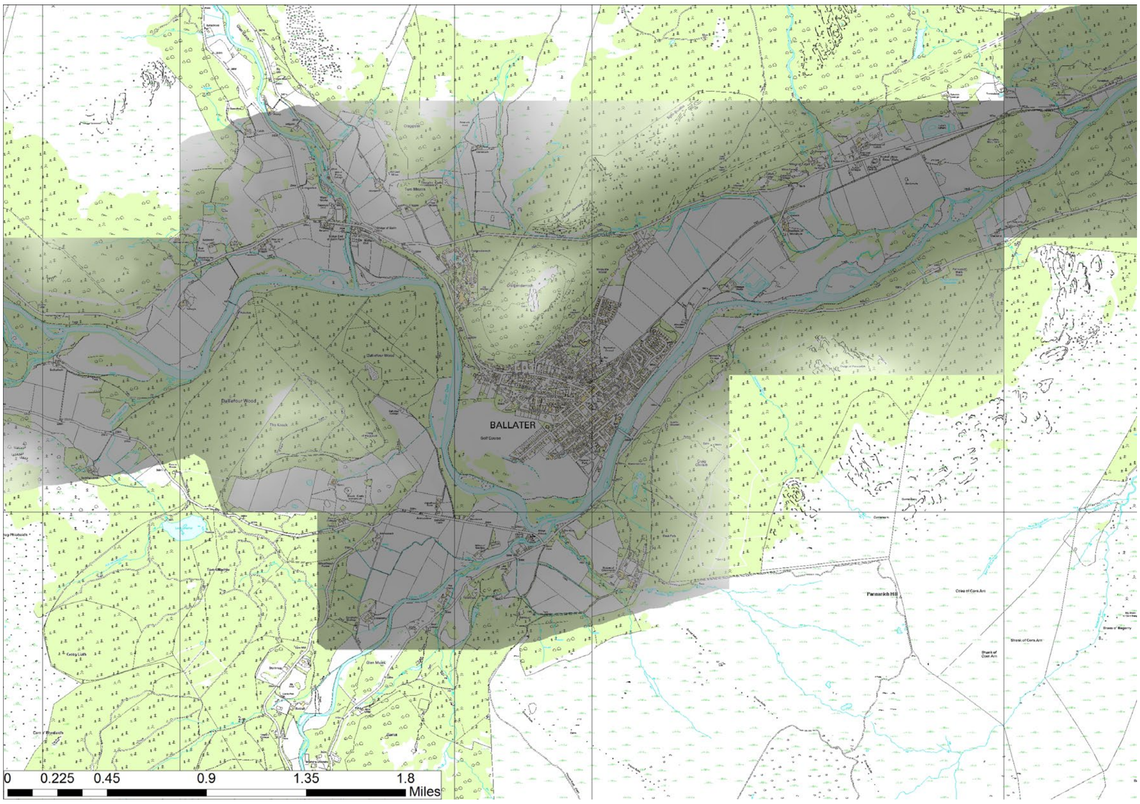


Figure 2.15 Ballater 2011 / 2012 LiDAR Extent

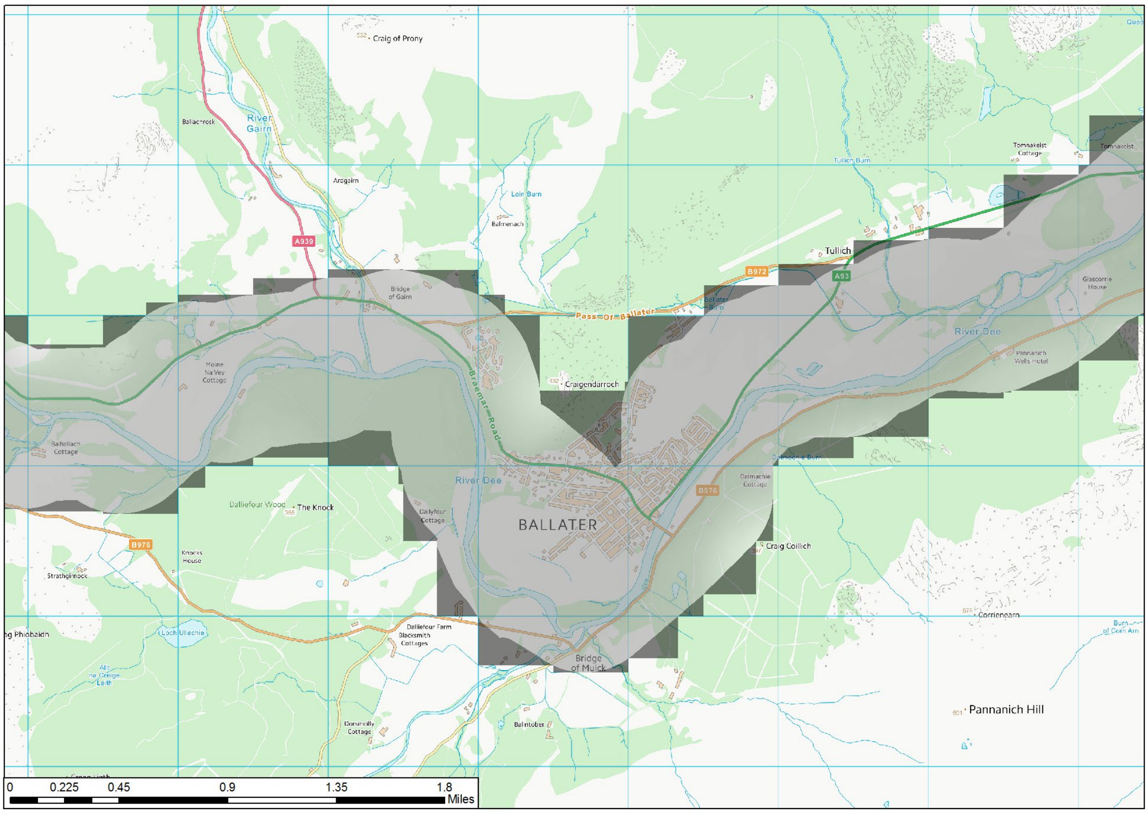


Figure 2.16 Ballater 2016 LiDAR Extent

2.3 EXISTING HYDRAULIC MODELS

Aberdeenshire Council supplied RPS with two existing hydraulic models constructed by SEPA. The SEPA NFUS Sediment Management Model was constructed to assess the impact of sediment removal on flood risk to agricultural land around Ballater. The Flood Forecasting and Warning Model was constructed to support SEPA's Flood Forecasting and Warning duties. Details of each model are provided in Table 2.2.

Table 2.2 – Details of existing SEPA Hydraulic Models

Hydraulic Model	**SEPA NFUS gravel deposit model**	**SEPA Flood Forecasting and Warning Model Review**
Model primary purpose (e.g. strategic, optioneering, design, FRA, flood forecasting, not flood risk)	Strategic assessment of impact of gravel bars on flooding.	Determining thresholds for flood warning models.
Hydraulic Model type (e.g. 1D steady state, 1D unsteady, 2D, 1D-2D linked, 1D-2D offline linked)	1D-2D linked	1D-2D linked
Date of model construction	2016/2017	2017
Date of XS survey	Autumn 2016	Autumn 2016
Flood Plain data type (e.g. Lidar, NextMap, Ground Based Survey, OS contours, Unknown)	Lidar	Lidar
Model software 1D	FloodModeller	FloodModeller
Model files available (yes, no, partial)	Yes	Yes
XS georeferenced (e.g. Fully georeferenced, Partially georeferenced, No)	Yes	Yes
Flood plain shape files available (e.g. Yes, No, Not applicable)	Yes	Yes
Geometry file available (e.g. Yes, No, Not applicable)	Yes	Yes
Model software 2D	FloodModeller	TuFLOW
2D grid resolution (m)	10 m	5 m
Model files available (yes, no)	Yes	Yes
Hydrology		
Date of hydrological assessment	Not carried out. Model run with storm Frank observed event data only.	Not carried out. Model run with storm Frank observed event data only.
Assessment method (FEH, FSR, Other (state))	N/A	N/A
Distributed boundaries (yes, no)	N/A	N/A
Storm durations (Single, Multiple)	N/A	N/A
Climate change allowance	N/A	N/A
Downstream boundary type	Normal depth	Normal depth
Model Performance		
Calibration/ Validation (e.g. Better than 250mm, Worse than 250mm, Verified against wrack marks, Verified against anecdotal data , only, Not calibrated)	Verified against maps from Dec 2015 event. Breaches not modelled.	Verified against maps from Dec 2015 event. Breaches not modelled. Model run using pre and post event out of bank DTM.
Numerical stability (Does not run, Problems at high flows, Problems at low	MB error at peak of event is around 5%. Larger MB errors	Not available.

Hydraulic Model	SEPA NFUS gravel deposit model	SEPA Flood Forecasting and Warning Model Review
flows, Seems fine, Insufficient data to check)	reported during initial wetting and drying.	
Audit report/QA report available (Yes, No)	No	No

2.4 EXISTING REPORTS

2.4.1 Dee Morphological Report

RPS received a report titled "Morphological changes to the River Dee, Aberdeenshire due to the 30th of December 2015 'Storm Frank' flood" by Macaulay Development Trust and The James Hutton Institute, August 2017. An investigation was commenced in 2016 to help understand how the River Dee had changed in response to the flood. Two of the main findings of the report were:

- 33% of the river length underwent significant change of morphology.
- The greatest changes in river morphology as a result of riverbank erosion and riverbed movement were concentrated in the middle section of the river between Abergeldie Castle and Drumnagesk and at Park (see Figure 2.17).

The report noted that changes to channel shape and course could have implications for the conveyance of water and in turn flood risk and suggested that further work was needed to assess if changes in channel capacity had altered flood risk.

Figure 2.17 The River Dee Catchment and sites of interest (from "Morphological changes to the River Dee, Aberdeenshire due to the 30th of December 2015 'Storm Frank' flood" by Macaulay Development Trust and The James Hutton Institute, August 2017)

2.4.2 Scottish Natural Heritage (SNH) Reports

RPS received reports from SNH entitled "The Geomorphological Character of the River Dee, Aberdeenshire – Volume I" and Volume 2 – Maps (2001). The report was commissioned to investigate the geomorphological character of the River Dee in light of many river engineering projects being carried out on the River Dee that raised concerns about the impact of bank and bed erosion and in particular, the impact this could have on salmon fishery. Some of the main findings of the report were:

- There are localised sections that exhibit high degrees of dynamism, interspersed with longer zones of relative stability.
- Sediment yields from tributary catchments are important in determining downstream channel character. Where this has negative effects, management should tackle the causes, such as grazing pressure and the use of the riparian zone for watering stock, rather than the symptom through the re-enforcement of riverbanks.
- As erosion is both a natural and an expected process, the Dee should be left to function as naturally as possible. Human intervention should be avoided in the most active segments.

2.4.3 NFUS Sediment and Flood Risk Report

RPS received the River Dee section of the Gravel Deposits and Flood Risk to Agricultural Land report (SEPA, 2017). The report states that there is a lot of sediment available for erosion and transport but it is mostly deposited upstream of Invercauld Bridge and that the bulk of the sediment passing through Ballater comes from the channel and tributaries between Invercauld Bridge and Ballater. NFUS found that there had been no clear trend in flows in the river since gauging started in the 1970s but that the last few years have seen some very high flows.

The report also presents flood modelling investigating the role of sediment deposits and erosion and concluded from their particular models, that significant removal of recently deposited sediment (about 30,000 tonnes within the side channel in the Red Brae area and roughly equivalent to works that were carried out in 1994) makes minimal or no difference to flood risk.

2.5 TOPOGRAPHICAL SURVEYS

RPS reviewed the existing survey data received (as outlined in Section 2.2) and following consultation with Aberdeenshire Council, procured additional survey information in order to facilitate the hydraulic modelling. The survey was undertaken by Aspect Surveys during July and August 2017 and included the following:

- Topographic & river cross-section survey of No. 104 locations on the River Dee (Figure 2.18);
- Topographic survey of 4km top of bank locations on the River Dee (levels at 25m centres), where levels had not been recorded previously during the October 2015 survey (as shown in Figure 2.14);
- Elevation/structure survey of No. 5 locations on the River Dee (upstream and downstream) (Figure 2.18);
- Topographic survey of 2.2km flood bund along the left bank of the River Dee, adjacent to Ballater Golf Course (Figure 2.18);
- Threshold levels of approximately 900 properties & flood markers within Ballater (Figure 2.18). Only five of the flood markers could be found during the survey.

The survey information is included in Appendix A.

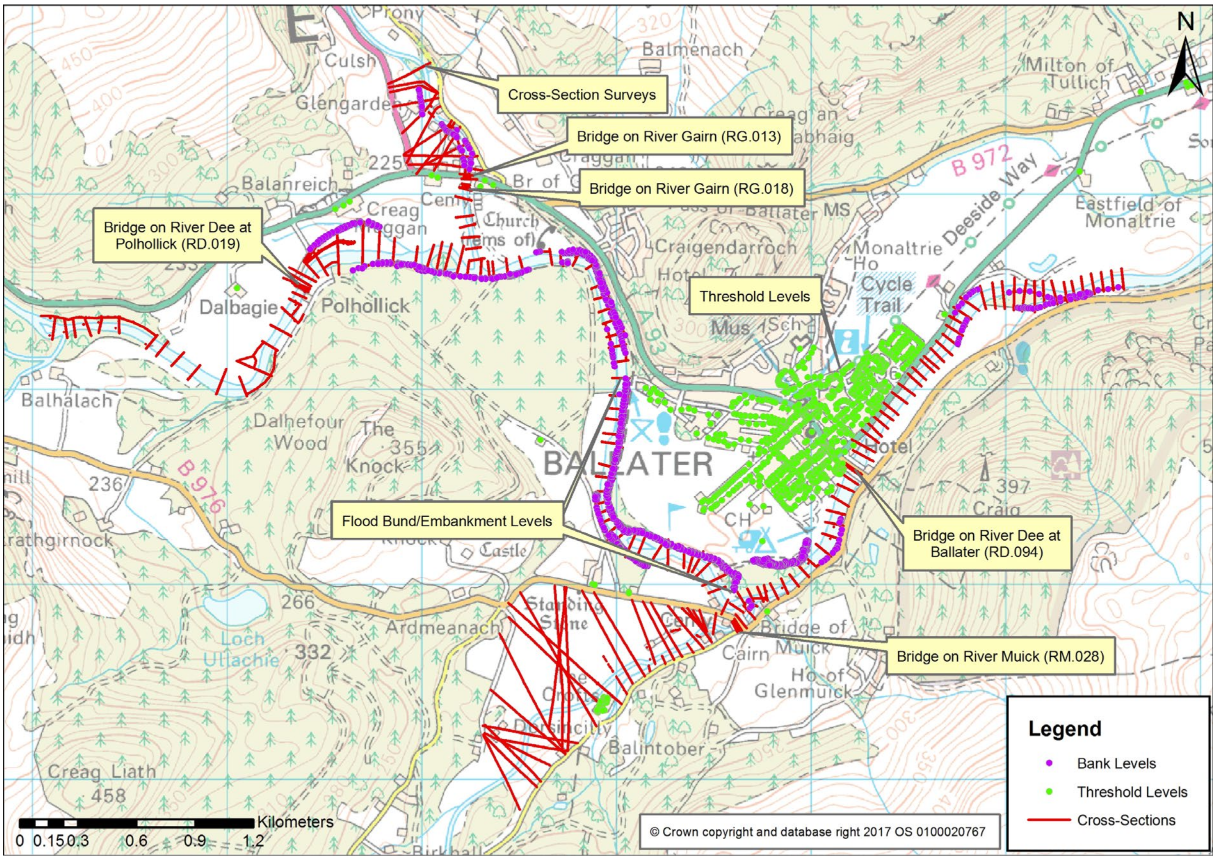


Figure 2.18 Extent of the Topographical Survey undertaken during July / August 2017

2.6 WALKOVER SURVEYS

RPS conducted a walkover survey in conjunction with Aberdeenshire Council on the 28th June 2017. The survey included visiting the bridge at Polhollick, the informal flood defence embankment at Ballater Golf Course, streets which flooded in December 2015 and various other locations along the

Dee, Gairn and Muick. The location of the breach in the informal flood defence embankment during the December 2015 flood event was identified by Aberdeenshire Council.

RPS held a second walkover survey in conjunction with Aberdeenshire Council on 9th October 2017. The survey included visiting the water treatment works adjacent to the River Gairn and the Pannanich Road area (located downstream of Ballater Bridge). Completion of the walkover surveys allowed RPS to review the area in the context of historical flooding mechanisms and collect information to facilitate the hydraulic modelling.

3 HYDRAULIC MODELLING AND MAPPING

3.1 MODEL CONCEPTUALISATION

RPS reviewed the existing models (described in Section 2.3) to ascertain if they could be wholly or partially used as a basis for the hydraulic modelling to be undertaken in this study. For a number of reasons including the resolution of the existing models and the lack of information on model construction and quality assurance procedures undertaken, it was concluded that a new hydraulic model should be constructed for the Ballater FPS.

RPS used Infoworks ICM to undertake the numerical modelling of the River Dee, Gairn and Muick. Infoworks ICM is an integrated hydrological and hydraulic modelling package developed by Innovyze. InfoWorks ICM includes full solution modelling of open channels, floodplains, embankments and hydraulic structures. Additionally, the 2-dimensional areas within Infoworks ICM are modelled through a triangular flexible mesh which allows for high levels of detail in specific areas (for example at river banks and around buildings) and a broader approach in other areas (for example open floodplains). This can give better results compared with a rectangular grid approach utilised in some other modelling packages.

The location of the model boundaries were selected at sufficient distances both upstream and downstream of Ballater to allow the model to replicate the flooding mechanisms within the town. The extent of the modelled watercourses are shown in Figure 3.1 and defined as:

- River Dee – from Balhalach to Eastfield of Monaltrie
- River Gairn – from Culsh to the confluence with the River Dee
- River Muick - from downstream of Birkhall to the confluence with the River Dee

Each river is modelled as 1D-2D, with the river channel modelled as 1D and its floodplain as 2D. The 1D channel model is connected to the 2D flood plain by banklines. The banklines are created using the levels at either end of the river cross sections. Levels between cross sections are either interpolated from the cross sections or created from the DTM.

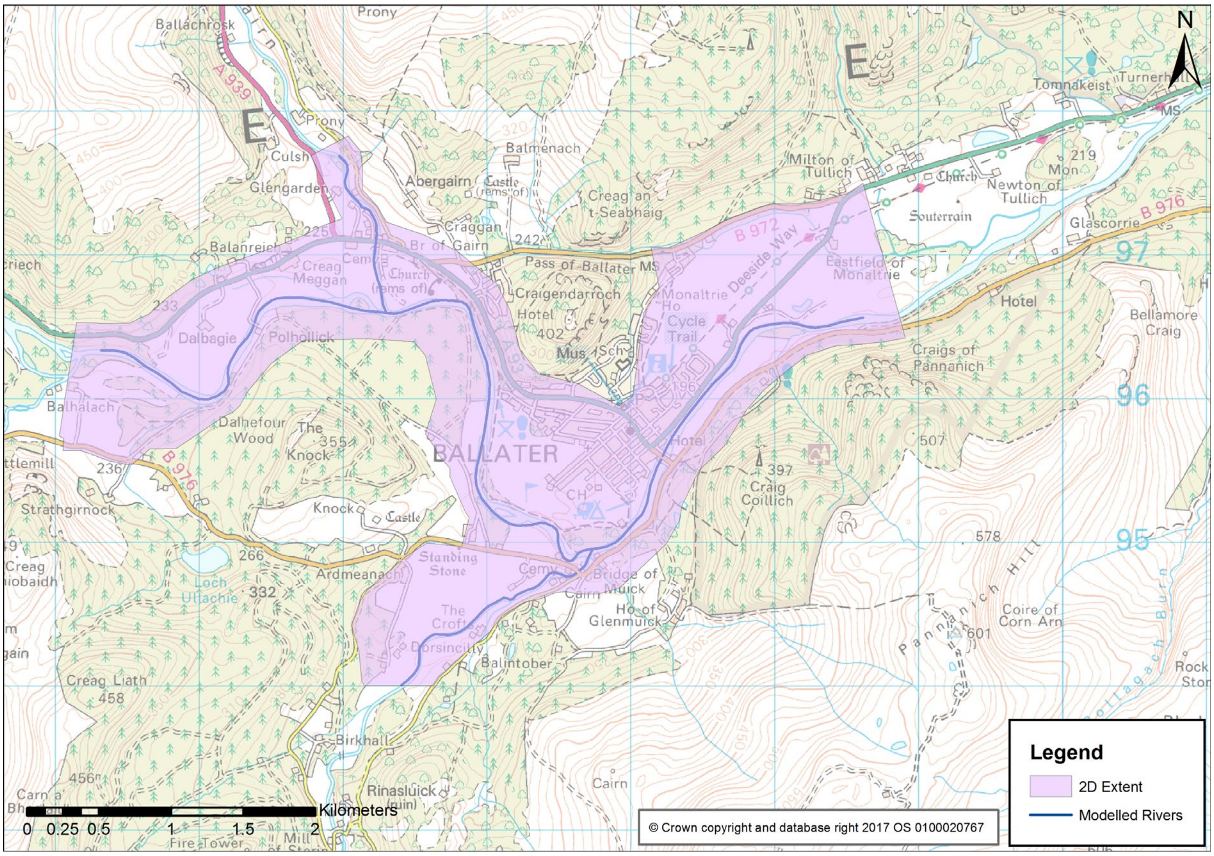


Figure 3.1 Extent of Hydraulic Model

3.2 HYDRAULIC MODEL CONSTRUCTION

3.2.1 1D Model Domain

The in-bank portion of the river model (1D) was created using cross section survey information from both the October 2016 survey (Section 2.2.1) and the August 2017 survey (Section 2.5). The August 2017 survey was used as the basis for incorporating all of the structures within the 1D model. There are 5 no. bridges, culverts and pipe crossings in the model, details of which can be found in Appendix B. The existing informal flood defence along the golf course on the River Dee was captured in the cross section survey and so is included in the baseline model as surveyed. The existing informal defence wall, located on the left bank of the River Dee upstream of the Royal Bridge, was also incorporated within the 1D model domain (as outlined in the Model Log in Appendix G).

3.2.2 2D Model Domain

The LiDAR data was used to model the floodplain (Section 2.2.2). The upstream extents of the modelled reaches of the River Gairn and River Muick are outwith the coverage of the 2016 LiDAR. The 2012 LIDAR does include these areas and, although the 2012 LiDAR is older and is of lower resolution, it is considered sufficient to adequately represent the flood plain within the model for these predominantly rural areas along the River Gairn and River Muick. Therefore, the 2012 LiDAR was used to supplement the 2016 LiDAR to create a ground model of the entire study area.

For an accurate assessment of 2D flow paths, the bare earth DTM data was used within the modelling package to generate the computational mesh; the mesh was then augmented to include buildings which will affect flow paths. Building footprints were defined by a GIS shape file which was extracted from the OS Master Map geodatabase supplied by Aberdeenshire Council. The building footprints were then imported into the model as porous polygons and designated as having a porosity of 0.01 to enable buildings to store some water. The finished floor levels (FFL) provided within the threshold survey (Section 2.5) were imported to the model as mesh zones with the *Ground level modification* set to the appropriate FFL. Boundary walls were incorporated into the 2D model domain where they may have a substantial impact on flowpaths. All flood receptors were contained within the 2D modelling domain.

The maximum mesh size used in the model was 100m^2 (generally this gives an element size of 75m^2) which was considered sufficient for modelling the larger open spaces. In areas where there are known flowpaths, including the golf course, and historic flooding has been reported, the mesh was refined with a maximum mesh size of 25m^2 (generally giving an element size of 3m^2). Terrain sensitive meshing was used which increases the resolution of the mesh in areas that have a large variation in height.

3.2.3 Model Boundaries

Upstream boundary conditions and input hydrographs for the model were provided from the Hydrological Assessment and have been introduced directly to the 1D domain as point or lateral inflows. The details of the hydrological analysis are available in separate reporting – IBE1358/Rp01 Rev D04. An input hydrograph was applied as a point flow at each upstream boundary (for the River Dee, Gairn and Muick). Lateral inflows were also applied along the length of each river. The lateral inflows were disaggregated between hydrology nodes and distributed pro-rata, based on length, and applied to each link (river reach) along the length of the river.

Downstream boundary conditions for the River Dee were defined by an outfall node located at a sufficient distance downstream of Ballater thereby ensuring that any backwater effect was accounted for in the model. The downstream boundary conditions for the River Gairn and River Muick were defined by the River Dee at their confluence. All watercourses within each simulation were modelled with the same return period. For example, in the 50% AEP simulation, a 50% AEP event was applied to all the watercourses. Therefore the downstream boundaries for the River Gairn and River Muick were the level in the River Dee during a 50% AEP (1 in 2 year return period) event. The modelled flows from the design events (which SEPA have confirmed as robust, making good use of available data and reflecting observed flooding), are compared with the estimated flow at each Hydrological Assessment Point (HAP) in Table 3.3.

3.2.4 Model Roughness

The roughness values were determined using the tables from Chow (1959) and based on information collected during the walkover survey and photographs provided along with the survey information. Within the 1D domain the in-bank roughness was given a Manning's n value of between 0.04 – 0.06. These figures were employed as the reaches vary from clean, winding watercourses to active mountainous watercourses with cobble beds and large boulders.

The out-of-bank 1D roughness varies from a minimum of 0.05 to a maximum of 0.072 as the banks vary from scattered brush to medium/dense brush. The 2D model domain was split into different land uses based on the Land Cover Map (LCM) 2007. All roads were extracted from the OS Master Map series and merged with the roughness zones from the LCM. Roughness values were assigned to the different land classes as per Table 3.1, with roads classified as 'urban' with a Manning's n value of 0.011.

Table 3.1 Land Class Roughness Values

Class	Manning's n
Broadleaved woodland	0.1
Coniferous Woodland	0.09
Arable and Horticulture	0.04
Improved Grassland	0.025
Rough grassland	0.05
Acid grassland	0.035
Heather	0.045
Heather grassland	0.04
Bog	0.06
Freshwater	0.033
Urban	0.011
Suburban	0.045

3.2.5 Other Model Information

The selection of the timestep has been set at 1 second to ensure model convergence. Version 8.5 of the ICM software has been used for the model. Further details on model construction can be found within the Model Log in Appendix G.

3.3 MODEL CALIBRATION AND VERIFICATION

The computational river model was calibrated by the undertaking the tasks below. Further details are provided in Section 3.3.1 to Section 3.3.7.

- Reviewing the current SEPA rating equations for the three gauging stations within the study area;

- Comparison of modelled and design flows and flood frequency curves;

- Comparing predicted flood extents and depths with field observations. Historical data including photographs and recorded flood data was used, where available (as outlined in Section 2.1);

- Public consultation on the draft flood extent maps.

3.3.1 Gauging Station Datum Review

RPS performed a review of the current SEPA ratings derived from historical observations at the Muick, Dee and Gairn river gauges. The gauge zero levels given on the NRFA website and in the continuous flow data record provided by SEPA are:

- Dee at Polhollick: 216.67m AOD
- Gairn at Invergairn: 217.71m AOD
- Muick at Invermuick: 200.70m AOD

During the topographical survey (Section 2.5), the survey team recorded the level of a concrete marker post located near to each staff gauge. Through consultation with SEPA, it was confirmed that there was no existing information available on the level of each post. Therefore, the level of the gauges could not be directly determined from this survey. RPS undertook a cross-validation check using the surveyed water levels nearest to the gauges and the water levels recorded by the gauges at the nearest 15 minute record interval to ensure they were within an acceptable tolerance. The results of the cross-validation are provided below in Table 3.2.

Table 3.2 – Gauge level cross-validation

Gauge	Date Surveyed	Time Surveyed	Surveyed Water Level at nearest point to gauge (m AOD)	Gauged Water Level on Date of Survey (m AOD)	Water level variance on date of survey (m)
Dee at Polhollick	16/08/2017	14:31	217.13	217.182	-0.052
Gairn at Invergairn	18/08/2017	10:33	217.82	217.987	-0.167
Muick at Invermuick	23/08/2017	16:23	201.24	201.274	-0.034

The difference in the surveyed and gauged water levels is minimal for the Dee and Muick river gauges; however, there is a more pronounced difference at the Gairn. Inspection of the continuous flow data at the Gairn revealed little variation in gauged water levels before and after the survey time. A more recent survey of the staff gauges was undertaken by SEPA in late-2016 which recorded the datum’s as:

- Dee at Polhollick: 216.62m AOD
- Gairn at Invergairn: 217.74m AOD
- Muick at Invermuick: 200.59m AOD

There is negligible difference between the 2016 survey and the NRFA levels for the Dee and Gairn river gauges. The difference in level at the Muick is greater and has previously been reported by CH2M in a study which aimed to investigate the flooding mechanism in Ballater for Storm Frank and a review of the data used with the operation flood forecasting models. In this report, the use of the 2016 gauge level was shown to reduce the maximum difference between the SEPA and modelled ratings and also appeared to bring the modelled rating curve into better agreement with the spot gaugings.

It was concluded that the discrepancy at the Gairn water level in the 2017 survey could be due to a number of systematic errors between the gauge readings and the survey readings. The cross-validation only relied on a single water level measurement that was not in line with the gauge location, but eight metres downstream. Consequently, the gauge zero levels recorded by SEPA in 2016 are preferred over those reported on the NRFA website and in the continuous flow data records. The rating reviews and associated stage level readings have been adjusted in accordance with their respecitve staff gauge zero. It is recommended that future studies record the actual level of the datum at each gauge to provide an additional source of information for use in future rating reviews.

3.3.2 Rating Reviews

The general form of a hydraulic rating equation is:

$$Q = C(h - a)^{\beta}$$

Where:
Q = river flow (m^3/s)
C, a, β = rating equation constants
h = stage height (m)

Figures and rating equation paramaters have been derived using stage heights relative to ordnance datum. Rating equation constants have been derived using Pythons Scipy Optimization and Curve Fitting module which generates optimal parameters such that the sum of squared residuals of observed and predicted discharge is minimised.

3.3.2.1 Muick at Invermuick (12005)

Figure 3.2 depicts the rating review undertaken at the Invermuick gauge (12005). The current SEPA rating visually provides a good fit to the spot gaugings and captures the highest spot gauge on record with a stage height and discharge rate of 202.298m AOD (1.708m from gauge zero) and $71.99m^3/s$ respectively. Spot gaugings recorded after the December 2015 event do not present any evidence suggesting there have been significant changes to the gauge structure or channel morphology within the range spot gauged levels. It is therefore assumed that the stage-discharge relationship at the gauge has not been affected by this event within the range of spot gauged levels.

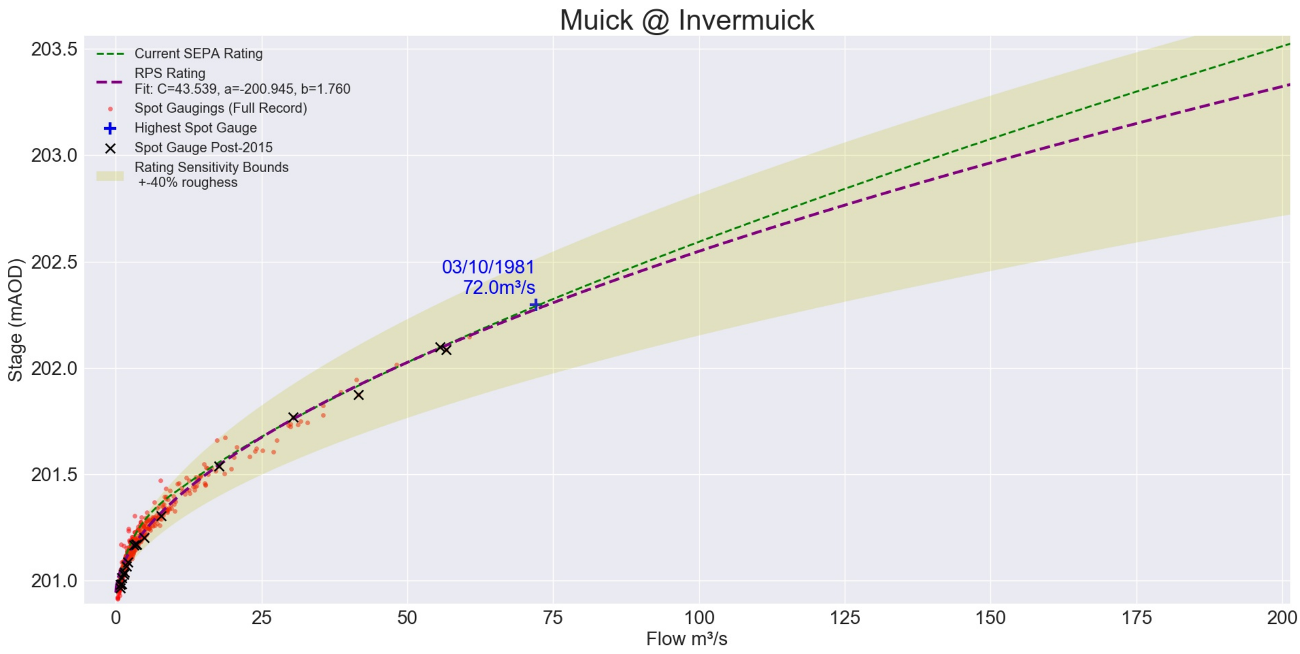


Figure 3.2 Invermuick (12005) Ratings

RPS considered the output stage-discharge relationship from the hydraulic model at the gauge location to validate and potentially improve the current SEPA rating. In order to achieve an acceptable fit to the spot gaugings, RPS had to make significant in-channel alterations. An artificial interpolated cross-section was inserted immediately downstream of the gauge and the interpolated bed level was raised from 200.04m to 200.86m AOD. The resulting rating curve and its optimal parameters provide a visually good fit to the spot gaugings. However, the modelled rating is not as good a fit to the highest spot gauging on record although it must be noted that this was recorded 36 years prior to the survey upon which the model was constructed. The modelled rating suggests a higher flow to stage ratio at flood flows than that predicted by the SEPA rating. However, given the uncertainties in relation to the rating review, particularly the need to add in an interpolated cross section and lift the bed level by almost 0.82m it is considered that the modelled rating is not sufficiently robust such that it could be used for the reprocessing of flood flows and as the basis for hydrological re-analysis. The modelled rating has been artificially modified by the introduction of an artificial bed level immediately downstream of the gauge. The elevated bed level at the interpolated section is so extreme, that the morphological representation is not supported by the channel survey information. Any increase in bed level as large as 0.82m would potentially imply a geological feature in the river channel that is unlikely to have been overlooked during the river survey and would be apparent from the detailed LiDAR. Use of the modelled rating would introduce additional uncertainties in any further hydrological analysis and for this reason, there is more confidence in the SEPA rating curve.

RPS undertook two sensitivity analysis model simulations which involved increasing and decreasing the 1D Manning's n roughness values by 40% respectively. Figure 3.2 shows how the rating equation is affected by these changes, showing the potential range in the rating equation for this gauge.

3.3.2.2 Dee at Polhollick (12003)

Figure 3.3 depicts the rating review undertaken at the Polhollick gauge (12003). The current SEPA rating visually provides a good fit to the spot gaugings and captures the highest spot gauge on record with a stage height and discharge rate of 219.01m AOD (2.39m from gauge zero) and 392.60m^3/s respectively. Spot gaugings recorded after the December 2015 event suggests that the December 2015 event may have modified the channel or gauge structure resulting in a change in the stage discharge relationship.

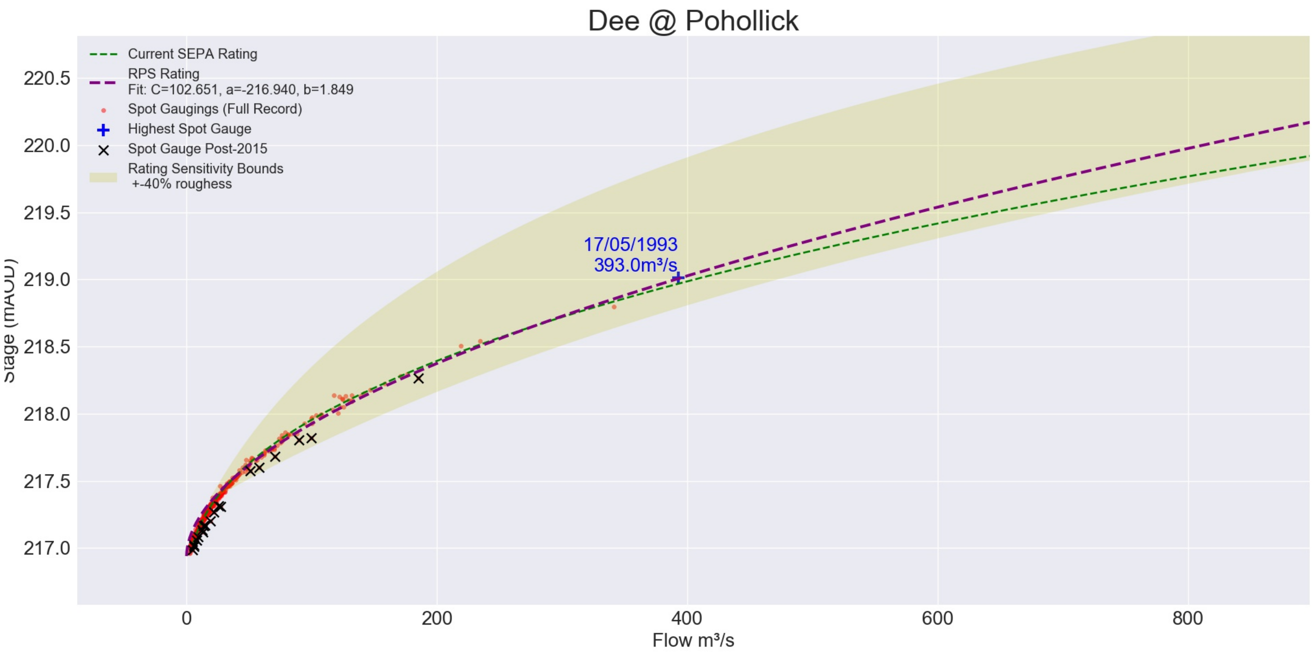


Figure 3.3 Polhollick (12003) Ratings

RPS considered the output stage-discharge relationship from the hydraulic model at the gauge location to validate and potentially improve the current SEPA rating. In order to achieve an acceptable fit to the spot gaugings, RPS had to make significant in-channel alterations. An artificial interpolated cross-section was inserted immediately downstream of the gauge and the interpolated bed level was raised from 215.80m to 216.80m AOD. The resulting rating curve and its optimal parameters provide a visually good fit to the spot gaugings. However, the modelled rating is not a significant improvement over the SEPA rating at flood flows although it does provide a better fit to the largest spot gauging on record. The modelled rating suggests a lower flow to stage ratio at flood flows than that predicted by the SEPA rating. However, given the uncertainties in relation to the rating review, particularly the need to add in an interpolated cross section and lift the bed level by 1.0m it is considered that the modelled rating is not sufficiently robust such that it could be used for the reprocessing of flood flows and as the basis for hydrological re-analysis. The modelled rating has been artificially modified by the introduction of an artificial bed level immediately downstream of the gauge. The elevated bed level at the interpolated section is so extreme, that the morphological representation is not supported by the channel survey information. Any increase in bed level as large as 1.0m would potentially imply a geological feature in the river channel that is unlikely to have been overlooked during the river survey and would be apparent from the detailed LiDAR. Use of the modelled rating would introduce additional uncertainties in any further hydrological analysis and for this reason; there is more confidence in the SEPA rating curve.

RPS undertook two sensitivity analysis model simulations which involved increasing and decreasing the 1D Manning's n roughness values by 40% respectively. Figure 3.3 shows how the rating equation is affected by these changes, showing the potential range in the rating equation for this gauge.

3.3.2.3 Gairn at Invergairn (12006)

Figure 3.4 depicts the rating review undertaken at the Invergairn gauge (12006). The current SEPA rating visually provides a good fit to the spot gaugings and captures the highest spot gauge on record with a stage height and discharge rate of 219.18m AOD (1.44m from gauge zero) and 48.825m^3/s respectively. Spot gaugings recorded after the December 2015 event suggests that the December 2015 event may have modified the channel or gauge structure resulting in a change in the stage discharge relationship at the gauging station. The spot gaugings would indicate that the flow to stage ratio has increased following the 2015 event.

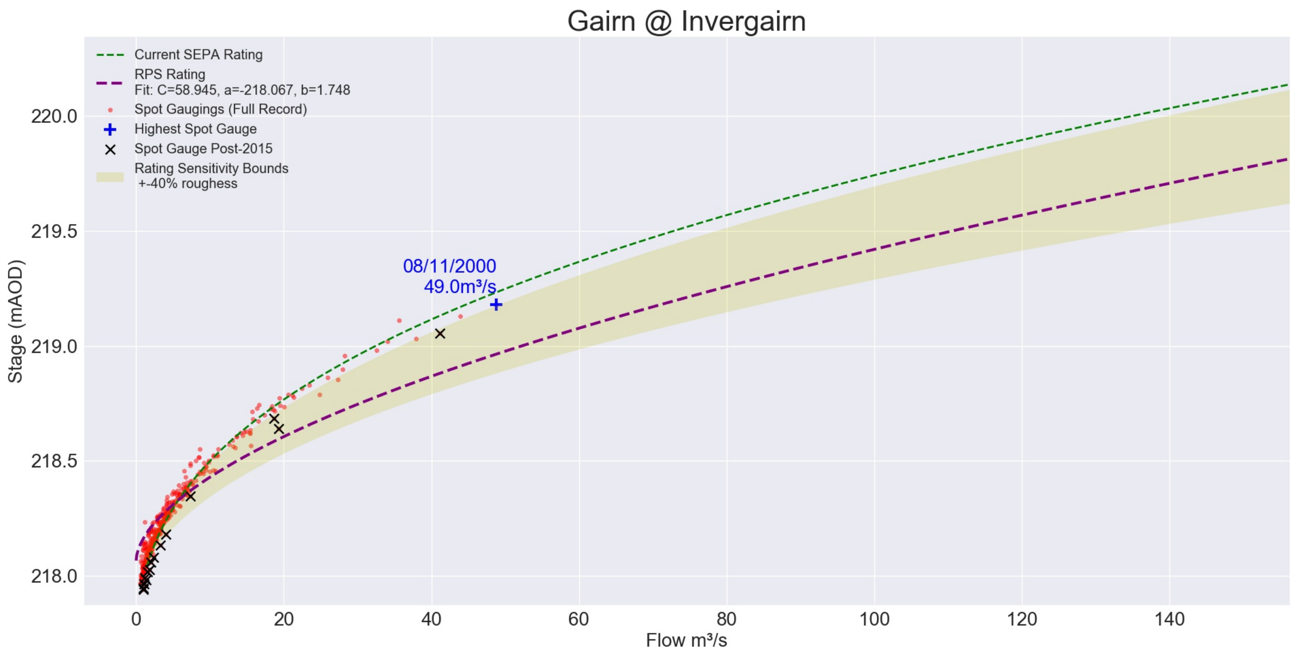


Figure 3.4 Invergairn (12006) Ratings

RPS considered the output stage-discharge relationship from the hydraulic model at the gauge location to validate and potentially improve the current SEPA rating. In order to achieve an acceptable fit to the spot gaugings, RPS had to make significant in-channel alterations. An artificial interpolated cross-section was inserted immediately downstream of the gauge and the interpolated bed level was raised from 217.12m to 217.90m AOD. The resulting rating curve and its optimal parameters fails to generate an adequate fit to the spot gaugings, particularly at levels above 218.65m AOD. The modelled rating also fails to capture the highest spot gaugings on record even after significant alteration to the bed levels. Given the uncertainties in relation to the rating review, particularly the need to add in an interpolated cross section and lift the bed level by 0.78m it is considered that the modelled rating is not sufficiently robust such that it could be used for the reprocessing of flood flows and as the basis for hydrological re-analysis. The elevated bed level at the interpolated section is so extreme, that the morphological representation is not supported by the channel survey information. Any increase in bed level as large as 0.78m would potentially imply a geological feature in the river channel that is unlikely to have been overlooked during the river survey and would be apparent from the detailed LiDAR. Use of the modelled rating would introduce additional uncertainties in any further hydrological analysis and for this reason, there is more confidence in the SEPA rating curve.

RPS undertook two sensitivity analysis model simulations which involved increasing and decreasing the 1D Manning's n roughness values by 40% respectively. Figure 3.4 shows how the rating equation is affected by these changes, showing the potential range in the rating equation for this gauge.

3.3.2.4 Model Sensitivity to Interpolated Cross-Sections

The impact of the elevated bed levels at each gauging station location was investigated. The 0.5% AEP (1 in 200 year return period) design network with the elevated bed levels was simulated and compared to the 0.5% AEP design simulation. An increase in levels in the 1D was noted in the vicinity of the gauges where the bed levels were raised (maximum 113mm at RG.016). However, there was a negligible impact on peak levels elsewhere within the model domain. The level difference within the River Dee channel through the town is less than 10mm. The design models exclude the interpolated cross-sections at the gauging stations, as stated in Section 3.3.7.

3.3.3 Comparison of hydrological flow estimates and modelled flows

Table 3.3 provides a comparison between the hydrological flow estimates (as detailed in the Hydrology Chapter IBE1358/Rp01 Rev D04) and those extracted from the model at the HAP check point locations (Figure 3.5) to determine if the model is well anchored to the hydrological estimates (i.e. that there is a good correlation between modelled flows and hydrological flow estimates at each HAP). The comparisons indicate that the model is well anchored to the hydrological estimates as there is a very good correlation during the high frequency events where little flow is lost to overland flow.

At HAP_04_Check, HAP_08_Check and HAP_09_Check, the modelled figures take into account both the 1D and 2D flow at these points. At HAP_04_Check and HAP_08_Check, there is a very good correlation (maximum 4% difference) across all return periods. At HAP_09_Check, which is located downstream of the model extents (Figure 3.5), there is a good correlation (maximum 6% difference) across all return periods.

At HAP_03_Check the correlation is very good during the high and medium frequency events where little flow is lost to overland flow. However, the modelled figures only show the 1D flows at this point as the 2D flow cannot be accurately separated between the River Gairn and the River Dee. Divergence of model flows from the hydrological estimates during the low frequency events can be attributed to the loss of flow from the watercourse to the floodplain.

At HAP_07_Check, the correlation is good during the high frequency events. Divergence of the modelled flows from the hydrological estimates during the medium and low frequency events can be attributed to the large floodplain attenuating flow (which is excluded from the reported discharges in Table 3.3 as the flow cannot be accurately separated between the River Muick and the River Dee).

The model is considered to be providing a good estimation of the flow continuity along the modelled reaches.

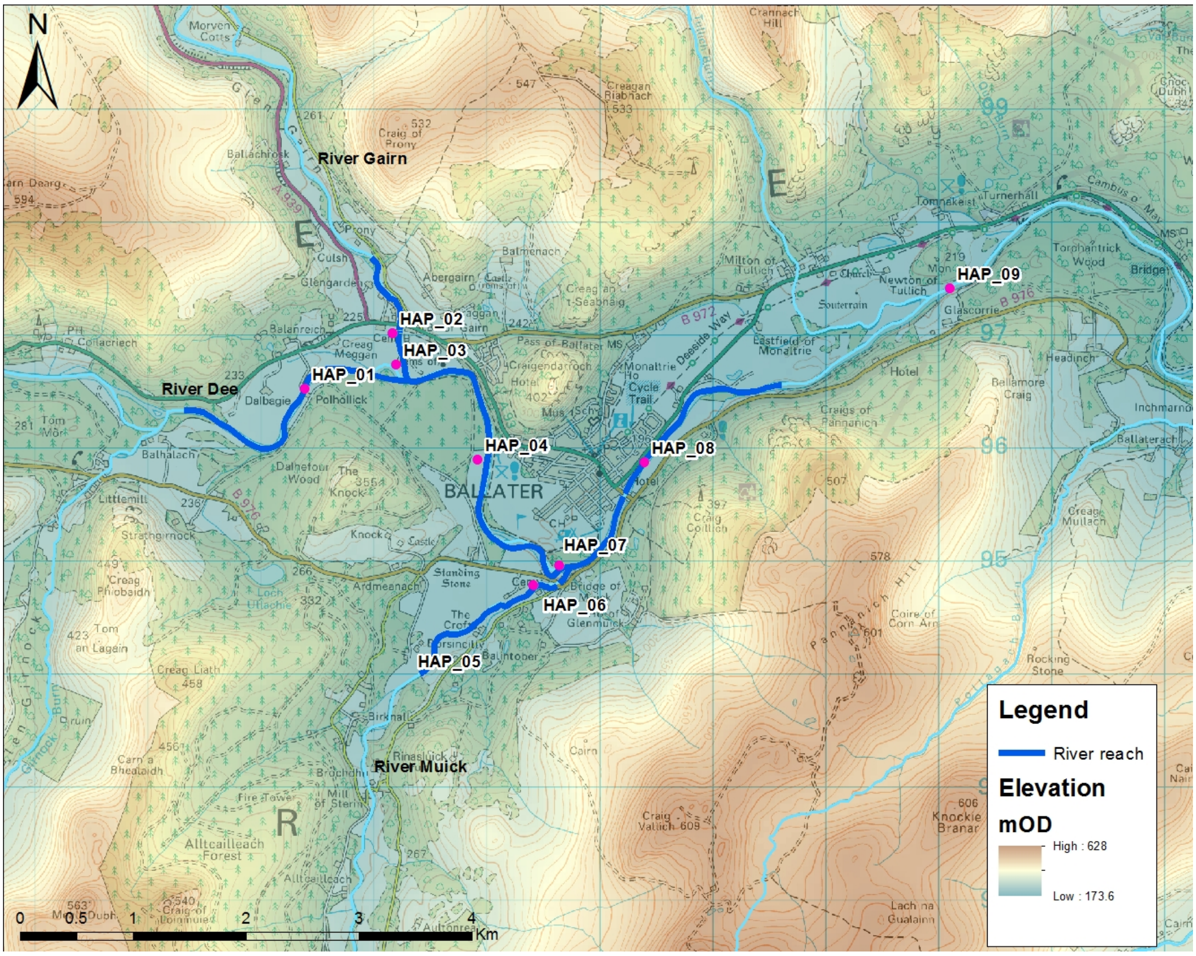


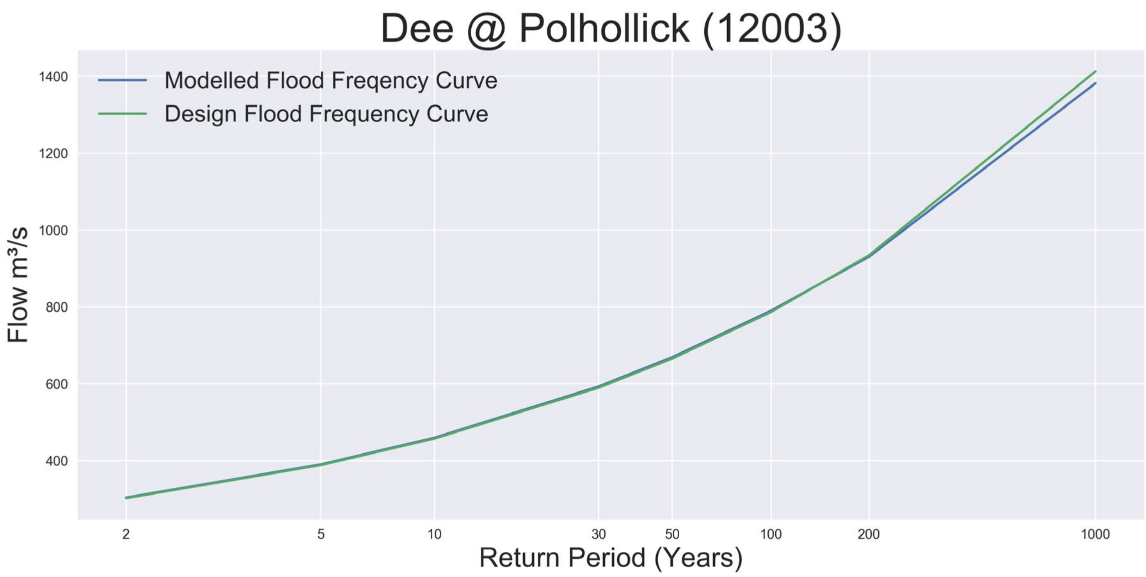
Figure 3.5 Location of HAP's

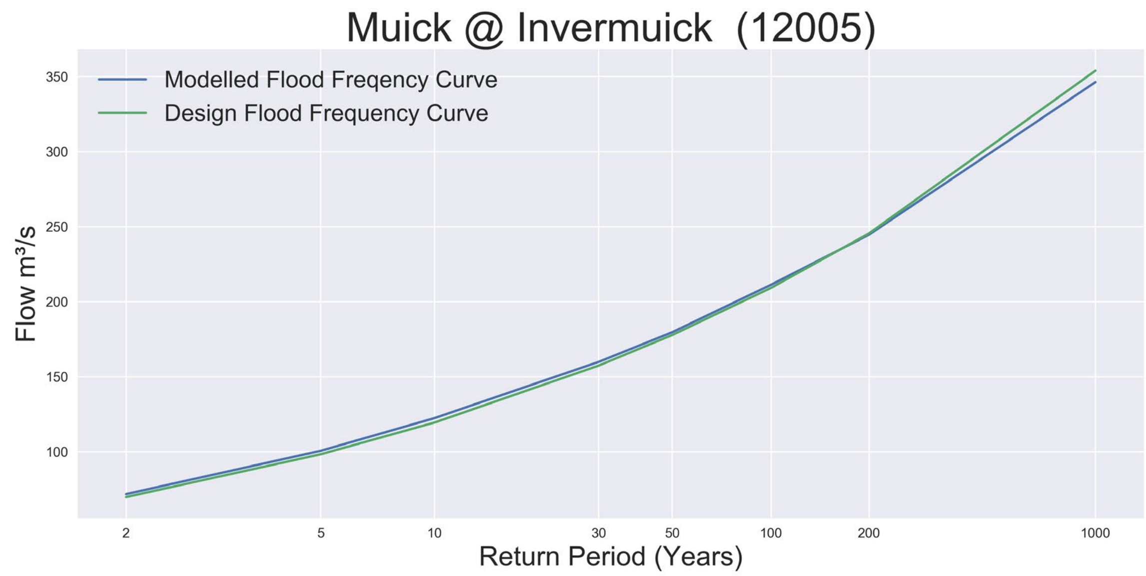
Table 3.3 Peak Flow Comparison

HAP Check Point (Sum of Inflows)		HAP_03_Check	HAP_04_Check	HAP_07_Check	HAP_08_Check	HAP_09_Check
Corresponding Model Section		**RG.024 (1D only)**	**RD.054 (1D&2D)**	**RM.030 (1D only)**	**RD.101 (1D&2D)**	**RD.130 (1D&2D)**
50%AEP (m^3/s)	Calculated Sum Flow	59	353	77	418	438
	Modelled	59	352	72	411	422
	% Difference	**0%**	**0%**	**6%**	**2%**	**4%**
20%AEP (m^3/s)	Calculated Sum Flow	83	459	108	550	576
	Modelled	83	458	102	543	555
	% Difference	**0%**	**0%**	**6%**	**1%**	**4%**
10%AEP (m^3/s)	Calculated Sum Flow	101	543	131	654	684
	Modelled	101	542	121	645	659
	% Difference	**0%**	**0%**	**7%**	**1%**	**4%**
3.33%AEP (m^3/s)	Calculated Sum Flow	133	703	173	849	886
	Modelled	132	701	155	836	850
	% Difference	**1%**	**0%**	**10%**	**1%**	**4%**
2%AEP (m^3/s)	Calculated Sum Flow	150	793	195	958	999
	Modelled	147	790	174	947	957
	% Difference	**2%**	**0%**	**11%**	**1%**	**4%**
1%AEP (m^3/s)	Calculated Sum Flow	176	937	229	1130	1178
	Modelled	167	931	204	1108	1128
	% Difference	**5%**	**1%**	**11%**	**2%**	**4%**
0.5%AEP (m^3/s)	Calculated Sum Flow	207	1110	269	1337	1392
	Modelled	192	1097	236	1313	1326
	% Difference	**7%**	**1%**	**12%**	**2%**	**5%**
0.1%AEP (m^3/s)	Calculated Sum Flow	299	1666	388	1992	2072
	Modelled	258	1625	321	1932	1946
	% Difference	**13%**	**2%**	**17%**	**3%**	**6%**

3.3.4 Comparison of modelled and design flood frequency curves

Figure 3.6 shows the design flood frequency curve (as derived in the Hydrology Chapter IBE1358/Rp01 Rev D04) in comparison with the modelled flood frequency curve for each gauging station location. This shows that there is a very close correlation between the modelled and design curves at each location, providing confidence that the model is accurately representing the frequency of flooding as determined through the hydrological analysis.





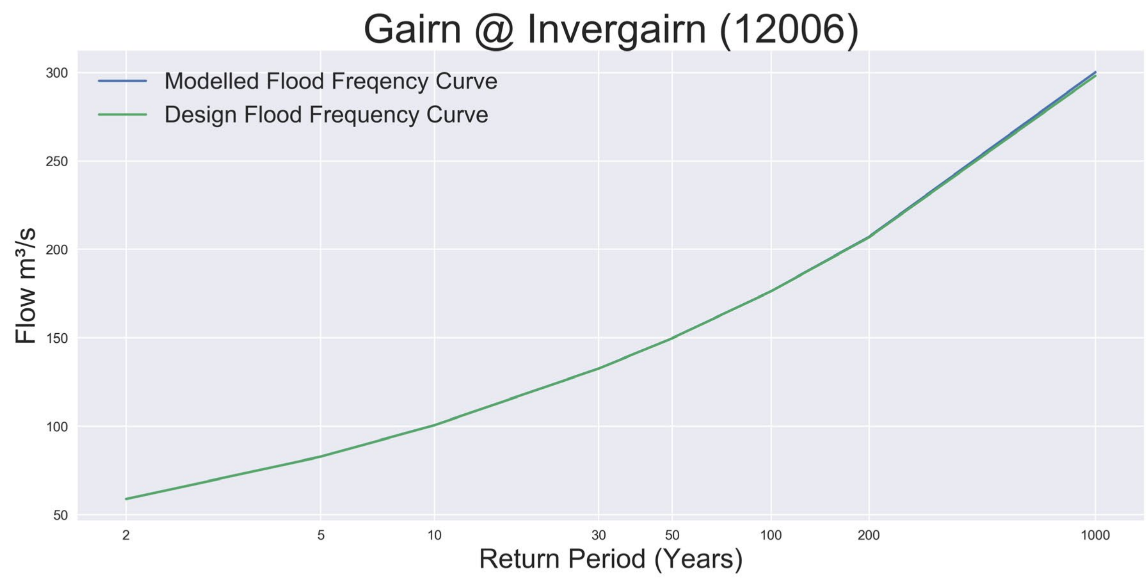


Figure 3.6 Comparison of modelled and design flood frequency curves at each gauging station

3.3.5 Key Historical Flood Events

There are a number of gauging stations in the area which record level and flow including Polhollick (12003) on the River Dee, Invermuick (12005) on the River Muick and Invergairn (12006) on the River Muick. Polhollick has reliable records for the period 1976 - 2015, Invergairn for 1989 - 2015 and Invergairn for 1978 - 2015. The gauging station records were combined to produce a synthetic station which can be considered to represent the most accurate picture of the flood frequency behaviour at Ballater. The three largest events to impact Ballater were December 2015, August 2014 and January 1993 as can be seen in Table 3.4.

Table 3.4 Five Highest recorded AMAX values for Synthetic Gauge 01 (12003 + 12005 + 12006) to nearest cumec

Hydrological Year	AMAX Date	Flow (m^3/s)	Return Period
2015	30 Dec 15	1247	126*
2013	11 Aug 14	651	11
1992	17 Jan 93	593	9
1989	05 Feb 90	560	6
1991	31 Oct 91	516	4

*Note: Estimated Return Period greater than record length – use with caution.

The above estimated AMAX values have been derived from the concurrent flow data available for the Invergairn, Polhollick and Invermuick gauges (hydrological year 1989 to hydrological year 2015) and associated return periods have been generated in WINFAP. It should be noted however, that the flood frequency distribution at this location will be heavily affected by the record period used which may lead to inconsistencies in estimated return periods. For example, the 2015 event at the Polhollick gauge has been estimated as an almost 200yr event (using the entire record period available at that location). By using the same record period adopted for the synthetic gauge, the 2015 event frequency at the Polhollick gauge is increased to an estimated 1:91yr event. It is therefore likely that the return period observed at synthetic gauge HAP04 would be closer to a 1:200yr event if the record length was the same as at Polhollick. Further details are provided in the Hydrology Chapter IBE1358/Rp01 Rev D04.

The recorded flows at the three gauging stations for each of these historic events have been input into the model and each model simulated to produce a modelled flood extent for each historic flood event. The outputs from the three historic simulations were plotted as flood depth maps and can be seen in Appendix C.

3.3.5.1 January 1993

An earth bund was constructed on the left bank of the River Dee adjacent to Ballater Golf Course in the early 1990's. It has not been possible to establish date of construction, however, it is thought to have been constructed after the 1990 flood event but before the 1993 flood event. In order to represent the event as accurately as possible, this bund has been included in the model for the 1993 event model simulation.

Newspaper reports (Deeside Piper) indicate that the depth of flood water on the golf course peaked at six feet during this flood event and that the basement of Montaltrie Hotel, Deebank House and two houses on Anderson Road were flooded.

The owners of Ballater Caravan Park (Ballater Community Enterprise Ltd) stated that although they didn't own the Caravan Park during this flood event, one of their current wardens who lived in Ballater at that time recalls that the flood extents and depths were very similar to the 2014 flood event.

An extract from the flood map for this simulated event (IBE1358_FE_331) can be seen in Figure 3.7 below which shows the caravan park and two houses on Anderson Road flooded, with flood depths within the golf course reaching 1.5m to 2m deep. This supports the anecdotal evidence available for this flood event. From the information available, the source of the flooding to the Monaltrie Hotel basement is unclear. It is possible that this has been caused by surface water flooding, drainage systems being overwhelmed or via groundwater through the basement walls. There are no reports or evidence of ground level flooding at the Hotel, which is supported by the 1993 flood extent map.

Based on the evidence available, it is considered that there is a very good correlation between the modelled flood extent and the actual flood extent for the 1993 event.

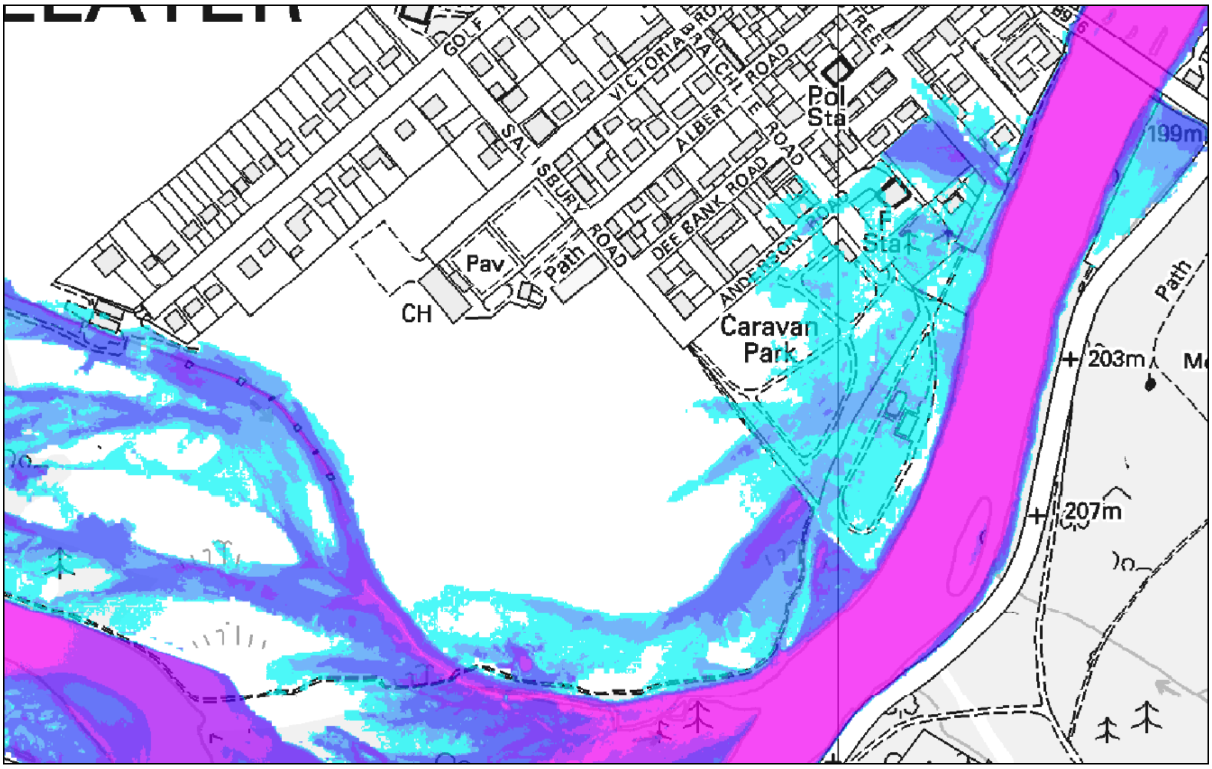


Figure 3.7 Extract from Drawing IBE1358_FE_331 - Flood Extent Map 17th January 1993

The observed flows and levels for this event at each of the gauges (12003, 12005 & 12006) have been compared to the flows and levels extracted from the model at the corresponding cross sections (RD.021, RM.022 & RG.016) in Figure 3.8. This shows that for each of the three gauges, the flows extracted from the model adequately represent the observed flows. The modelled levels at section RD.021 on the River Dee also represent the observed levels at the Polhollick gauge (12003) well. However there is a difference between the modelled and observed levels of approximately 500mm at the River Gairn gauge and approximately 300mm at the gauge on the River Muick. The issues in achieving model calibration at each gauging station location has been further explained in Section 3.3.2, including Section 3.3.2.4.

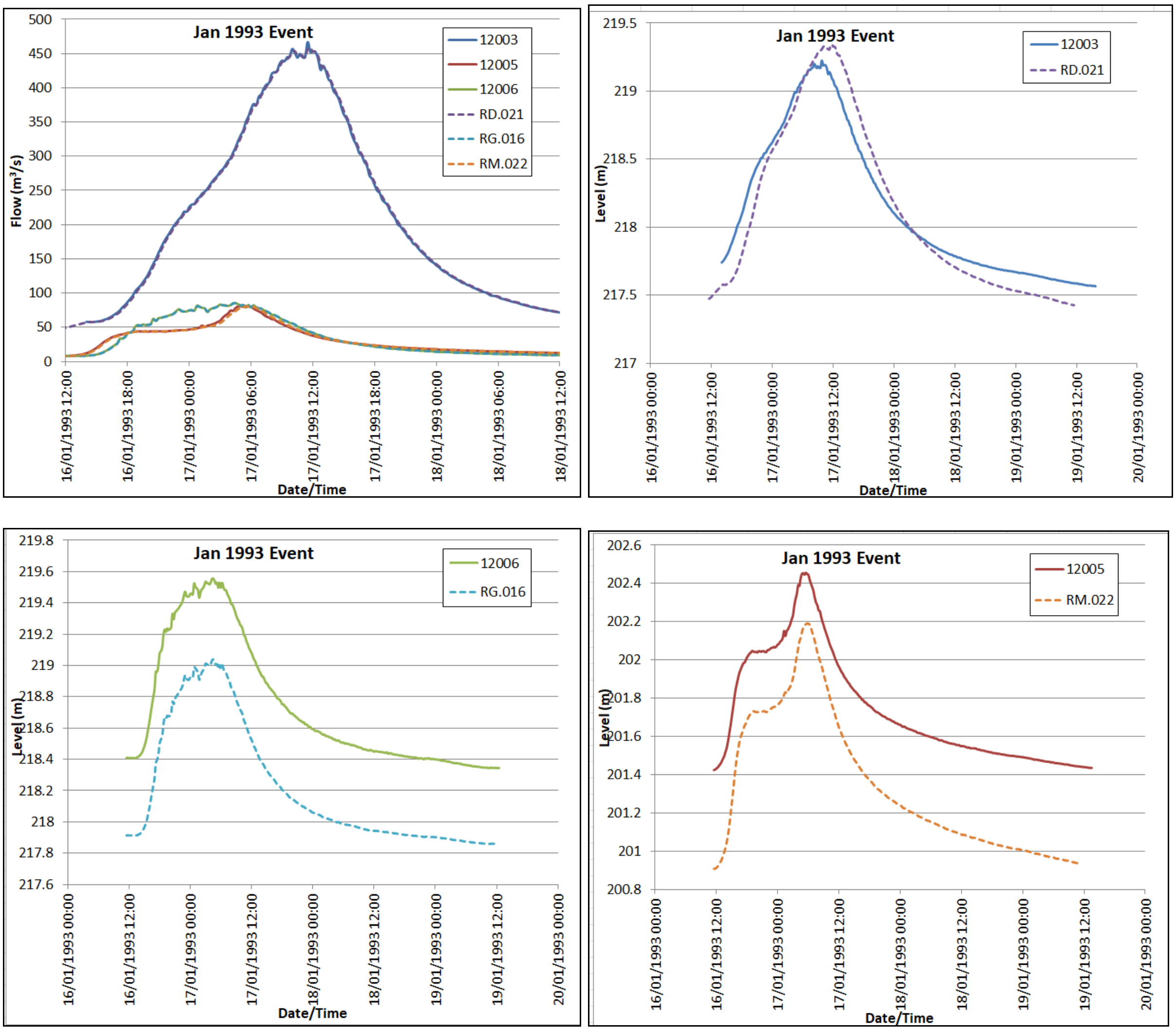


Figure 3.8 Modelled vs observed flow and level time series plots

3.3.5.2 August 2014

On the 11th August 2014, water levels in the River Dee rose to cause flooding in Ballater. Section 2.1.3 outlines the data available to facilitate model calibration. Media reports state that the caravan park was closed and people were evacuated from the site as well as a number of roads being closed as a result of the River Dee Flooding.

An extract from the flood map for this simulated event (IBE1358_FE_321) can be seen in Figure 3.9 which shows the caravan park, properties on Anderson Road flooded, and flooding (between 0 m and 0.25 m deep) as far as Dee Bank Road. A comparison between the flood map and the photographs shown in Figure 2.2 to Figure 2.6 (taken within 1 hour and 15 minutes of the peak flow recorded at the Polhollick gauge on the River Dee) shows that:

- Figure 2.2: The photograph shows flooding as far as the junction of Richmond Place and Dee Street, with the flood map showing flooding beyond this point to Dee Bank Road.

- Figure 2.3: The photograph shows the water level on the upstream side of the Royal Bridge, and does not provide an indication of the extent of flooding. The water level can be seen at approximately one block below the arch at the upstream face of the bridge. Using the topographical survey and assuming a block height of 350mm the water level in this photo is estimated to be 197.76mOD. A peak level water of 197.799mOD was extracted from the model at the upstream face of the Royal Bridge which correlates well to the aforementioned estimated level of 197.76mOD.

- Figure 2.4: The photograph shows flooding along the path approximately in line with where the road within the caravan park has a right angle turn. The flood map shows flooding on the pathway a short distance beyond this point towards Salisbury Road.

- Figure 2.5: The photograph shows flooding within the open area adjacent to the fire station, with the flood map showing flooding around the fire station (between 0 m and 0.25 m deep).

- Figure 2.6: The photograph shows flooding within the caravan park, which is supported by the flood map. The photograph does not provide any further indication of the extent of flooding, as the whole area within the photograph is flooded with no discernible extent to the flooding identified.

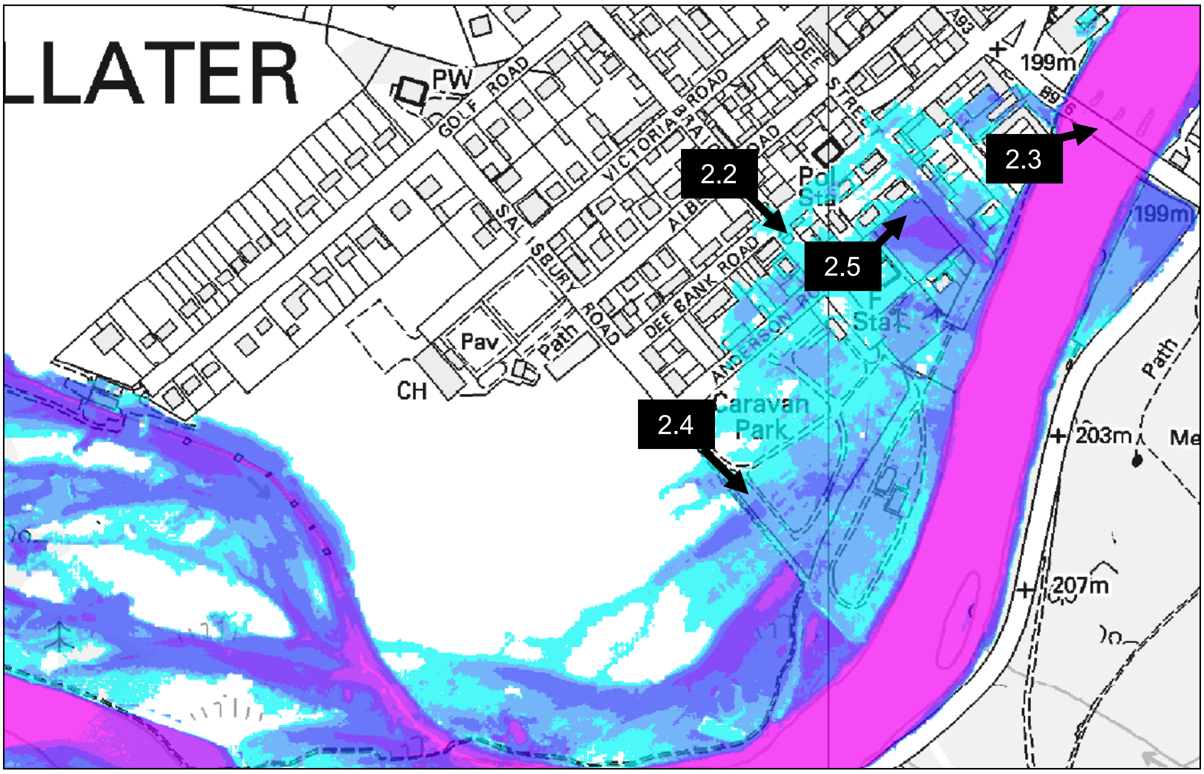


Figure 3.9 Extract from Drawing IBE1358_FE_321 - Flood Extent Map 11th August 2014 with approximate location of photographs in Figures 2.2 to 2.5 identified.

Based on the evidence available, it is considered that the modelled flood extent is greater than the actual flood extent for the 2014 event. RPS undertook a series of model simulations in order to improve the calibration between the modelled extents and the actual flood extent, as outlined in Section 1.3 of the 'Calibration' document within Appendix G. RPS were able to better represent the 2014 flood event by reducing the roughness parameter within the 1D model domain by 13% (in comparison with the December 2015 model), however, it was not possible to justify this change for a flood event occurring during the summer when vegetation cover would be greater. RPS liaised with SEPA who stated that it would be preferable to adopt a single design model network for all three historical flood events (as opposed to two or three networks with differing model parameters to achieve better calibration for a particular flood event).

As the design network model shows a very good correlation for both the 1993 flood event and the largest, most recent flood event in December 2015 (Section 3.3.5.1 and Section 3.3.5.3 respectively), it was concluded that the differences between the modelled and actual flood extents for the 2014 flood event should be accepted. If the amendments required to the 2014 model to improve calibration are applied to the 1993 and 2015 models, this results in a poorer correlation between the modelled and actual extents for both these events. This is not considered an appropriate method, as the largest flood event (which occurred most recently and has the most data to facilitate calibration) should achieve the best calibration possible.

This will be considered further during the optioneering phase of the Ballater Flood Protection Study to ensure that the preferred option robustly reduces the flood risk for events of all return periods up to the standard of protection.

The observed flows and levels for this event at each of the gauges (12003, 12005 & 12006) have been compared to the flows and levels extracted from the model at the corresponding cross sections (RD.021, RM.022 & RG.016) in Figure 3.8. This shows that for each of the three gauges, the flows extracted from the model adequately represent the observed flows. The modelled levels at section RD.021 on the River Dee also represent the observed levels at the Polhollick gauge (12003) well. However there is a difference between the modelled and observed levels of approx. 400mm at the River Gairn gauge and approx. 300mm at the gauge on the River Muick. The issues in achieving model calibration at each gauging station location has been further explained in Section 3.3.2, including Section 3.3.2.4.

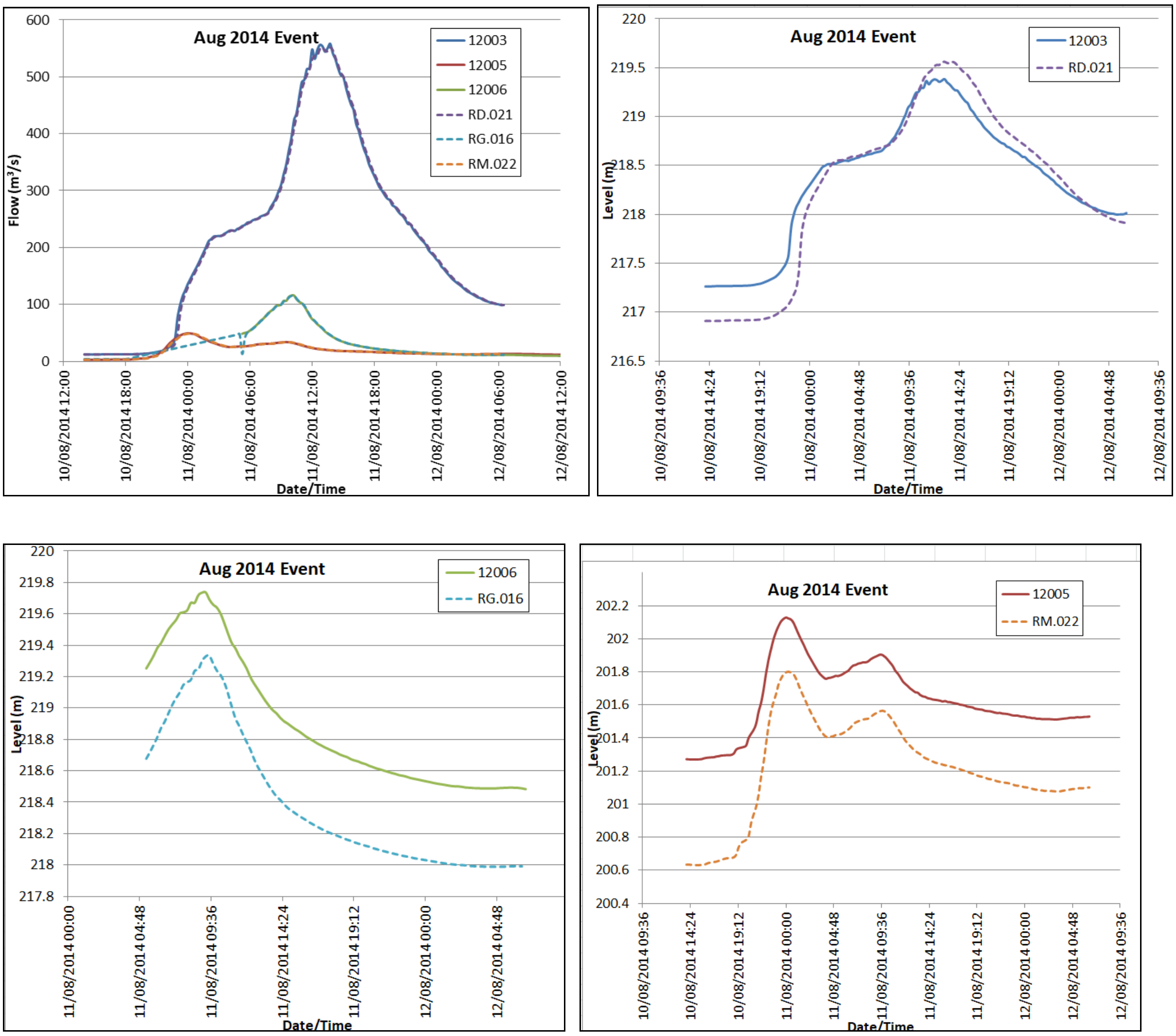


Figure 3.10 Modelled vs observed flow and level time series plots

3.3.5.3 December 2015

Ballater suffered extensive flooding in December 2015. Media reports state that flooding effected over 300 residential and commercial properties resulting in hundreds of residents being evacuated. YouTube videos show the River Dee swollen well beyond its banks with high velocity flows through the town. Mobile homes from the caravan park are seen being carried through the streets on the flood waters and along the river. A couple of mobile homes are seen to be caught on the bridge piers before being demolished and the remnants carried under the bridge.

Anecdotal evidence collected by RPS from local residents and Aberdeenshire Council (as stated in Section 2.6) suggested a breach in the informal flood bund along the golf course contributed to the overland flooding from that direction. This was represented in the simulation using a Real Time Control. The breach was assumed to occur near instantaneously as the defence level was exceeded, with the crest level reduced to the adjacent ground level. The breach length was defined as approximately 35m as shown in Figure 3.11, in view of information received during the walkover survey and Aberdeenshire Council briefing notes. The 2012 LiDAR was checked against the 2017 topographical survey for this area to ensure that the bund was not rebuilt to a higher crest level than it was before the breach occurred. The 2012 LiDAR was found to have approximately 100mm higher levels than the 2017 survey. The accuracy of the 2012 LiDAR is +/- 150 millimetres (root mean square error) and is considered the most likely explanation for the difference in bund levels between the two survey datasets.

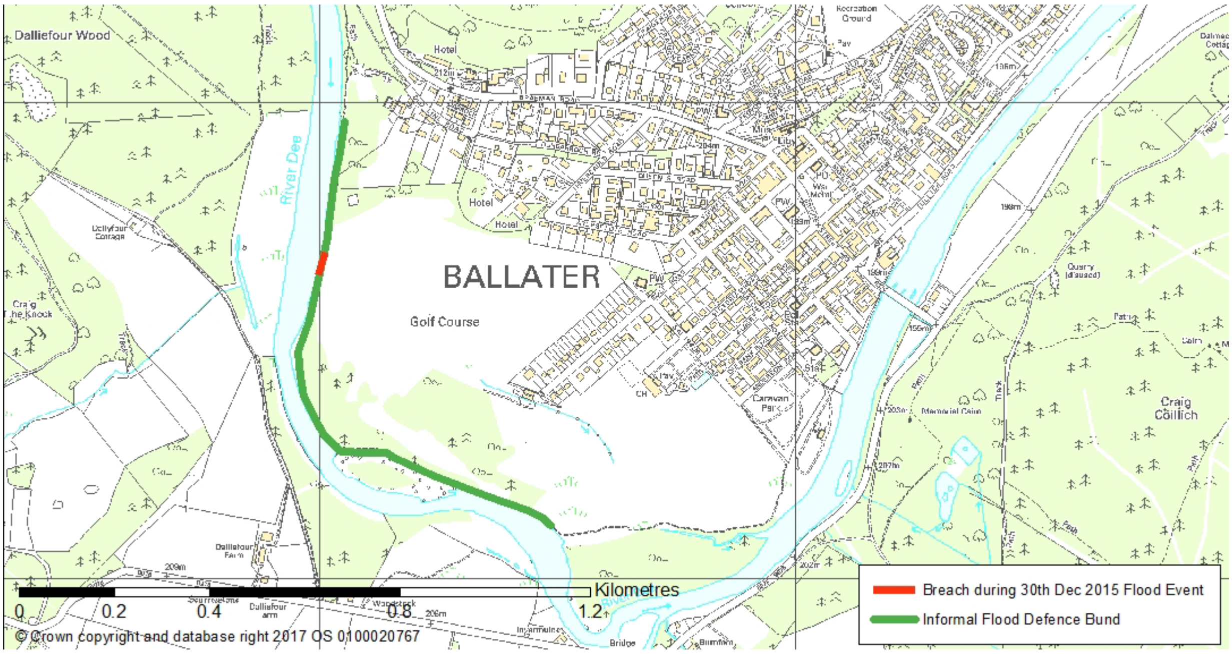


Figure 3.11 Location and extent of breach scenario for the 30th December 2015 flood event

The recorded levels from the survey of the flood markers (Section 2.1.4) and AutoCAD drawing were compared to the levels extracted from the model simulation at the corresponding locations, as shown in Appendix D and Figure 3.12. This shows that 82% of the modelled levels are within +/- 300mm and 50% are within +/- 150mm of the recorded levels. It must be noted that it is not possible to determine the accuracy of the flood markers (in terms of who placed the markers, when this occurred and how representative they are of the actual flood levels which occurred), and it would not be possible to ensure all of the modelled levels are within +/- 300mm of recorded levels, due to the variation in the recorded levels. RPS considers that the December 2015 model achieves a 'best fit' to the available recorded levels.

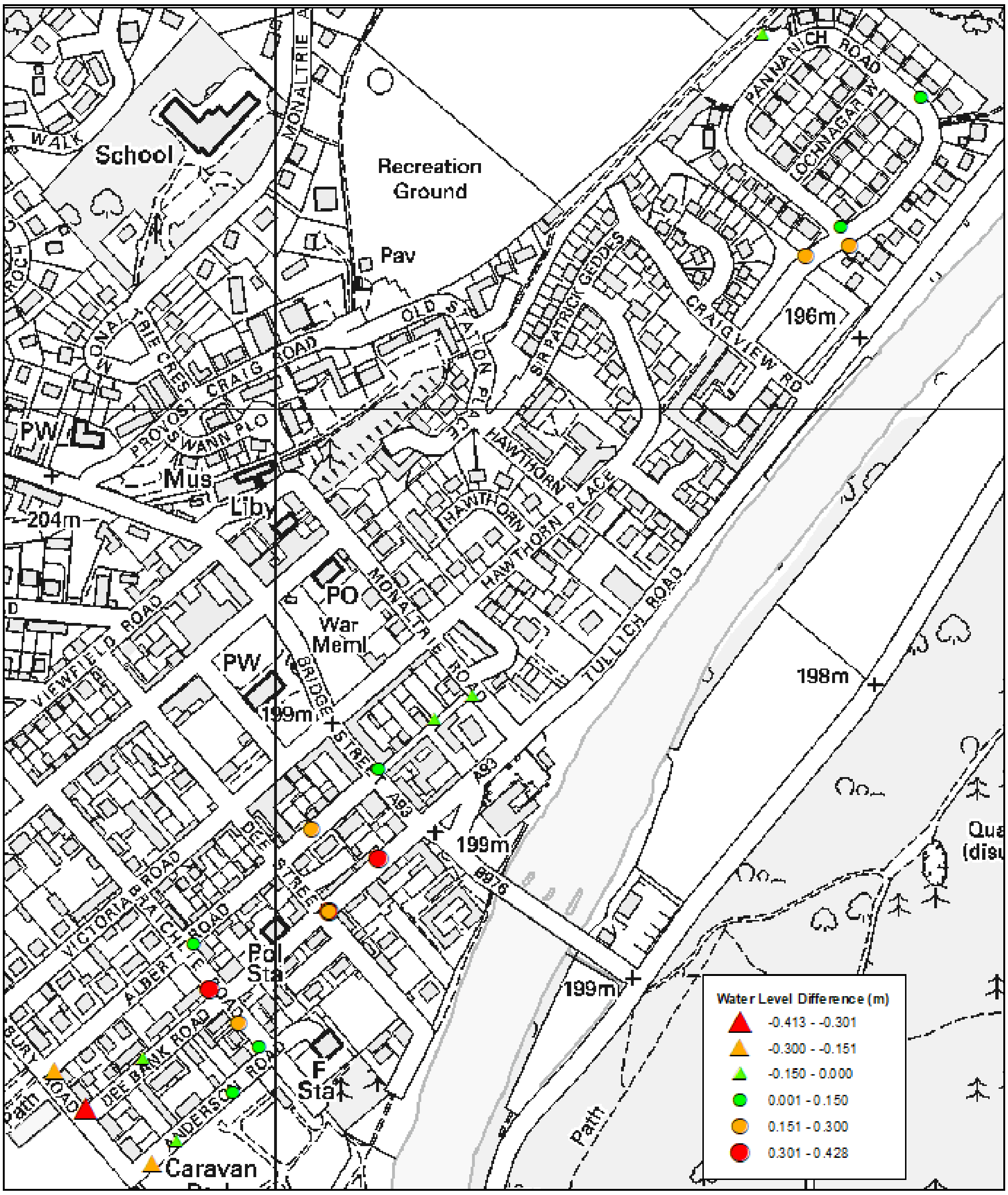


Figure 3.12 Comparison of modelled levels with recorded levels (modelled levels minus recorded levels) at flood marker locations

Extracts from the flood map for this simulated event (IBE1358_FE_301) can be seen in Figure 3.13 and Figure 3.14 which shows a large area of town affected by flooding. This supports the anecdotal evidence available for this flood event shown in Figure 2.8. Figure 2.9 and Figure 2.10 give an indication of the flooding, however, do not provide clarity on the extent or depth of flooding.

Figure 2.11, taken one hour and twenty minutes prior to peak flow recorded at Polhollick, shows the water level on the downstream side of the Royal Bridge, but does not provide an indication of the extent of flooding. The water level can be seen at approximately the springing level of the arch. Using the topographical survey, the water level in this photo is estimated to be 198.11mOD. A peak water level of 198.59mOD was extracted from the model at the downstream face of the Royal Bridge. At the time the photograph was taken, the modelled water level at the downstream side of the bridge is 198.41mOD, which correlates well to the aforementioned estimated level of 198.11mOD. Figure 2.12, taken over one hour and thirty minutes prior to the peak flow recorded at Polhollick, shows flooding up to Hawthorn Place along Bridge Street. The flood map shows shallow flooding beyond this point which is considered representative given the time that the photograph was taken. Figure 3.12 shows that the modelled level is within 150mm of the recorded level at the junction of Bridge Street and Albert Road (which is the next junction along Bridge Street).

Based on the evidence available, it is considered that there is a very good correlation between the modelled flood extent and the actual flood extent for the 2015 event.

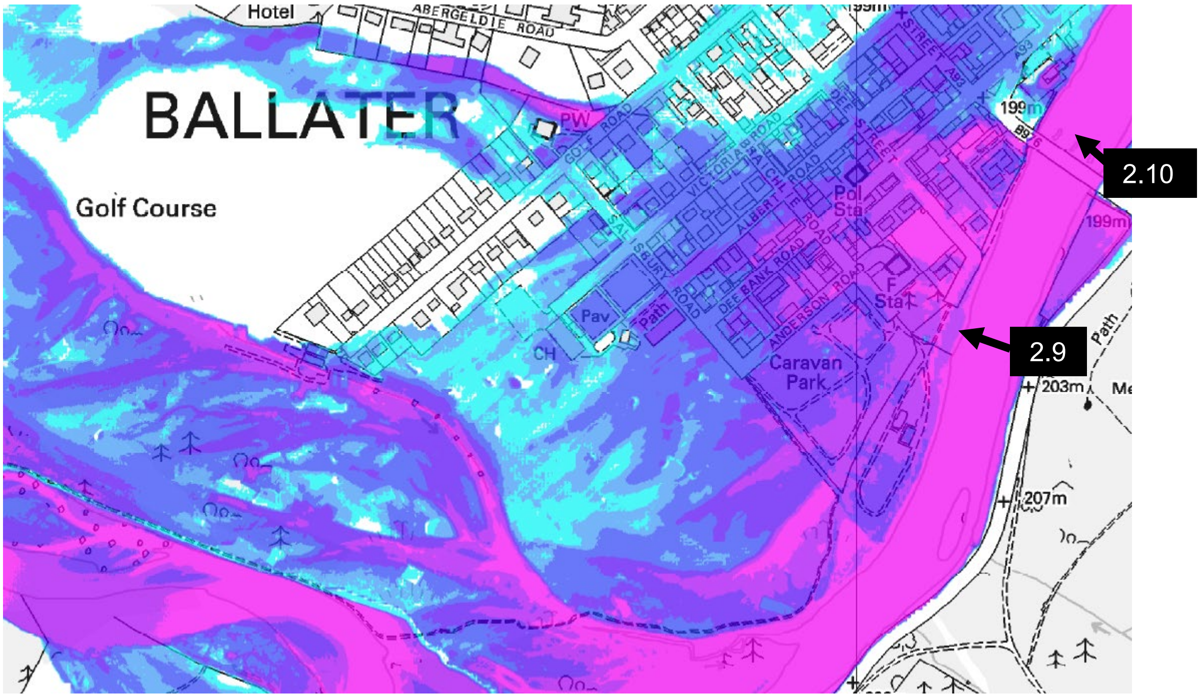


Figure 3.13 Extract from Drawing IBE1358_FE_301 - Flood Extent Map 30th December 2015 with approximate location of photographs in Figures 2.9 to 2.10 identified

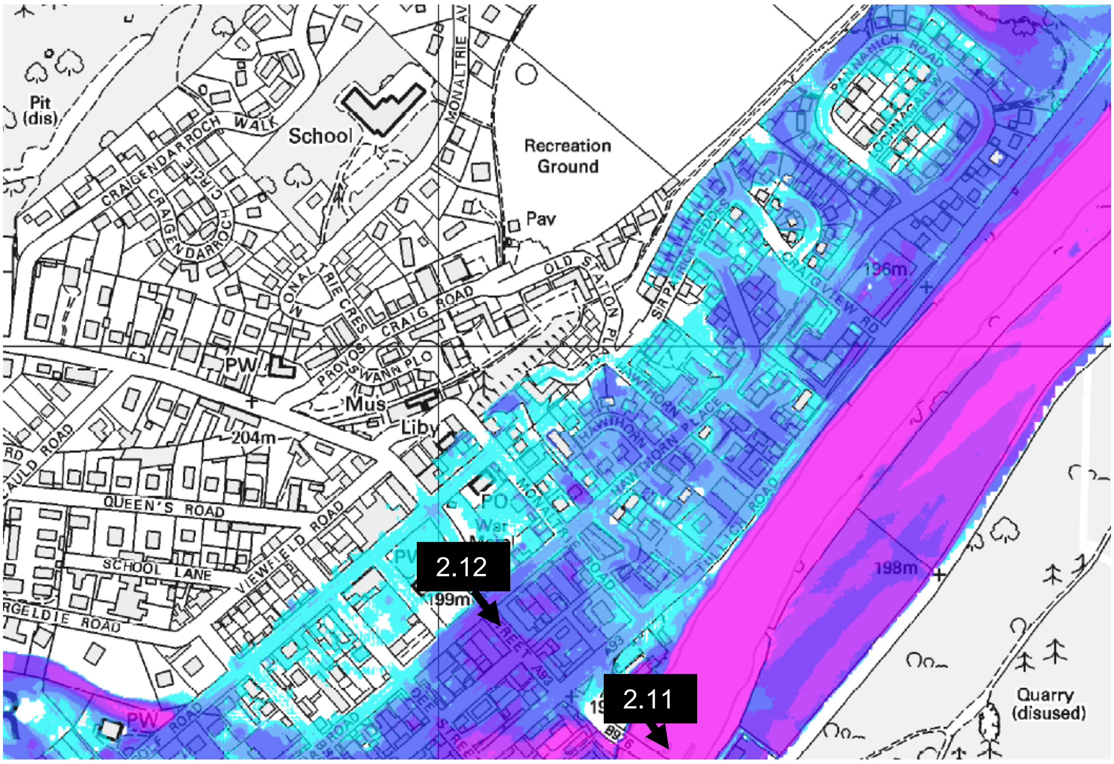


Figure 3.14 Extract from Drawing IBE1358_FE_301 - Flood Extent Map 30th December 2015 with approximate location of photographs in Figures 2.11 to 2.12 identified

The observed flows and levels for this event at each of the gauges (12003, 12005 & 12006) have been compared to the flows and levels extracted from the model at the corresponding cross sections (RD.021, RM.022 & RG.016) in Figure 3.8. This shows that for each of the three gauges, the flows extracted from the model adequately represent the observed flows. The modelled levels at section RD.021 on the River Dee also represent the observed levels at the Polhollick gauge (12003) well. However there is a difference between the modelled and observed levels of approx. 400mm at the River Gairn gauge and approx. 500mm at the gauge on the River Muick. The issues in achieving model calibration at each gauging station location has been further explained in Section 3.3.2, including Section 3.3.2.4.

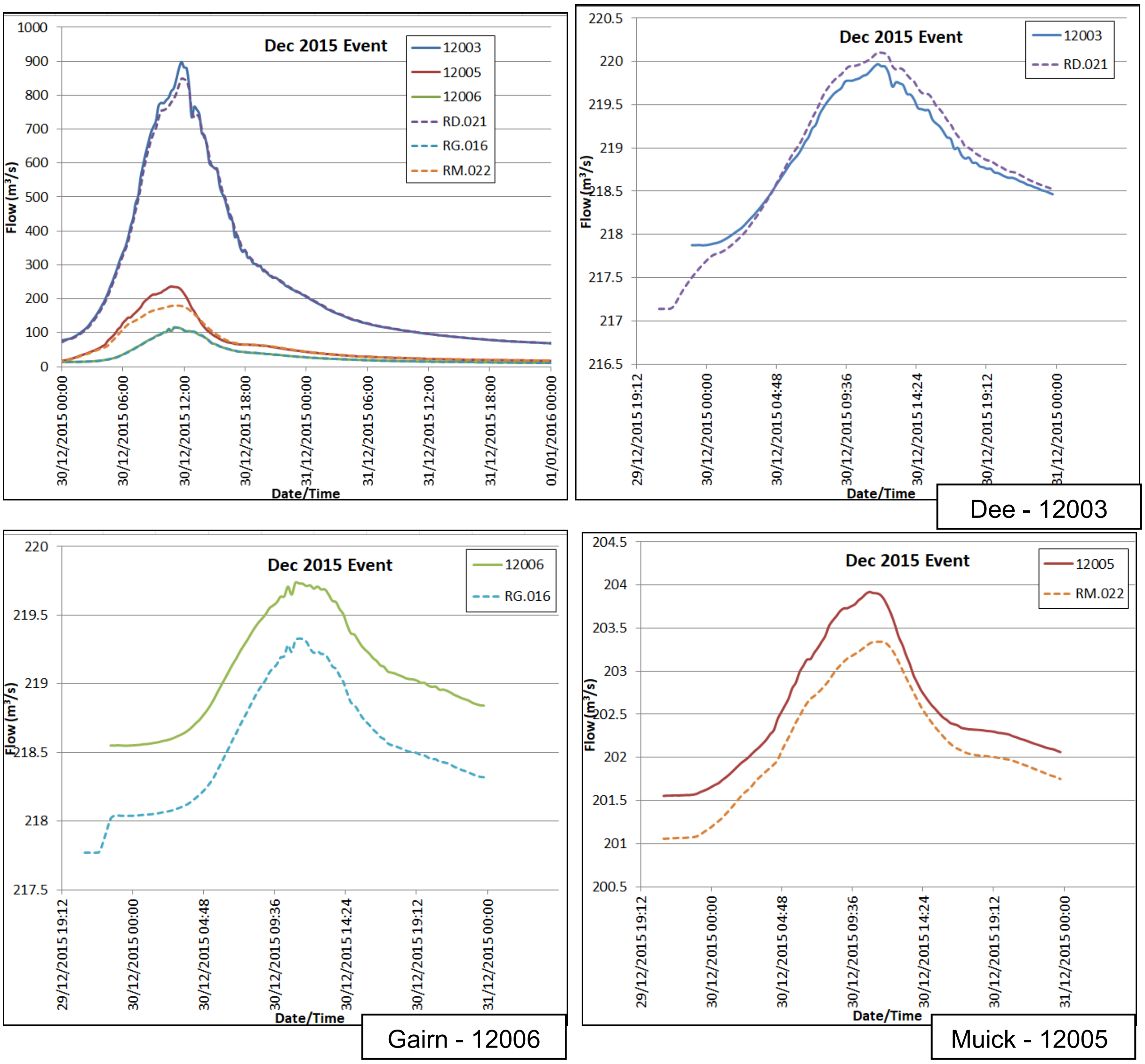


Figure 3.15 Modelled vs observed flow and level time series plots

3.3.6 Public Consultation on Draft Flood Mapping

RPS and Aberdeenshire Council held a public consultation meeting on the draft flood extent mapping in Ballater on Monday 11th December 2017. A total of 15 people attended and the comments received focussed on the December 2015 flood extent mapping and included:

- Feedback on the flood extents shown for the December 2015 event was positive. There were no significant discrepancies with the flood extents identified.
- It was suggested that the area off Craigview Road was flooded twice via two separate mechanisms. The first flood was due to flood water which had flowed through the town via the golf course, with the second flood as a result of direct inundation from the Dee (downstream of Ballater Bridge).

The flood maps subject to consultation were based on the outputs from Simulation No.1, as detailed in the Calibration note in Appendix G. In order to replicate the flooding mechanism at Craigview Road (as described during the consultation), a number of adjustments were made to the model. However the adjustments required to achieve the two separate mechanisms in the order described were beyond acceptable limits and would not be justified without further specific recorded information.

Following the public consultation, RPS received additional data (which is discussed in Section 2) which allowed model calibration to be improved, as outlined in Appendix G. RPS have reviewed the comments received during the public consultation in conjunction with the updated flood mapping (Appendix C and Appendix F) and are satisfied that the flood extents are representative of the comments received.

3.3.7 Summary

Although Ballater has suffered extensive flooding in the past, there is limited recorded information available from historic events which can be used to facilitate model calibration and verification. RPS have used the information that is available, in conjunction with anecdotal evidence and comments from the public consultation, to achieve model calibration.

There is some uncertainty associated with the reported flooding mechanism in the area off Craigview Road during the December 2015 event. However, the modelled peak flood levels correlate well with the recorded flood mark levels (with all five of the modelled levels within +/- 300mm and three of the five within +/- 150mm of the recorded level in this area). In order to calibrate the modelled stage-discharge relationship at low flows at each gauging station, RPS had to add an artificial interpolated cross-section immediately downstream of each gauge. These amendments were made in order to calibrate the model at low flows only, and are excluded from the calibrated model used in the sensitivity analysis and design simulations.

There is a very good correlation between the modelled flood extents and the reported flood extents for both the 1993 and 2015 flood events. It is considered that the modelled flood extent is greater than the actual flood extent for the 2014 event. However, in order to adopt a single design network for this study, it was concluded that the differences between the modelled and actual flood extents for the 2014 flood event should be accepted. This will be considered further during the optioneering phase of the Ballater Flood Protection Study to ensure that the preferred option robustly reduces the flood risk for events of all return periods up to the standard of protection.

It is noted that the Scottish Water Sewage Works (located adjacent to the River Dee, downstream of Ballater) is at risk of flooding from the 20% AEP event and the Scottish Water Water Works (located adjacent to the River Gairn, upstream of the Bridge of Gairn) is at risk of flooding from a 0.5% AEP event.

RPS consider that the model has been calibrated to best represent the flooding mechanisms in Ballater and is suitable to be used in sensitivity analysis simulations and design model simulations.

3.4 HYDRAULIC MODEL SENSITIVITY

A sensitivity test was carried out to assess the impact of changes to various inputs and parameters on the flood levels in the model. The testing was carried out on the 0.5%AEP (1 in 200 year return period) design model and the following parameters and inputs were adjusted;

1. Floodplain and channel roughness - increased and decreased by 40%
2. Input flow - increased and decreased by 20%
3. Blockages – 50% blockage to the Gairn Bridge and the Bridge of Muick, 25% blockage to the Royal Bridge

Tables showing the predicted water levels at the modelled cross sections for the sensitivity tests can be seen in Appendix E.

3.4.1 Roughness

Adjusting the floodplain and channel roughness had the greatest impact on the river levels affecting them by a maximum of +764mm and -1.060m. Figure 3.16 and Figure 3.17 show the study area indicating that the model has a high sensitivity to change in roughness values. It is estimated that there is an increase of 2% in the number of properties affected due to the increase in roughness and a reduction of 37% in the number of properties affected due to the decrease in roughness, showing that there is a low impact to the number of properties affected when roughness is increased, and a high impact to the number of properties affected when roughness is decreased.

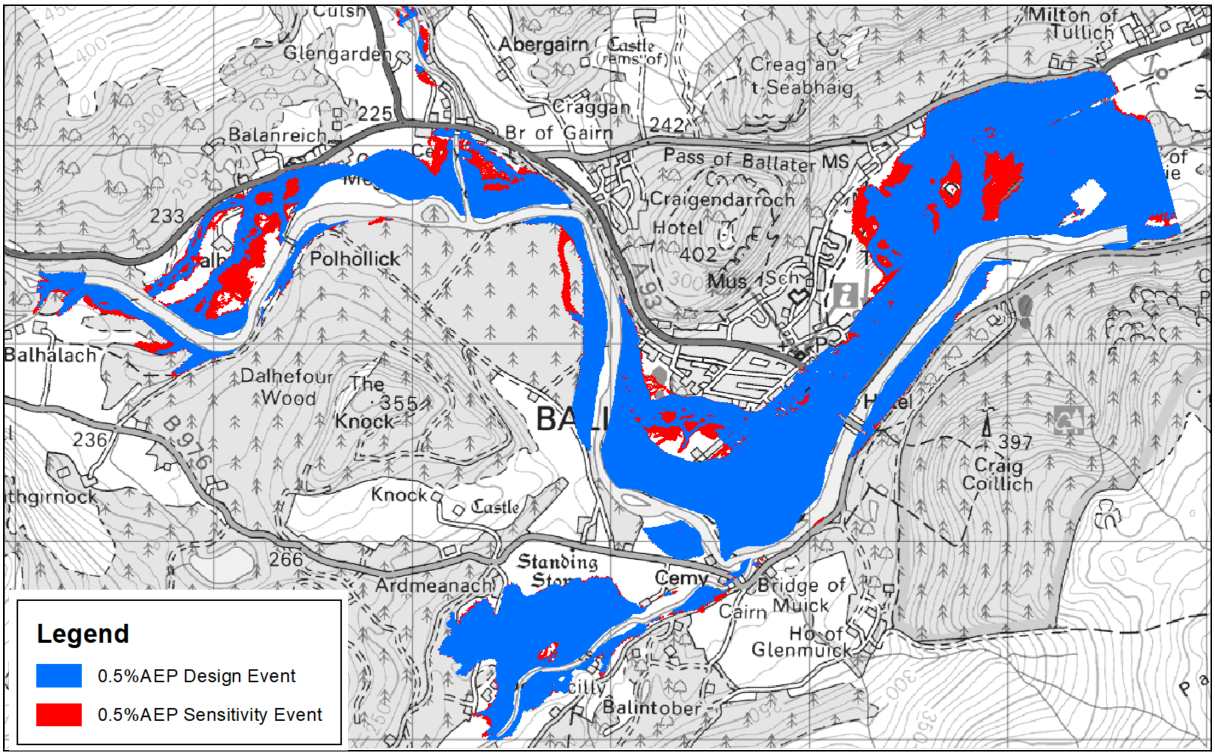


Figure 3.16 Comparison between 0.5%AEP Design Event and 0.5%AEP Sensitivity Roughness Increase Event

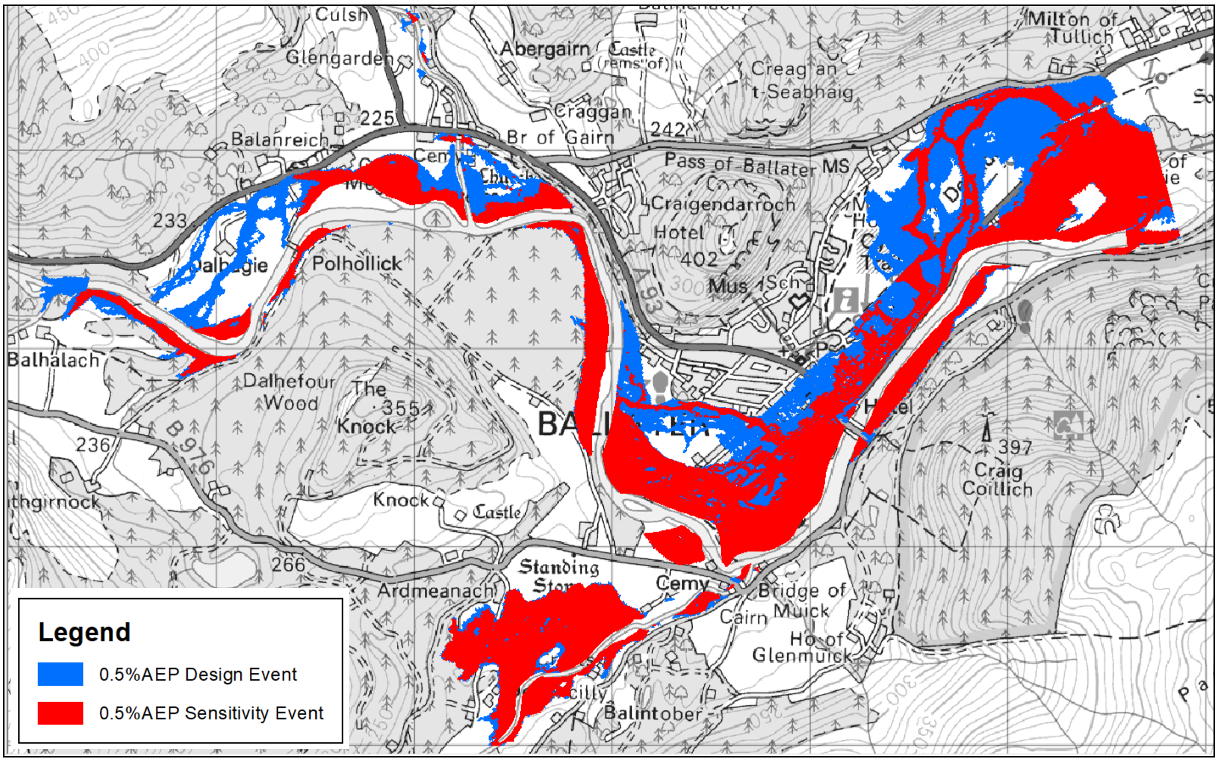


Figure 3.17 Comparison between 0.5%AEP Design Event and 0.5%AEP Sensitivity Roughness Decrease Event

3.4.2 Input flow

The model inflows had generally less of an impact on river levels in the model than changes in roughness coefficients. When the inflows were increased and decreased by 20%, the maximum impact on the river levels was +476mm and -516mm respectively. Figure 3.18 and Figure 3.19 show the study area indicating that the model has a moderate sensitivity to flow parameters with a low impact to properties across the study area. It is estimated that there is an increase of only 1% in the number of properties affected due to the increase in flow and a reduction of 13% in the number of properties affected due to the decrease in flows.

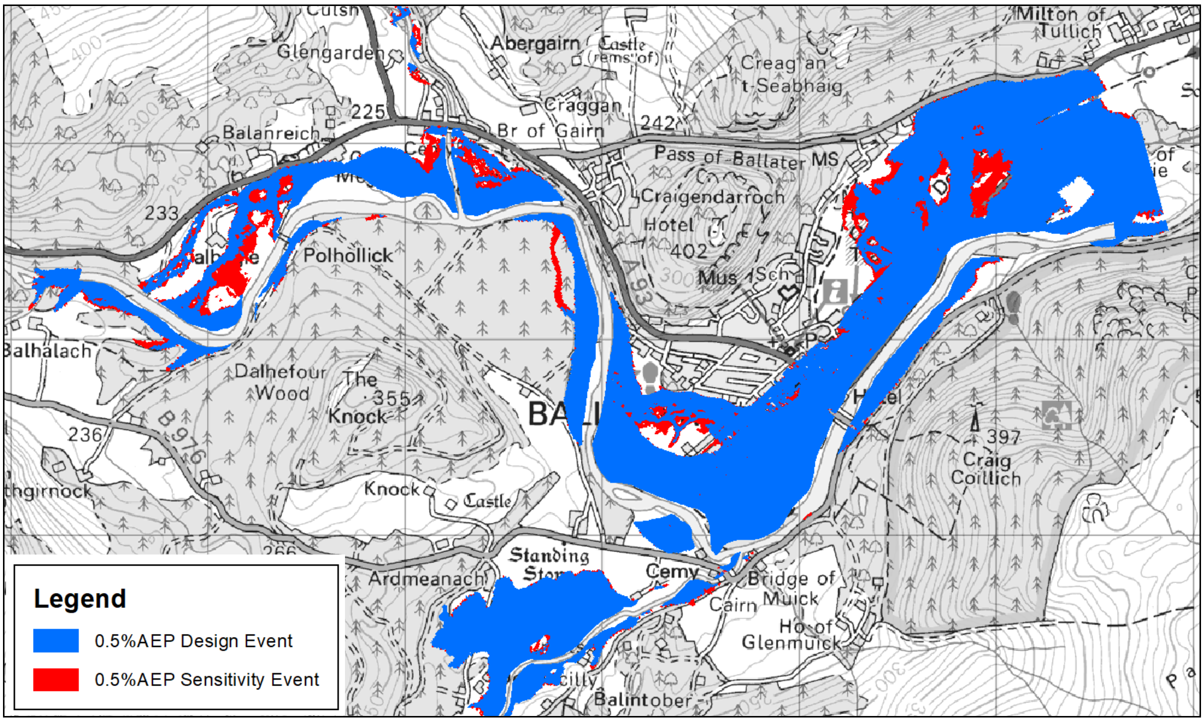


Figure 3.18 Comparison between 0.5%AEP Design Event and 0.5%AEP Sensitivity Flow Increase Event

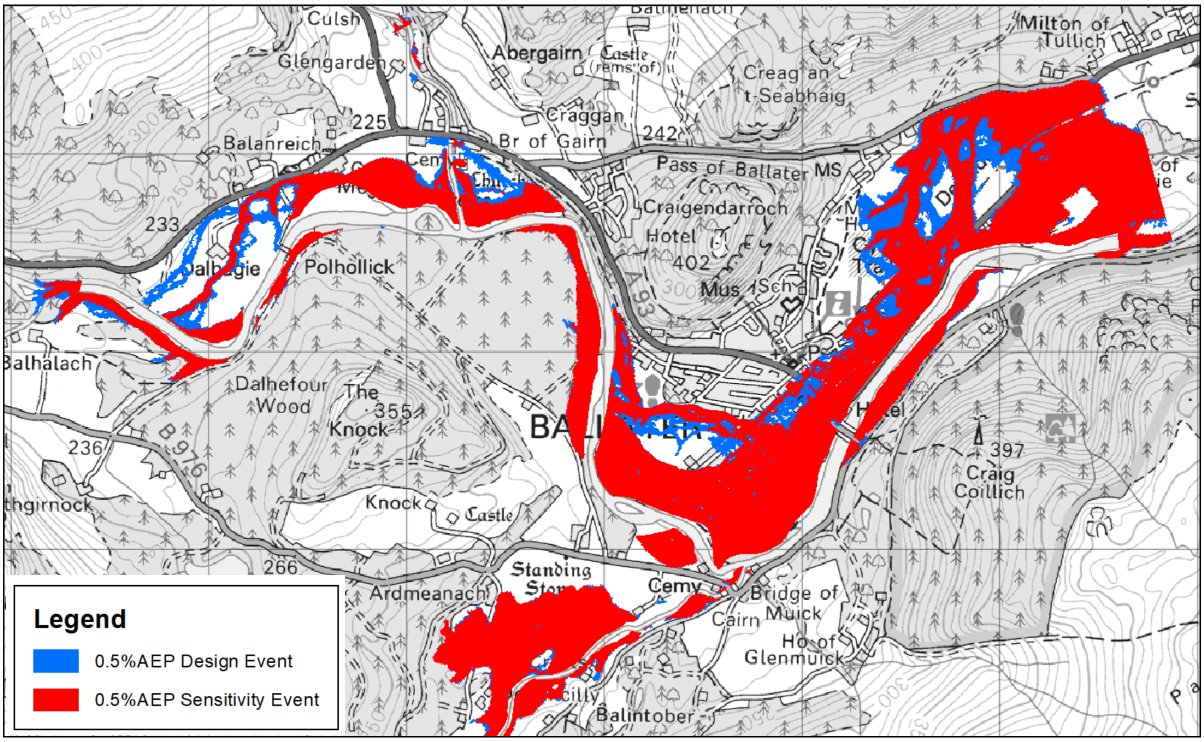


Figure 3.19 Comparison between 0.5%AEP Design Event and 0.5%AEP Sensitivity Flow Decrease Event

3.4.3 Blockages

Blockage of three structures, namely the Royal Bridge, the Gairn Bridge and the Bridge of Muick, were assessed in three separate simulations. A blockage of 50% of the opening of the Gairn Bridge and the Bridge of Muick was applied using the ‘sediment’ option within the software at each bridge. The ‘sediment’ option reduces the capacity of the bridge by obstructing the flow in the model. The Sediment Depth represents permanent, consolidated sediment deposits. The system assumes that the sediment is constant; it does not allow for the erosion or deposition of sediment. The transport of sediment through the system is not modelled. A blockage of 25% of the openings to the Royal Bridge was applied by removing one of the four arches. Due to the size of the arches in the Royal Bridge, it is unlikely that a blockage greater than this would occur.

3.4.3.1 Royal Bridge (B971)

The largest impact on water levels is seen at the upstream face of the bridge where the water depth increases by 81mm. It made no significant difference to the river levels or flood extents, and had no impact on the number of properties affected. Therefore the model can be considered to have a low sensitivity to blockage at the Royal Bridge, with a low impact on the number of properties affected.

3.4.3.2 Gairn Bridge (A93)

Applying a 50% blockage of the opening to the Gairn Bridge equates to a depth of sediment of 2.8m. The largest impact on water levels is seen at the upstream face of the bridge where the water depth increases by 2.9m. The impact on levels in the River Gairn is seen for approximately 260m upstream of the bridge where the increase in level reduces to 68mm at section RG.008. The increase in flood extent is minimal as seen in Figure 3.20, however it brings an additional 3no. properties into the flood extent on the right hand bank of the River Gairn immediately upstream of the Gairn Bridge. This equates to less than 0.5% in the number of properties affected due to the blockage, and so the model can be considered to have a low sensitivity to blockage at the Gairn Bridge, with a low impact on the number of properties affected.

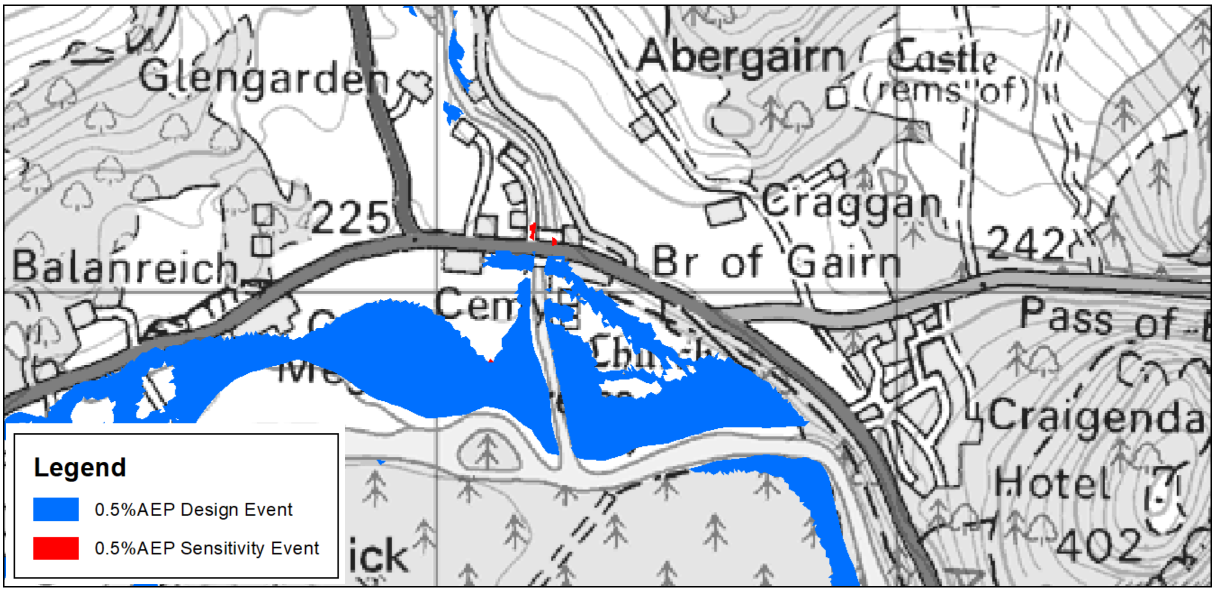


Figure 3.20 Comparison between 0.5%AEP Design Event and 0.5%AEP Sensitivity Gairn Bridge Blockage Event

3.4.3.3 Bridge of Muick (B976)

Applying a 50% blockage of the opening to the Bridge of Muick equates to a depth of sediment of 2.6m. The largest impact on water levels is seen at the upstream face of the bridge where the water depth increases by 1.4m. The impact on levels in the River Muick is seen for approximately 500m upstream of the bridge where the increase in level reduces to 35mm at section RM.016. The increase in flood extent is minimal as seen in Figure 3.21 and no additional properties are affected, and so the model can be considered to have a low sensitivity to blockage at the Bridge of Muick, with a low impact on the number of properties affected.

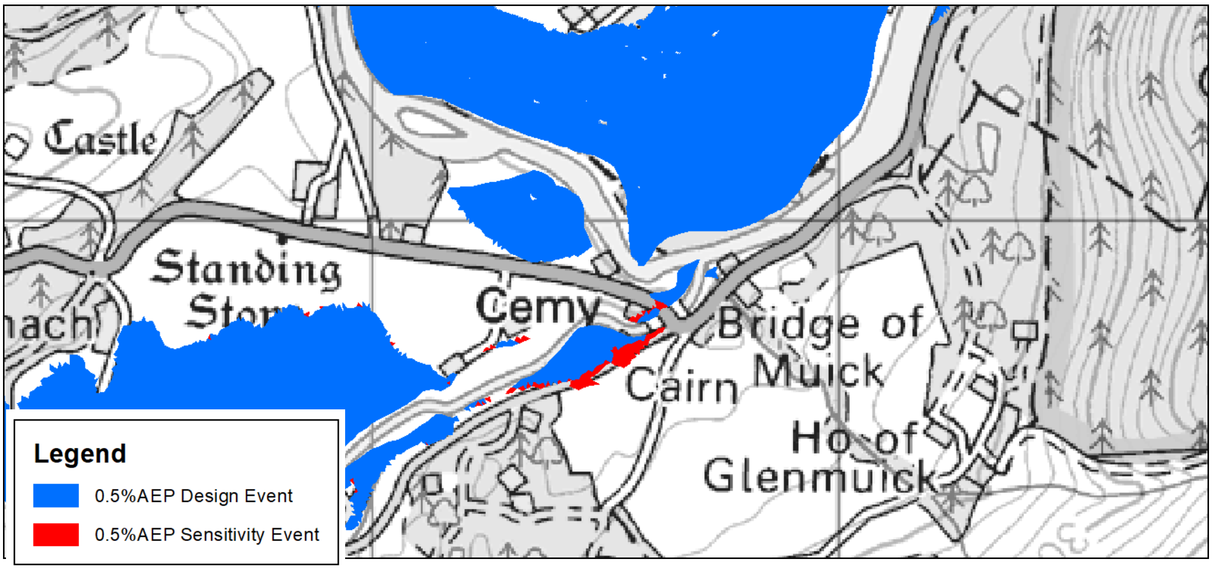


Figure 3.21 Comparison between 0.5%AEP Design Event and 0.5%AEP Sensitivity Bridge of Muick Blockage Event

3.4.4 Summary

The largest negative effect on the river levels was an increase in level by 764mm when the roughness was increased by 40%. This occurs on the River Dee where it meanders south between Dalliefour Wood and Craigendarroch (RD.041) where the flow is restricted within the valley. This indicates that the model is sensitive to changes in the roughness coefficients. The model is considered to have a low sensitivity to changes in the blockages at each of the three bridges and changes to input flows.

3.5 HYDRAULIC MODEL PERFORMANCE

A mass balance check has been carried out on the 0.5% AEP (1 in 200 year return period) model to ensure that the total volume of water entering and leaving the model at the upstream and downstream boundaries balances the quantity of water remaining in the model domain at the end of a simulation. As a general rule of thumb, mass errors should be less than 2%. If the mass error is greater than 2%, the cause and location of the mass error within the model schematisation should be identified and the consequence of this error assessed and improvements to the model considered. If the mass error is greater than 5%, then it suggests that the model schematisation is not robust and needs to be reviewed (Environment Agency, 2010). The mass balance assessment of the model is within acceptable bounds with a Volume Balance Error of -0.01% during the 0.5% AEP (1 in 200 year return period) flood event.

3.6 MODEL SIMULATIONS

3.6.1 Design Scenarios

The calibrated river model was simulated to determine water levels for a range of flood events. Flood maps have been generated for the following range of return periods:

1. 50% AEP (1 in 2 year return period)
2. 20% AEP (1 in 5 year return period)
3. 10% AEP (1 in 10 year return period)
4. 3.33% AEP (1 in 33 year return period)
5. 2% AEP (1 in 50 year return period)
6. 1% AEP (1 in 100 year return period)
7. 0.5% AEP (1 in 200 year return period)
8. 0.1% AEP (1 in 1000 year return period)
9. 3.33% AEP plus 20% for climate change (1 in 33 year return period plus climate change)
10. 0.5% AEP plus 20% for climate change (1 in 200 year return period plus climate change)

The design scenarios have been simulated with the existing informal flood bund along the golf course included. The flood maps are presented in Appendix F. Further detail on the model can be seen in the model log in Appendix G. The model files are provided in Appendix H.

3.6.2 Existing Defences

An earth bund was constructed on the left bank of the River Dee adjacent to Ballater Golf Course in the early 1990's. There is no information available that the structure was designed to a standard of protection. The bund protects against the high frequency flood events. However, during the simulated 10% AEP (1 in 10 year return period) event, the bund is overtopped.

An additional 'without defence' scenario has been undertaken to define the area that benefits from this defence. In this simulation the informal flood bund along the golf course has been removed with the bank levels reduced to natural ground level. The 20% AEP (1 in 5 year return period) event was used as this is the largest event which does not overtop the defence. The extent of the defence removed and the benefitting area can be seen in the drawings in Appendix I. This shows that there are numerous properties within Ballater town centre which would be protected from flooding by the informal embankment if a flood event with an AEP of 20% (1 in 5 year return period) were to occur. This assumes that the informal embankment remains intact during the flood event.

3.6.3 Breach Scenarios

The informal defence along the River Dee at Ballater Golf Course overtops in the design simulation for a 10% AEP (1 in 10 year return period) flood event.

A breach scenario was undertaken for the December 2015 flood event. The breach was assumed to occur near instantaneously as the defence level was exceeded, with the crest level reduced to natural ground level. The breach length was defined as 35 metres and located as shown in Figure 3.11, based on information received during the walkover surveys where estimated extents of the breach where discussed and by briefing notes provided by Aberdeenshire Council.

3.6.4 Removal / addition of Sediment Scenarios

RPS liaised with Alasdair Matheson (SEPA) regarding the requirement to undertake Sediment Scenario simulations. It was agreed that at this stage, it would be very difficult / impossible to provide estimated depths / volumes of sediment to be removed / added to commence a model simulation which would provide value to the Ballater Flood Study. Sediment management is likely to only be significant should proposed flood defences be located directly on the river bank (instead of being set back), where erosion could impact the integrity of the defence in the future. Consequently, the requirement to undertake these simulations will be reviewed following the identification of a preferred option.

3.6.5 Comparison with SEPA Strategic Flood Maps

The 0.5% AEP (1 in 200 year return period) event was compared with the SEPA Fluvial Medium Likelihood flood mapping. The extents are not expected to be the identical as different survey, hydrological analysis and hydraulic modelling analysis were used in the two studies, with the SEPA study being undertaken at a higher, strategic level. However, the extents are generally similar as can been seen in Figure 3.22 and Figure 3.23. An in-depth comparison of the two sets of extents is outwith the scope of this study; however, the main differences are detailed below:

- Greater flood extent along the River Gairn in the SEPA mapping compared to the Ballater model;
- Greater flood extents predicted by the Ballater flood model both in the immediate Ballater area and downstream of the town compared to the SEPA flood extent mapping.

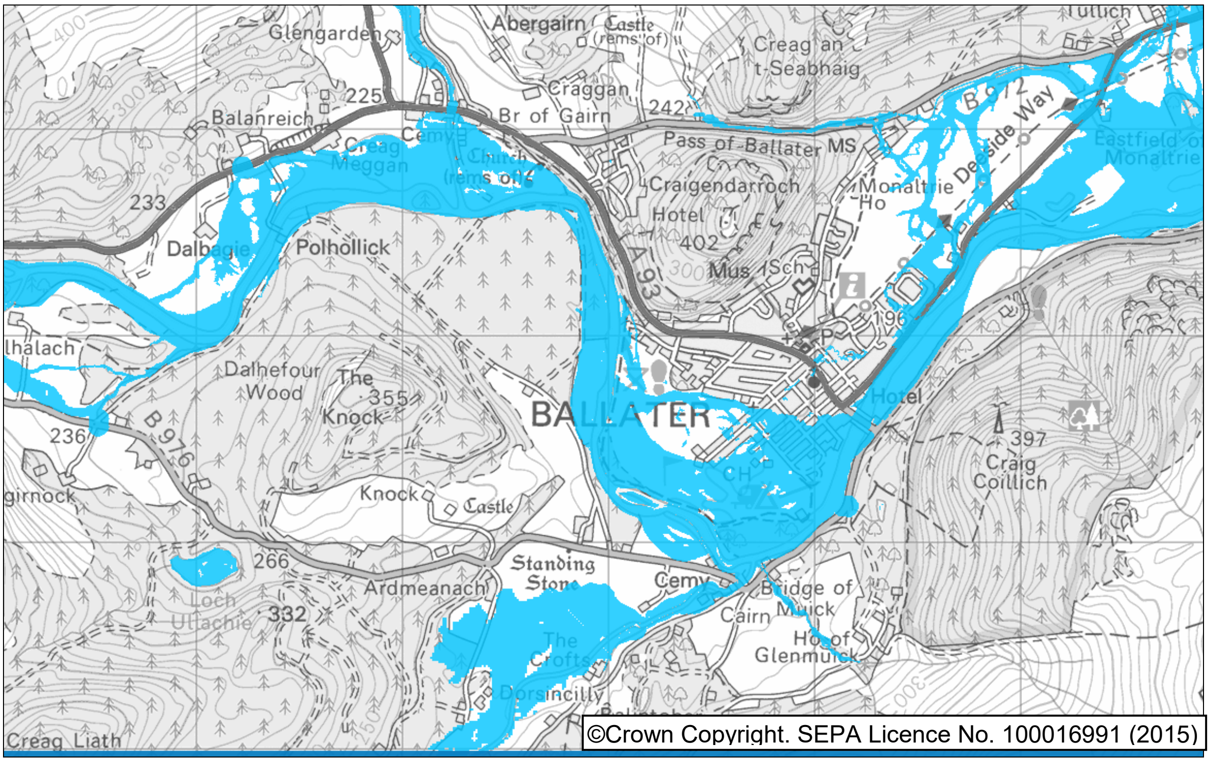


Figure 3.22 SEPA Medium Likelihood Fluvial Flooding (0.5% AEP, 1 in 200 year return period)

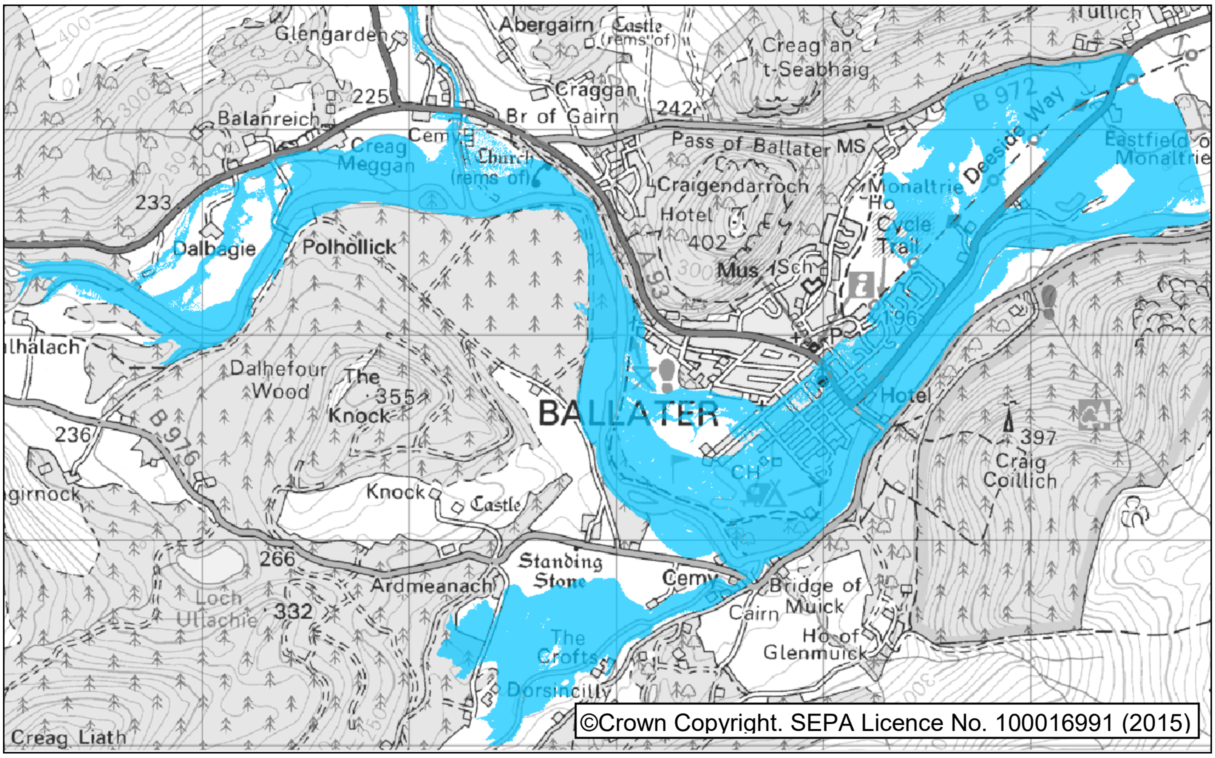


Figure 3.23 Modelled Ballater Flood Protection Study 0.5% AEP Design Event (1 in 200 year return period)

3.7 CONFIDENCE TRACKING

SEPA has considered how confidence is assessed and recorded in support of Flood Risk Management (Scotland) Act (FRM Act) hazard map outputs. An approach to assessing and tracking uncertainty in models and modelled outputs has been established through the development of a confidence framework for FRM Act outputs. The framework is based on the key principles of proportionality, alignment with modelling strategy, data availability and simplicity of approach and use. This approach has been applied to the Ballater Flood Study outputs. The tables below detail the confidence scores for various categories. The total score for the entire modelled reach is 16. Calibration/verification scored as ‘Good’, whereas Hydrology, Topography and Method all scored as ‘Excellent’.

Table 3.5 Summary of confidence categories and scoring requirement for each category

Hydrology	Relative confidence (5 = higher confidence, 1 = lower confidence)	Confidence score for this domain.
Detailed hydrological analysis using gauging station data. Well gauged catchment (record length, and proximity of gauge to site) Expect unsteady inflows or justification why not used.	5	X
Domain containing gauging station where flow grid updated using that gauging stations data. Or detailed hydrological analysis where the catchment is not well gauged.	4	
Catchments/reaches where design flows derived by catchment weighting based on flood frequency analysis (FEH statistical method) using SEPA gauging station data. Station within the catchment but may be some distance from this domain. **OR** locations where design flows from the flow grid have been used, but they do not differ by more than 25% relative to estimates produced at the gauge using station data - FEH Statistical method.	3	
Catchments/reaches where the design flows have been adopted directly from the flow grid (automated FEH statistical method) with no comparison to local data.	2	
Hydrological approach taken is not the preferred approach or not considered suitable for the site in question.	1	

Topography	Relative confidence (5 = higher confidence, 1 = lower confidence)	Confidence score for this domain.
Survey	5	
LiDAR (more than 70% over the floodplain in the study area)	4	X
Combination of LiDAR and NextMap in domain (10-70% LiDAR over floodplain in the study area)	2.5	
NextMap (less than 10% LiDAR over the floodplain in the study area)	1	

Modelling	**Relative confidence (5 = higher confidence, 1 = lower confidence)**	**Confidence score for this domain.**
Detailed model, considered representative of hydraulic processes. Generally a 1D-2D model expected, or a 1D model if very well defined flow routes and limited floodplain flow. - detailed representation of hydraulic structures including weirs, culverts and flood defences. - out of bank flow paths well resolved - combined source modelling where appropriate	5	X
2D modelling where the channel is well resolved and there are either no significant hydraulic structures or structures/defences are well represented. **OR** 1D modelling where there is limited out of bank flow e.g. for a narrow incised channel.	4	
2D modelling where either: the channel is not well resolved and there are no structures **OR** there are structures/defences that are not well represented and the channel is well defined **OR** there are structures/defences that are represented using some local information. **OR** 1D modelling where there is significant out of bank flow.	2	
Simplified approach e.g. RFSM (irrespective of whether structures/defences represented)	1	

Calibration/ Verification	**Relative confidence (5 = higher confidence, 1 = lower confidence)**	**Confidence score for this domain.**
Model results compare well with higher quality historical information e.g. levels at gauge or historic flood extent from survey for MULTIPLE events. Model calibrated.	5	
Model results compare well with higher quality historical information e.g. levels at gauge or historic flood extent from survey Model calibrated.	4	
Model results compare well with results of other independent accepted studies.	3	
Model results compare well with anecdotal evidence (e.g. LA understanding) or lower quality historical information.	2	X
Model not calibrated or validated at present	1	

Summary	
Total Score (Hydrology + Topography + Method + Calibration/Verification)	16
Confidence Category (Assigned based on the score achieved for each of the elements - see table below for summary of confidence categories and scoring requirements for the different categories)	Good

		Scoring Requirements for assigning to this category			
Confidence category	General description	Hydrology	Topography	Method	Calibration/Verification
Excellent	*A relatively high confidence is given to this information. This is provided by the use of calibrated and/or validated detailed models using local hydrological analysis. The method of modelling sufficiently represents hydraulic processes and uses LIDAR DTM or survey information.* *The data represents local conditions well and reflects real flood events or compares well with other supporting information such as other accepted detailed studies.*	≥ 4	≥ 4	≥ 4	≥ 3
Good	*Reasonable confidence in hydrology, topography and method. Reflects real flood events and scenarios or compares well with other supporting information such as other accepted detailed studies or anecdotal evidence from partners.*	≥ 3	≥ 3	≥ 3	≥ 2
Intermediate	*Varied level of confidence in this data.* *There is a reasonable level of confidence in at least one of the elements (topography, hydrology, method) but not all elements have an appropriate level of confidence to be included in the "Good" category.* *Developing some elements of the data would improve the level of confidence to good.*	At least one element with score ≥ 3			If at least one of Topography, Hydrology and Method are < 3 then CV score can be any value. If Hydrology, Topography and Method are ≥ 3 then CV score must be 1 to remain in this category.
Acceptable to meet statutory requirements	*This data is acceptable for use at a strategic level and meets the requirement of the FRM Act.* *The data supports national, strategic modelling and mapping but is not suitable for more detailed assessments, given the lower relative confidence in this data.*	< 3	< 3	< 3	Any, although typically score = 1.

4 SUMMARY AND RECOMMENDATIONS

Ballater is located at the confluences of the River Gairn and the River Muick with the River Dee in West Aberdeenshire. The town has a history of flooding with the most recent flood event occurring in December 2015, when more than 100 residents had to be evacuated and some 300 properties suffered inundation.

RPS have undertaken a comprehensive review of existing information including historical flood event data, survey information, existing models and reports in addition to procuring additional topographical survey information for the purposes of this study. Following walkover surveys, RPS used Infoworks ICM to undertake the numerical modelling of the River Dee, Gairn and Muick within the study area. RPS constructed a 1D in channel model, incorporating all hydraulic structures, combined with a 2D flood plain model, incorporating the informal flood defence, to provide an accurate assessment of both the in channel flow regime and floodplain flow paths.

Although Ballater has suffered extensive flooding in the past, there is limited recorded information available of historic events which can be used to facilitate model calibration and verification. There is a gauging station on each of the three watercourses upstream of Ballater. Data from each gauge for each of the three largest flood events during the period of record (December 2015, August 2014 and January 1993) was incorporated into the model and simulated to create modelled flood extents for each historical event. It is recommended that future studies record the actual level of the datum at each gauge to provide an additional source of information for use in future rating reviews. RPS have used the information that is available, including anecdotal evidence and comments from the public consultation, to achieve model calibration.

There is some uncertainty associated with the reported flooding mechanism in the area off Craigview Road during the December 2015 event. However, the modelled peak flood levels correlate well with the recorded flood mark levels (with all five of the modelled levels within +/- 300mm and three of the five within +/- 150mm of the recorded level in this area). There is a very good correlation between the modelled flood extents and the reported flood extents for both the 1993 and 2015 flood events. It is considered that the modelled flood extent is greater than the actual flood extent for the 2014 event. However, in order to adopt a single design network for this study, it was concluded that the differences between the modelled and actual flood extents for the 2014 flood event should be accepted. It is recommended that this is considered further during the optioneering phase of the Ballater Flood Protection Study to ensure that the preferred option robustly reduces the flood risk for events of all return periods up to the standard of protection.

The calibrated river model has been simulated to determine water levels for a range of flood events for both ‘with defence’ and ‘without defence scenarios’, with flood extent and depth maps being generated for each return period. Breach scenarios and sensitivity analysis simulations were undertaken. This indicated that the model is sensitive to changes in the roughness coefficients. It is recommended that the model is reviewed and updated prior to the detailed design of the flood alleviation scheme with more detailed information on the roughness coefficients, to provide increased confidence in the model outputs. The model is considered to have a low sensitivity to changes in the blockages at each of the three bridges and changes to input flows.

RPS consider that the model has been calibrated to best represent the flooding mechanisms in Ballater and is suitable to be used as a basis for identifying flood alleviation options in Ballater. It is recommended that extensive data collection is undertaken during and after any future flood events, which would provide information to further improve confidence in the hydraulic model. It is also recommended that, due to dynamic nature of the River Dee, the model is reviewed and updated prior to the detailed design and construction of a flood protection scheme.

APPENDIX A

Topographical Survey Data

APPENDIX B

Structure Details

APPENDIX C

Flood Maps – Historic Events

APPENDIX D

Modelled and Recorded Level Comparison

APPENDIX E

Sensitivity Analysis Output Tables

APPENDIX F

Flood Maps – Design Scenarios

APPENDIX G

Model Log and Calibration Document

APPENDIX H

Model Files

APPENDIX I

Flood Maps – Without Defences