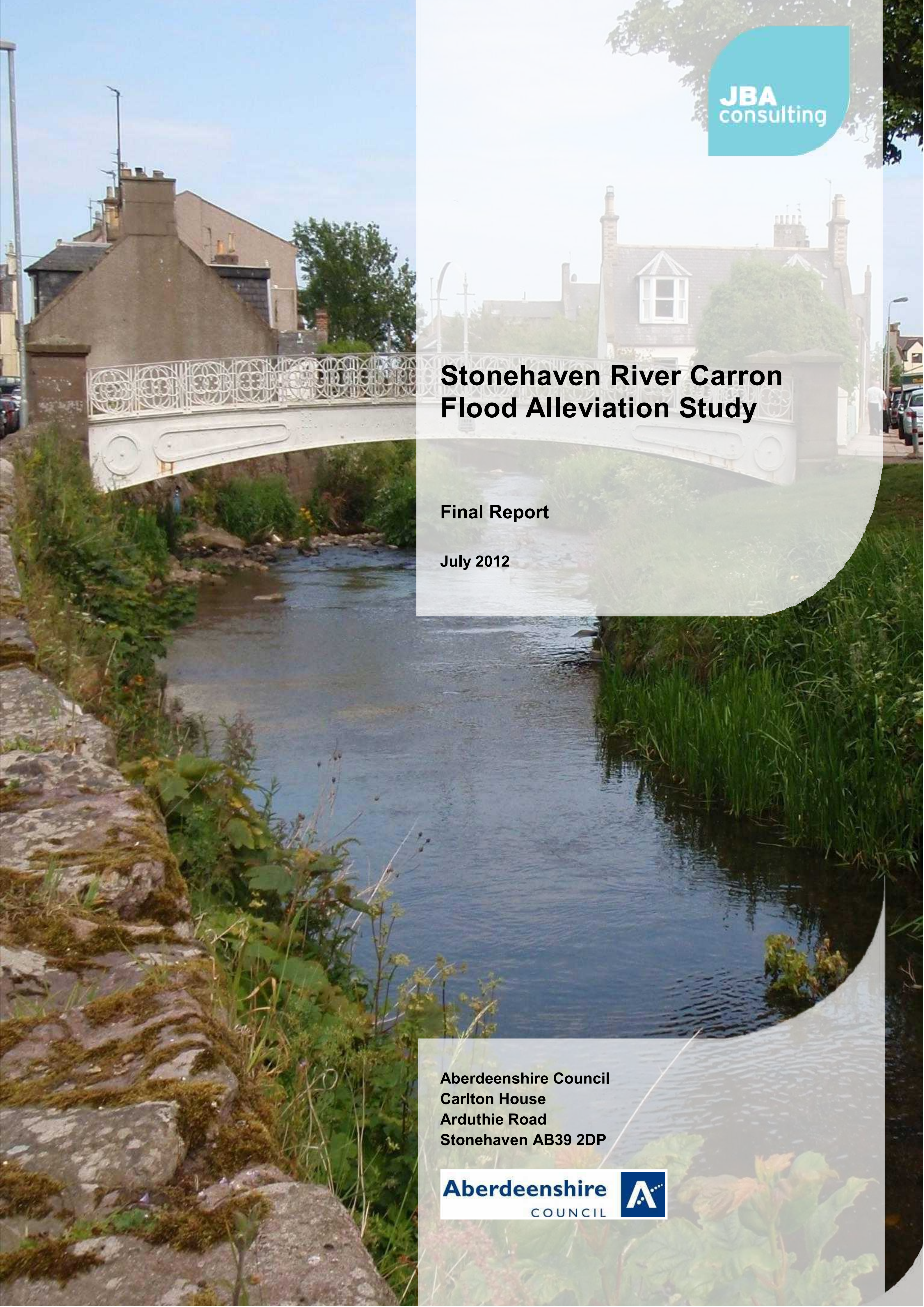

JBA consulting

Stonehaven River Carron Flood Alleviation Study

Final Report

July 2012

Aberdeenshire Council
Carlton House
Arduthie Road
Stonehaven AB39 2DP

Aberdeenshire COUNCIL

JBA Office

JBA Consulting
Port Neuk
1 Longcraig Road
South Queensferry EH30 9TD

JBA Project Manager

Caroline Anderton BSc MSc CEnv CSci MCIWEM C.WEM

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This report describes work commissioned by Steve McFarland, on behalf of Aberdeenshire Council, by Purchase Order number 1150994 dated 7th March 2011. Marion McMillan, Angus Pettit, Stephen Farrar, Chris Toop, Caroline Anderton and David Bassett of JBA Consulting carried out this work.

Prepared by .... Marion McMillan MA

Analyst

Prepared by .... Christopher Toop BSc

Analyst

Prepared by .... Angus Pettit BSc MSc CEnv CSci MCIWEM C.WEM

Senior Analyst

Prepared by .... Stephen Farrar MEng CEng MICE

Senior Engineer

Prepared by .... Caroline Anderton BSc MSc CEnv CSci MCIWEM C.WEM

Principal Analyst

Reviewed by .... David Bassett BSc MSc CEnv MCIWEM C.WEM

Divisional Manager

Purpose

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The Scotsman, Mearns Leader, Press and Journal, Stonehaven Journal and Kincardine Observer news reports for historical flood events.

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Executive Summary

Stonehaven is a town of approximately 11,000 population, located in Aberdeenshire in northeast Scotland. The town is situated on the coast and at the outfall of two significant rivers: the Carron and the Cowie. The town extends across the flat, low-lying coastal plain and onto higher ground. In November 2009 Aberdeenshire suffered widespread flooding, with a total of 300 people in 50 separate sites affected by internal flooding. In Stonehaven the town flooded extensively. 50 people were evacuated with many homes and businesses damaged & interrupted during post flood restoration.

Investigations show the town is potentially vulnerable to flooding from the Rivers Carron and Cowie as well as coastal flooding and overland flow. Our feasibility study has focused on assessing options for alleviating the risk associated with the Carron. In 2009 flood water left the Carron around the Green Bridge flooding Low Wood Road, Carron Terrace, and flowing north east and west to flood Cameron Street, the area around the Market Square, the High Street and Old Town. Review of historical records shows that the Carron has been reported as running high and caused significant flooding in 1979, 1946, 1907, 1882 and 1873.

Careful review of the hydrology suggests that the flow in the Carron in 2009 was of the order of $37m^3/s$ and the 0.5% Annual Probability (AP) (200 year) flow is around $45m^3/s$. A hydraulic model of the river has been constructed and used to assess a range of flood flows and options to reduce the risk. The options have been assessed using multi-criteria analysis to determine the benefits and costs of appraised options.

The model was calibrated against recorded data and shows that flood water will leave the Carron, first upstream of the Green Bridge at flows of 22 m^3/s (equivalent to a 10 year return period), and at lower frequency events will extend downstream to the White Bridge and inundate progressively greater areas to the north & south of the river. Flows in the Carron that are greater than $35m^3/s$ will flood on the right bank and be joined by flood waters from the Glaslaw Burn when flows exceed $4m^3/s$ in the Glaslaw Burn.

Pluvial flood risk is flooding as a direct result of rainfall onto the ground surface and its subsequent runoff via overland flow routes leading to pooling in topographically low-lying areas. The flooding often also referred to as surface water flooding poses a hazard as it flows over land and in the pooling in low lying areas or behind barriers. Additional modelling undertaken to route rainfall overland shows a concentration of flood risk in the lower parts of the town around Market Square and Arbuthnot Place. The modelling deducted the 5 year rainfall storm from the effective rain to account for the sewer capacity. Retrofitting SuDs and provision of increased sewer capacity and pumping could alleviate this risk.

A range of options are assessed economically and environmentally using approached outlined by the Scottish Government, Treasury and Defra and recommendations and a technically preferred option is identified. Options considered are:

- Option 1: Continuation of maintenance and repairs;
- Option 2: Construction of direct defences as a stand-alone solution;
- Option 3: Construction of direct defences combined with modifications to the channel and bridges;
  - raising of Green Bridge and removal of remains of weir at Green Bridge;
  - raising of Green Bridge and White Bridge and removal of remains of weir at Green Bridge;
  - raising of Green Bridge and lowering the river bed at the Green Bridge weir in conjunction with removing the remains of weir at Green Bridge;
- Option 4: Provision of upstream storage;
- Option 5: Construction of direct defences combined with upstream storage; and
- Option 6: Resilience approach.

Some options such as channel modification and storage alone cannot achieve the desired 1% - 0.5% AP defence standard. Although there are no environmental designations, the river is important for salmon, trout and otter. The surrounding habitat is good for bats. The final

designs will need to be sensitive to improve their habitat and ensure that construction work does not affect the populations. Giant Hogweed and Himalayan Balsam both invasive non native species will require careful management and regulation in the process of any construction work.

The preferred option that is most sustainable and economically viable is the provision of direct defences with bridge raising and localised channel modification. This improves channel capacity and through local modifications will allow the reduction in required defence heights compared to direct defences alone. The option includes raising the Green Bridge; reducing the bed below the Green Bridge; and the provision of sensitively designed walls, to provide more capacity. Local channel modification at the Green Bridge to reduce the step and improve capacity and fish passage is the most sustainable and economic solution. Although the Green Bridge is not currently DDA compliant, a new bridge may need to be, and this could increase the engineering requirement around the bridge or relocation to a more suitable location. Improvements to the discharge of the historic Mill Lade, or provision of pumping could reduce local surface water problems, but may need further investigation with sea levels to confirm its suitability.

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Abbreviations

1D .... One Dimensional (modelling)

2D .... Two Dimensional (modelling)

AMAX.............................. Annual Maximum

DDF................................. Depth Duration Frequency

DTM .... Digital Terrain Model

FEH................................. Flood Estimation Handbook

GL .... General Logistic Distribution

JBA .... JBA Consulting − Engineers & Scientists

JFLOW............................ 2D hydraulic modelling package developed by JBA

mAOD .... metres Above Ordnance Datum

NGR .... National Grid Reference

OS.................................. Ordnance Survey

POT................................. Peaks Over a Threshold

QMED .... Median Annual Flood (with return period 2 years)

ReFH.............................. Revitalised Flood Hydrograph method

RMSE............................. Root Mean Square Error (objective function)

SAAR .... Standard Average Annual Rainfall (mm)

SAC................................ Special Area of Conservation, protected under the EU Habitats Directive

SEPA .... Scottish Environment Protection Agency

SSSI................................ Site of Special Scientific Interest

SUDS.............................. Sustainable Urban Drainage Systems

1 Introduction

1.1 Site location

Stonehaven is a town of approximately 11,000 population, located in Aberdeenshire in northeast Scotland. The town is situated on the coast and at the outfall of two significant rivers: the Carron and the Cowie. The town extends across the flat, low-lying coastal plain and onto higher ground. It is subject to flooding from fluvial, surface water and coastal sources, and in November 2009 suffered serious flooding from the River Carron which caused around 50 people to be evacuated from their homes.

Figure 1-1: Site location

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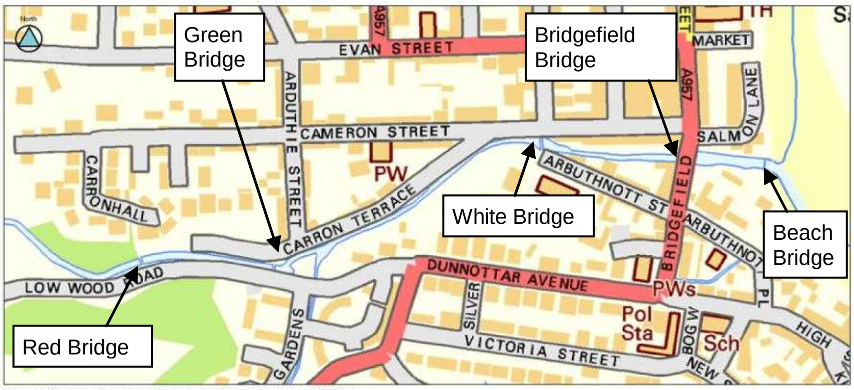
1.2 Previous studies

1.2.1 Channel capacity study (2010)

In 2010 JBA Consulting undertook a Channel Capacity Study for the River Carron[1] at Stonehaven, as the first stage of developing options for fluvial flood mitigation. This study used 1D modelling to identify locations on the River Carron channel where the capacity was particularly low and hence should be targeted for reducing flood risk. Following the recommendations from the study, Aberdeenshire Council carried out some short term measures to improve channel capacity at the Green Bridge, a critical location within the town.

Figure 1-2: River Carron bridge locations in Stonehaven



Contains Ordnance Survey data © Crown copyright and database right 2011.

[1] JBA Consulting, July 2010. Stonehaven Channel Capacity Study. Report for Aberdeenshire Council. Updated in letter report to Aberdeenshire Council, 26 October 2010.

1.2.2 Geomorphological audit (2010)

A geomorphological audit of the River Carron was undertaken by JBA Consulting in 2010[2]. The report classified the Carron as a moderately active single thread river displaying morphological features such as riffles and bars which are associated with temporary storage of the cobble and gravel bed material. The report noted that the river has been extensively altered through Stonehaven with a number of crossings, bank protection structures and grade control structures which have disrupted the sediment balance.

The report suggested that the sediments found in the in-channel bars through Stonehaven are principally sourced from localised erosion of fluvial-glacial deposits in the lower reaches of the river. Any attempt to control this sediment source would be difficult as there are a number of supplying locations, and removal of the deposits downstream would be an ongoing process. Although these bars appear permanent, the report notes that sediment is only stored temporarily before continuing its journey downstream and being replaced by new sediment. These bars form at low-energy locations, where structures inhibit river flow and where the channel has been artificially over-widened.

The report recommended a number of actions to improve sediment management on the Carron, and to help establish an equilibrium.

1.3 Study aims and objectives

The present study follows on from the 2010 Channel Capacity Study to develop outline options for flood alleviation in Stonehaven relating to fluvial flooding from the River Carron. The aims of this study are:

- To develop the existing 1D InfoWorks-RS of the River Carron into a linked 1D-2D model to allow improved assessment of the extent of flooding and the effectiveness of proposed flood alleviation measures;
- To assess the existing flood risk to Stonehaven from fluvial flooding from the River Carron and Glaslaw Burn, including consideration of overland flow routes on the floodplain;
- To assess the existing flood risk to Stonehaven from surface water flooding result from intense rainfall events using a 2D surface water model;
- To propose a range of flood alleviation measures for Stonehaven;
- To test the proposed measures for the feasibility in terms of hydraulics and the mitigation of flood risk, structural engineering, environmental impacts and benefit-cost analysis;
- To undertake multi-criteria analysis and recommend option(s) to be taken forward.

1.4 Types of flooding

Stonehaven is at flood risk from a number of sources. These include:

- Fluvial flooding from the River Carron;
- Fluvial flooding from the River Cowie;
- Surface water flooding; and
- Coastal flooding.

This report addresses the risk of fluvial flooding from the River Carron and Glaslaw Burn and surface water flooding. The nature and context of these risks is discussed in more detail below.

[2] JBA Consulting, October 2010. Geomorphological Audit of the River Carron. Report for Aberdeenshire Council.

1.5 Fluvial flooding from the River Carron

Fluvial flood risk from the River Carron results from heavy or prolonged rainfall and / or snowmelt in the Carron catchment causing river levels to rise, with the potential for the river banks to be overtopped and flooding to land and properties to occur.

The key mechanisms for flooding from the Carron experienced in 2009 were out of bank flow, particularly around the Green Bridge where the water overtopped both the left and right bank.

Overland flow was then a key mechanism that resulted in property damage. To the north of the channel, water flowed along Carron Terrace and Cameron Street, and spread north along Barclay Street where levels are very flat. Modelling suggests that with a greater flow, water would continue north along Barclay Street towards David Street and could affect properties in the Hanover Court area. Overtopping of the left bank would also occur around the junction of Carron Terrace and Cameron Street, exacerbating flooding via the overland flow routes described above.

To the south of the river in 2009 water was conveyed via Low Wood Road and Dunnottar Avenue towards the High Street, where ponding occurred. Modelling suggests that during a more extreme event, the right bank could also be overtopped at the White Bridge, and flow overland via Arbuthnott Street.

1.6 Surface water flooding

Surface water flooding is flooding as a direct result of rainfall onto the ground surface and its subsequent runoff via overland flow routes leading to pooling in topographically low-lying areas. Surface water flooding is commonly associated with convective summer storms where rainfall has high intensity and as a result, drainage systems are unable to cope.

The topography of Stonehaven means that surface water will be shed from the higher areas, in the central, west and northwest parts of the town, towards the lower areas at the coast and the Carron and Cowie valleys. The drainage system in Stonehaven will remove some surface water but its capacity will be limited by the pipe sizes which vary across the town.

1.7 Flood warning

At present, Aberdeenshire Council liaise with SEPA for providing early warnings of fluvial flooding from the River Carron, and warnings are based on observed levels on the River Bervie which are used as an indicator of likely flooding on the River Carron.

Flood warning is currently being developed by SEPA for the River Carron Stonehaven, utilising a new gauge upstream of the A90. This is currently awaiting funding approval from the Scottish Government prior to commencing. Once implemented, this will help to give prior warning to residents and businesses in Stonehaven to allow them to prepare for possible high river flows.

1.8 Flood history

There are a number of documented fluvial flood events from the River Carron. Historical newspaper reports and other available information concerning these events were gathered to gain an idea of the magnitude of these events. The collation of these flood events are detailed within this section.

November 2009

The most substantial flood event in living memory in Stonehaven was a recent one, occurring in November 2009. The Mearns Leader described the "devastation" as the River Carron burst its banks and flooded businesses and houses, causing around 50 people to be evacuated[3]. This event prompted the Council's current efforts to develop a long-term sustainable strategy

[3] The Mearns Leader, 5th November 2009. 'Emergency Services stretched to the limit', www.mearnsleader.co.uk (accessed 12 July 2011).

for flood alleviation in Stonehaven. Flooding in November 2009 was widespread in Aberdeenshire with a total of 300 people affected by internal flooding at 50 separate sites[4].

Out of bank flooding occurred around the Green Bridge with overland flow both to the north and south of the river. Property flooding occurred on Carron Terrace and Cameron Street, in the Market Square area and on Barclay Street. There was also flooding to properties on Low Wood Road, Dunnottar Avenue and in the High Street, Arbuthnott Place and Bridgefield area. Figure 1-3 below shows a sketch of the flood extents provided by Aberdeenshire Council and Figure 1-4 shows some photographs of the flooding.

Figure 1-3: Sketch plan of November 2009 flood extents

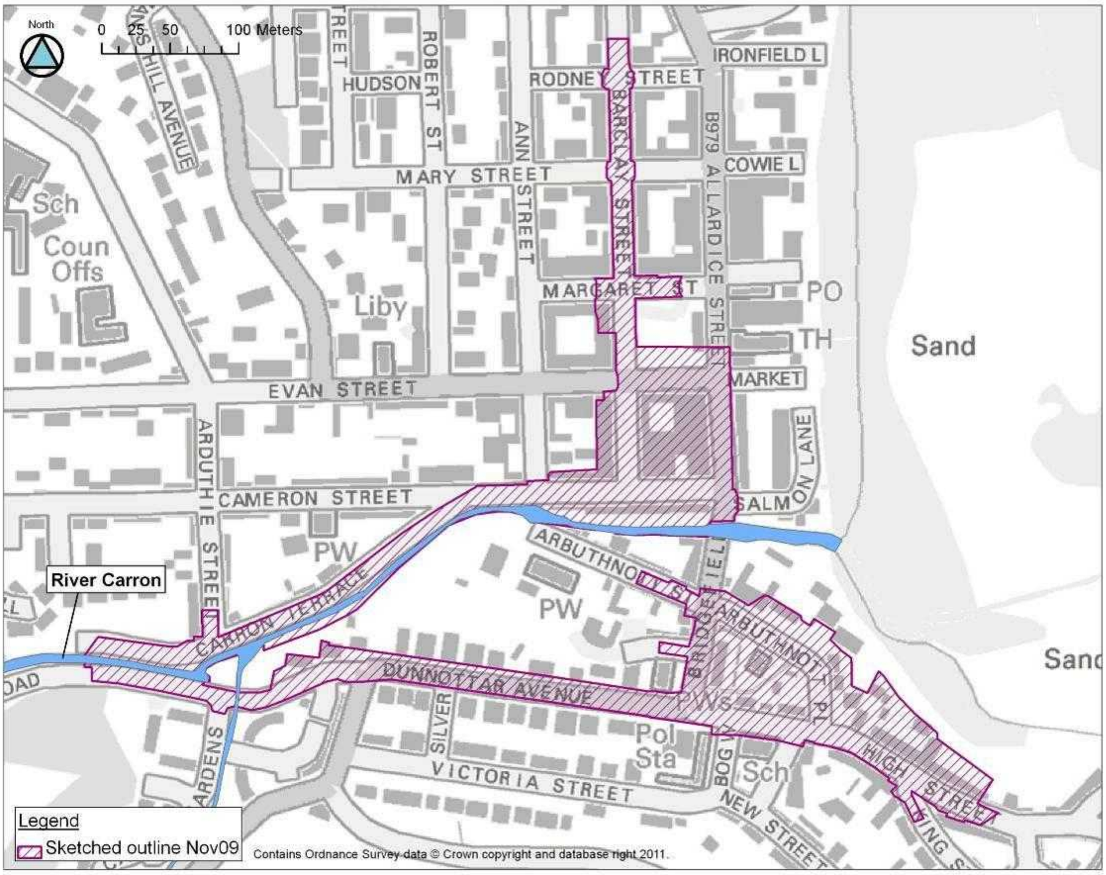


Figure 1-4: The 2009 flood and aftermath

Market Square

Cameron Street

[4] Aberdeenshire Council

 The White Bridge	 The rescue effort
 Low Wood Road (upstream of Green Bridge)	 The Green Bridge
 Arbuthnott Place	 High Street

October 2009

Just a few days before the November 2009 event the Carron had come close to bursting its banks. The Mearns Leader reported that "Stonehaven... was battered by storms. A massive 37.3 mm of water fell on October 21 alone... The River Carron came perilously close to flooding houses in Cameron Street"[5].

This storm contributed to the very wet antecedent conditions in the catchment which increased runoff in the larger event just a few days later.

July 2009

The Mearns Leader reported that "Parts of Stonehaven became submerged under water last Friday afternoon, when drainage systems struggled to cope with the unusually large amount of rainfall"[6]. This surface water flooding event was sufficient to cause flooding to properties.

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[5] The Mearns Leader, 30th October 2009. 'High alert as storms hit Mearns', www.mearnsleader.co.uk (accessed 12 July 2011).

[6] The Mearns Leader, 31st July 2009. 'Flash floods cause town centre chaos', www.mearnsleader.co.uk (accessed 12 July 2011).

October 2002

In October 2002 the Press and Journal reported that "the North-east [is] suffer[ing] what is shaping up to be its wettest October ever"[7]. However, although the Carron was at a high enough level to be out of bank, no damage was caused: "Politicians and Stonehaven residents yesterday praised the flood resistance measures introduced by Aberdeenshire Council at the River Carron... though some water toppled over the riverbank on Tuesday night, it was not enough to cause damage to nearby property"[6].

April 1998

Photographs provided by Aberdeenshire Council show the River Carron at a sufficiently high level to cause flooding to the rear gardens of properties on Cameron Street, but no reports have been found of flooding to property.

Figure 1-5: April 1998 event

Cameron Street gardens

Low Wood Road

December 1985

The Press and Journal described how areas including Stonehaven were affected by "widespread flooding which followed a sudden thaw combined with heavy overnight rain"[8]. Photographs in the newspaper showing property flooding on Cameron Street and at the southern end of Barclay Street up to around threshold level, and the fire service working to pump away the water.

October 1979

In 1979 severe flooding from the Carron again caused damage to properties in the town centre. The Press and Journal suggested that "In Stonehaven, the combination of a high tide at noon and floodwater pouring down the two rivers either side of the town centre wreaked havoc. Fire services fought a losing battle to pump shops and homes clear and sandbags were brought in to try and stem the floodwaters"[9].

Photographs provided by Aberdeenshire Council show flooding to properties on Cameron Street and Barclay Street, and water levels in the river reaching the soffit of both the Green Bridge fretwork and Bridgefield Bridge.

[7] The Press and Journal, 24th October 2001. 'Council riverbank work praised'.

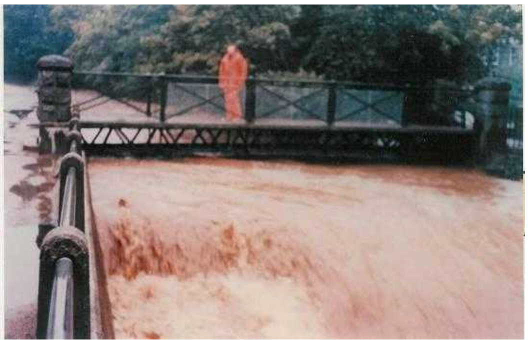
[8] The Press & Journal, 7th December 1985. 'Water, water everywhere'.

[9] The Press & Journal, 5th October 1979. 'Flood havoc hits N-East'.

Figure 1-6: The 1979 flood

Cameron Street

Barclay Street



Green Bridge

Sand bagging at the Green Bridge

Bridgefield Bridge

August 1958

The Mearns Leader described how heavy rain at the start of August had lead to a hurried evacuation of the Mill Lade campsite due to flooding from the Cowie and rainwater, and that "Householders near the lower reaches of the Carron, which was also running high, took precautions against the flooding of their properties"[10]. At the end of the month there was a further flood event on the Cowie, and landslides at the Bervie Braes, although no mention of flooding from the Carron was made.

September 1956

A report in the Mearns Leader described how "Stonehaven got its full share of the heavy rain... The result was that both the Cowie and Carron waters came down in spate... On

[10] The Mearns Leader, 1st August 1958. Article [no title], www.mearnsleader.co.uk (accessed 12 July 2011).

Carronside, several householders in the Cameron Street area, with recollections of former spates, took the precautions of erecting flood barriers at their doors"[11].

March 1947

In March 1947 again the Carron was at a sufficiently high level to pose a risk to property: "The River Carron is... running exceptionally high and last night tenants of dwelling houses on the river bank took all precautions against flooding"[12].

November 1946

It was reported in the Scotsman that "Over the four days... Aberdeen had 2.98 inches of rain... There was an alarming experience for many householders in Cameron Street, Stonehaven... when the River Carron, in spate, rose to an unusual height. Household goods were carried to upstairs rooms and back doors barricaded with sandbags and wooden boarding. The water gradually subsided, and severe flooding was narrowly averted"[13].

June 1938

The Scotsman reported that "the streams Cowie and Carron were running in spate after 12 hours continuous rain. Householders along the banks were greatly alarmed by the rising waters"[14].

October 1907

October 1907 was by all accounts a very wet month, with two severe storms a week apart on the 11th and 18th October.

The Scotsman reported a severe wind and rain storm on the 11th which "brought a great deal of sand and stones from the higher parts of the town to Barclay Street and Market Square, and the drains in that part being unable to carry away the rush of water, a great many of the houses were flooded. In the Old Town, in one or two of the low-lying houses, the flooding was serious"[15]. Although the rivers were in spate, the flooding to properties was from surface water.

The Kincardineshire Observer reported on the 18th that "Rain fell in the Stonehaven district all day yesterday... the weather conditions were of the most wretched description... The heavy rainfall has not occasioned any serious damage in Stonehaven. The Cowie and Carron are in spate, but not to the extent these rivers attained on Thursday of last week"[16].

October 1906

The Mearns Leader described "A heavy storm of wind and rain, accompanied by a gale at sea, occurred at Stonehaven... The rain fell incessantly... and as a consequence some of the houses at the top of High Street and Arbuthnott Place were flooded. The rivers Cowie and Carron were in spate"[17]. This implies that it was surface water flooding that caused property damage.

December 1882

A report in the Scotsman described a sudden and rapid thaw of snowmelt causing a number of rivers across Scotland to be in spate, the result of which was that "Many houses in Stonehaven have... been flooded to a depth of two or three feet"[18]. Historical reports have suggested that the Carron is more likely to cause flooding to property than the Cowie. This report suggests a considerable amount of damage to property resulted.

November 1873

[11] The Mearns Leader, 7th September 1956. Article [no title], www.mearnsleader.co.uk (accessed 12 July 2011).
[12] The Scotsman, 22nd March 1947. 'Flood waters continue to fan out'. www.proquest.com (accessed 12 July 2011).
[13] The Scotsman, 22nd November 1946. 'Wild weather'. www.proquest.com (accessed 12 July 2011).
[14] The Scotsman, 3rd June 1938. 'Stormy weather in Scottish districts'. www.proquest.com (accessed 12 July 2011).
[15] The Scotsman, 11th October 1907. Article 55 [no title]. www.proquest.com (accessed 12 July 2011).
[16] The Kincardineshire Observer, 18th October 1907. 'Stonehaven'.
[17] The Mearns Leader, 25th October 1906. 'Sea inroads', www.mearnsleader.co.uk (accessed 12 July 2011).
[18] The Scotsman, 18th December 1882. Editorial Article 1 [no title]. www.proquest.com (accessed 12 July 2011).

The Scotsman reported that "The easterly gales and heavy rains of the last two days have flooded many of the rivers... [In] Stonehaven, and other places, houses have been flooded to considerable depth"[19].

[19] The Scotsman, 8th November 1873. Article 5 [no title]. www.proquest.com (accessed 12 July 2011).

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2 Hydrology of the Carron catchment

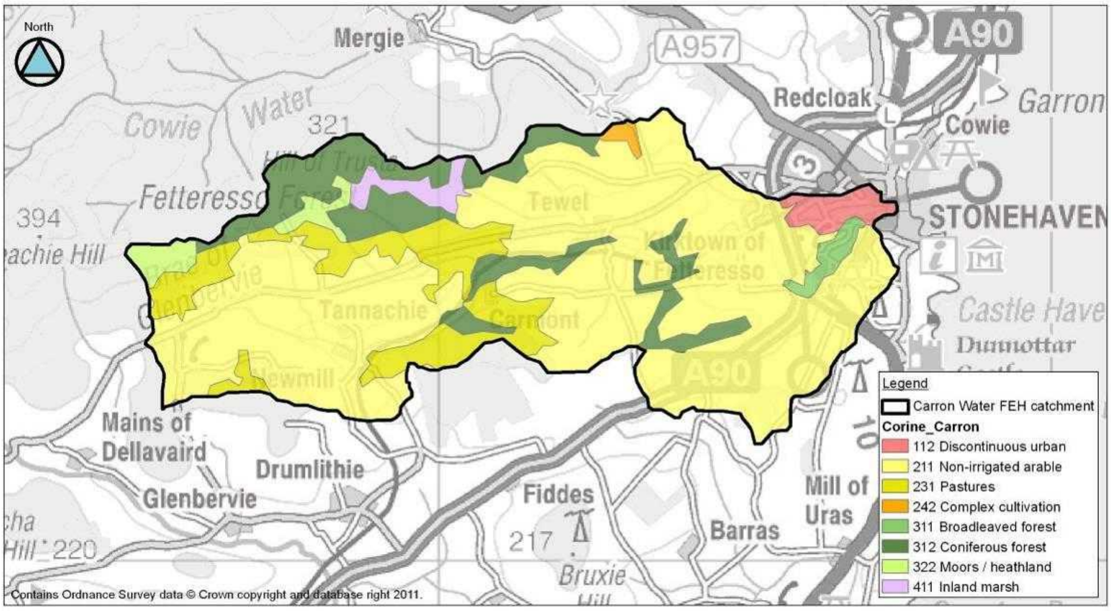
2.1 Catchment characteristics

The catchment of the Carron Water to the Stonehaven tidal boundary covers an area of approximately 43 km^2. The Carron Water rises in low coastal hills with the highest elevation in the catchment at 321 mAOD on the Hill of Trusta. It flows from its source in the Brae of Glenbervie (to the south of Fetteresso Forest) in a south easterly direction before passing under the A90 which marks the western boundary of Stonehaven. The Carron passes along the southern periphery of the town centre where it merges with the Glaslaw Burn before reaching its coastal outfall.

Land use within the catchment is a mixture of pasture, forestry and the urban area in the lower catchment, with the URBEXT2000 value from the Flood Estimation Handbook (FEH) CD-ROM at 0.0114[20], indicating that the catchment is "essentially rural"[21]. The Standard Percentage Runoff for the catchment from the FEH is 37.15% and the Baseflow Index 0.581. The Standard Average Annual Rainfall is 869 mm.

Figure 2-1 below shows the Carron Water catchment and land use taken from the Corine dataset[22].

Figure 2-1: River Carron catchment and land use



2.2 Hydrometric data availability

The following hydrometric data was made available for use in this study:

[20] FEH CD-ROM version 3.

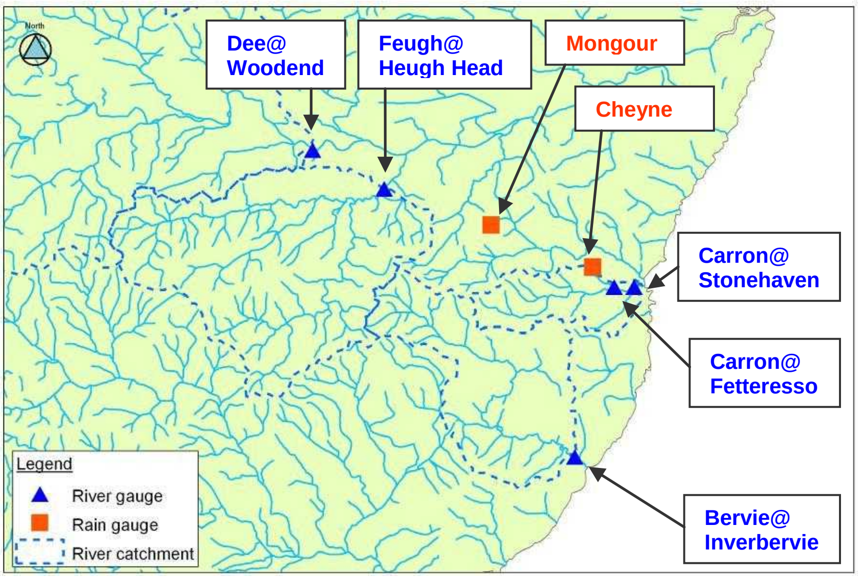
[21] FEH volume 5.

[22] http://www.eea.europa.eu/

Table 2-1: Hydrometric data

Gauge name	Gauge ref	Gauge type	Period of record
Carron at Stonehaven	13030	River level / flow	March 2003 - April 2011
Carron at Fetteresso	-	River level	July 2010 -
Bervie at Inverbervie	13001	River level / flow	August 1979 - March 2011
Feugh at Heugh Head	12008	AMAX river level / flow	1985 - 2010
Dee at Woodend	12001	AMAX river level / flow	1930 - 2010
Cheyne	-	Recording raingauge	April 2005 - April 2011
Mongour	-	Recording raingauge	October 1995 - May 2011

Figure 2-2: Hydrometric data locations



2.3 Rating review

SEPA's gauge on the Carron Water at Stonehaven (OS NGR 8693 8565) is not a HiFlows-UK gauge and no Annual Maximum (AMAX) or Peaks over Threshold (POT) series are available from SEPA as it is a wading gauge only. However, its 8 year record of 15 minute data and the range of gaugings available (from April 2003 to March 2010[23]) make it useful for calculating hydrological inputs to the model.

A review of the SEPA rating for the gauge was carried out using available data for JBA's channel capacity study in 2010[24]. This is summarised below.

2.3.1 SEPA rating - prior to removal of log weir

The rating equation applicable for the gauge prior to removal of the log weir was supplied by SEPA[25] and is as follows:

$$Q = 14.8469 \times (H - 0.037) ^\wedge 2.4172$$

SEPA suggested that the rating was valid between stages of 0.175 - 0.600 m, although the highest gauging is approximately 0.83 m; above this any flow estimate required extrapolation.

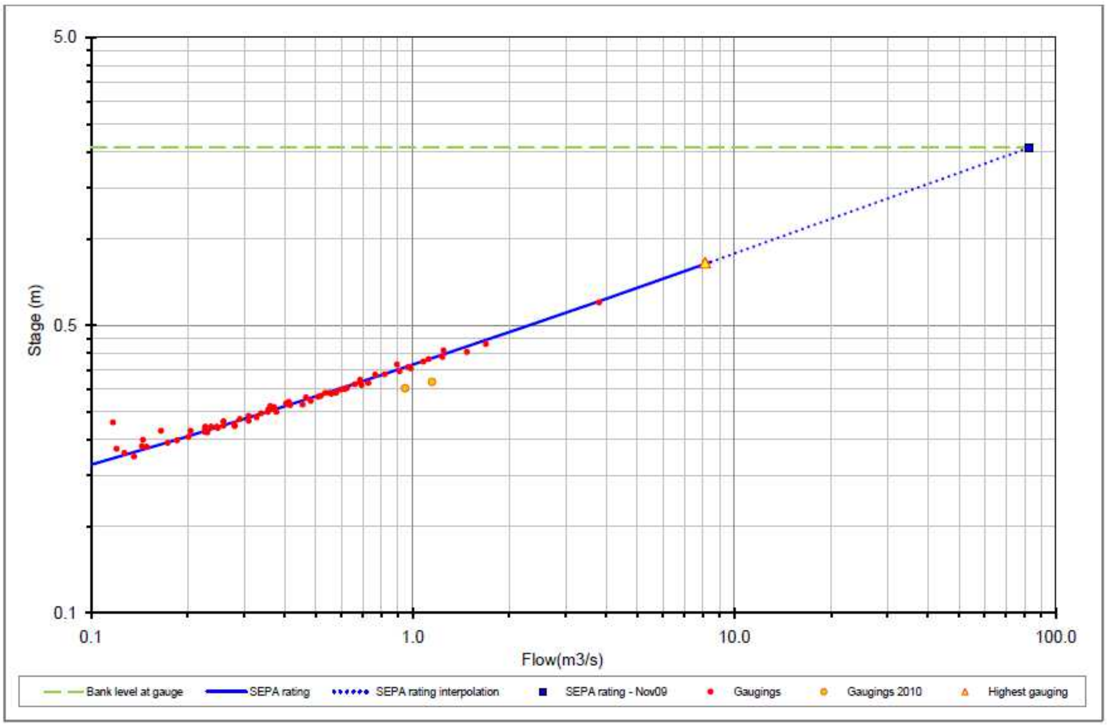
Figure 2-3 below compares the rating equation with spot gaugings (using a log scale).

[23] Email from Derek Fraser, 24 March 2010.

[24] JBA Consulting, July 2010. Stonehaven Channel Capacity Study. Draft Report for Aberdeenshire Council. Updated in letter report to Aberdeenshire Council, 26 October 2010.

[25] Email from Derek Fraser, 26 March 2010.

Figure 2-3: SEPA rating and gaugings



The chart shows that the rating equation compares well with gaugings taken up to September 2009. Since September 2009 two additional gaugings have been taken: in February 2010 and March 2010, which are not so well represented by the rating equation. The probable causes are the large flood event in November 2009 which resulted in a significant amount of gravel movement in the channel, and further removal of gravel in January 2010 by Aberdeenshire Council immediately upstream of the Green Bridge, both of which may have altered the bed control at the gauge.

The rating is only applicable within the range of gaugings taken to verify it, and given that this is a wading only station the highest gauging is at a level of approximately 0.83 m and 8 m^3/s. The bankfull stage at this location is approximately 2.07 m and therefore 0.83 m is well within bank.

This analysis suggests that the existing rating equation may no longer be applicable to new gaugings, nor should it be used for estimating flows at high stages (this is consistent with communications with SEPA whereby the gauge was installed primarily for gauging low flows). More gaugings will be necessary in order to confirm that a change in the rating is consistent and permanent and to confirm the rating at higher river stages.

2.3.2 Model rating - prior to removal of log weir

The calibrated hydraulic model developed for this study, which is described in Section 3.3, was used to give an alternative rating for the gauge based on the simulated levels and flows. This is useful given the questionable accuracy of the SEPA rating at high flows and can be used to give a flow estimate for the November 2009 flood event.

This analysis was undertaken for the 2010 study and is revised here based on the new 1D-2D linked model which gives improved representation of the relationship between river level and flow during extreme events when it is out of bank. As the model is based on survey taken in 2010, the model rating should reflect any change in the bed control that took place in November 2009.

Figure 2-4 below shows the SEPA and modelled rating ('with log weir' series) against spot gaugings and shows the estimates of flow derived by the two ratings for the November 2009 event (for which a gauged maximum level is known).

The rating review corroborates the suggestion that the SEPA interpolated rating may be substantially overestimating the flow at high stages. The model rating diverges from the SEPA rating at a low flow (approximately 2 m^3/s) and at bankfull level equates to a flow approximately 40 m^3/s less than that estimated from the SEPA rating. The model rating overestimates the stage at the highest gauged flow (by approximately 0.21 m). At the lowest modelled flow it is consistent with the SEPA rating and lower gaugings.

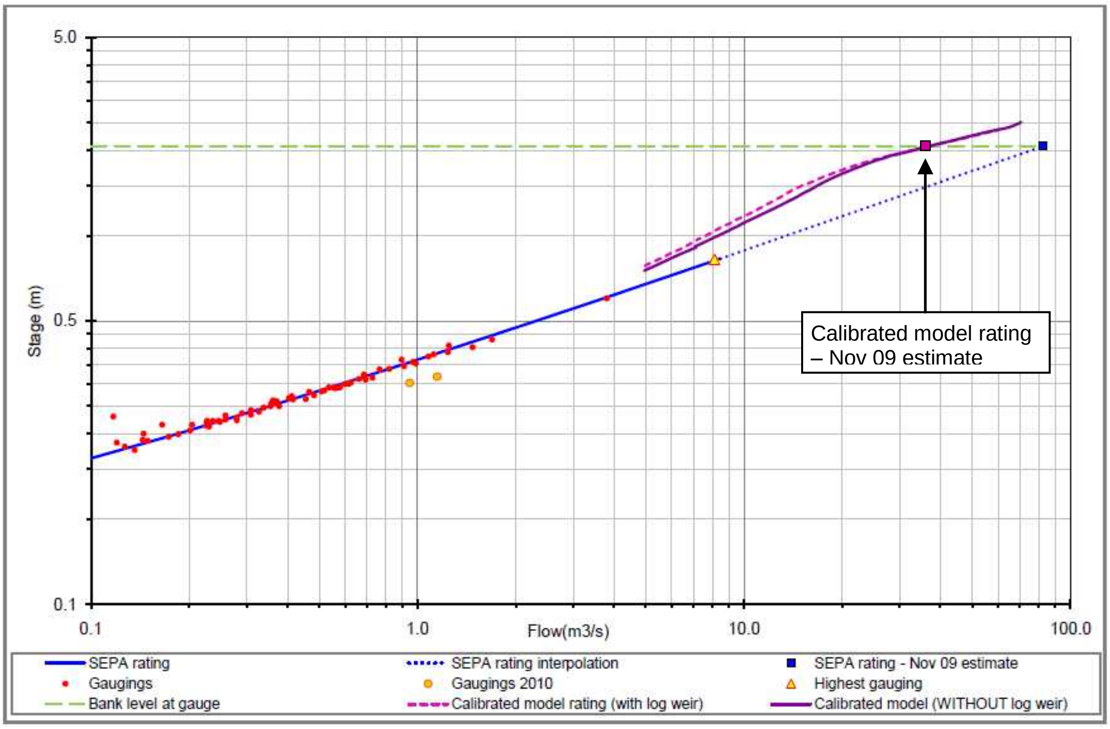
The estimated flow for the 2009 event from the calibrated model is approximately 37 m^3/s. The estimated annual probability and return period of this event are discussed in Section 2.7 below.

Following the removal of the log weir this rating is not applicable to gaugings taken. However, the calibrated model can be amended to represent the removal of the log and an up to date rating derived.

2.3.3 Model rating - following removal of log weir

The model was amended to remove the log weir and a new rating extracted for comparison. The new model rating is shown alongside the model rating from the scenario with the log weir in place for comparison. This demonstrates the increase in channel capacity at moderate flows resulting from the log's removal, as the same flow equates to a lower stage for the scenario without the log weir. This effect is relatively small at the location of the gauge, but is more pronounced downstream towards the location of the weir.

Figure 2-4: Comparison of modelled ratings with and without log weir in place



2.4 Flow estimation - Flood Estimation Handbook (FEH) method

Important inputs into estimations of flood hydrology include the analysis of historical events and the estimation of flood flows for a range of annual probabilities or 'design' events. Flood estimates for catchments of this size and type are generally undertaken using the FEH.

The FEH offers three methods for analysing design flood flows: the statistical, rainfall-runoff and hybrid methods. The statistical method combines an estimation of the median annual maximum flood (QMED) at the subject site with a growth curve, either derived from a pooling group of gauged catchments that are considered hydrologically similar to the subject site, or through single site analysis of a nearby gauge. The Rainfall-Runoff method combines design rainfall with a unit hydrograph derived for the subject site. Hybrid methods involve a combination of the two.

The default method of flow estimation via the FEH statistical method is to derive an estimation of QMED through data transfer and then apply a growth curve for a pooling group of hydraulically similar catchments. However, in some instances where the gauged record is deemed sufficiently long a consideration of single site analysis is also viable. Both versions of the method include the use of catchment descriptors, which have been digitally abstracted from the FEH CD-ROM v3 and verified through the use of OS background mapping.

2.4.1 QMED estimation

An estimate of QMED at the Carron gauge is required, and growth factors will be applied to this to give the range of design flows. There are several possible methods for calculating QMED for the Carron at Stonehaven.

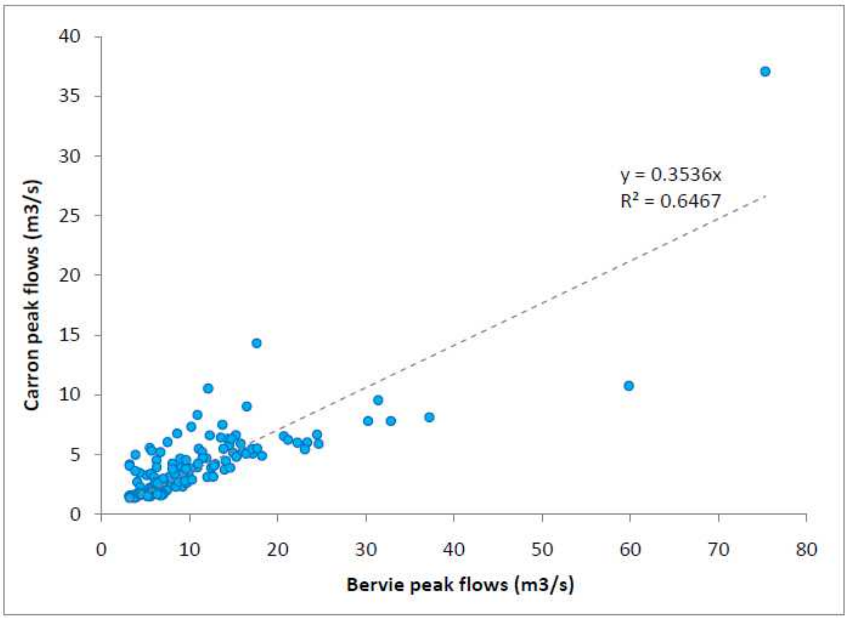
QMED from POT series

FEH guidance recommends that for gauged records of less than 14 years, QMED should be estimated using a derived Peaks Over Threshold (POT) series[26]. A threshold was applied to the gauge series to give approximately 4-5 peaks per year, along with independence criteria, in line with FEH guidance. Flows were derived from the level series at the gauge using the model rating as this was deemed more reliable that the SEPA rating. An estimate of QMED could then be made using the equation given in the FEH Volume 3. The estimated value for QMED using the POT series method is 10.4 m^3/s.

QMED from AMAX series extended with regression

Peak flows on the River Carron at Stonehaven (derived from recorded stage using the model rating) were compared to those recorded on the adjacent River Bervie at Inverbervie during the period in which these gauged records overlap (2003-2010), and a reasonable correlation was found to exist. This relationship is shown in Figure 2-5 below.

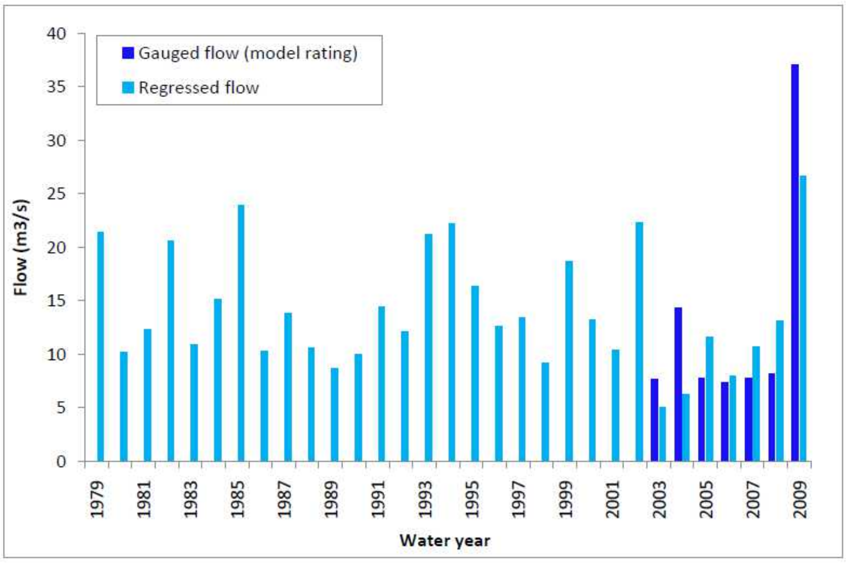
Figure 2-5: Carron-Bervie peaks regression



Regression analysis was carried out using this correlation to enable estimates of Annual Maxima (AMAX) flows on the Carron to be made from the Bervie series which extends back to 1979. These are shown Figure 2-6 in below along with the gauged flows on the Carron for the overlapping period.

26 Institute of Hydrology, 1999. Flood Estimation Handbook, Volume 3.

Figure 2-6: Carron AMAX flows from regression



The median of the AMAX series for the Carron composed of gauged flows and regressed flows was then calculated to give an estimate for QMED of 12.6 m^3/s.

QMED from catchment descriptors and donor catchments

It is also possible to derive an estimate for QMED from the catchment descriptors derived for the Carron catchment from the FEH CD-ROM, and by using the adjacent catchments of the Bervie and Feugh as donors through the application of an adjustment factor. The results of these alternative methods for calculating QMED are given in Table 2-2 below.

Table 2-2: Estimates of QMED

Method	QMED estimate (m3/s)
QMED from POT series	10.4
QMED from AMAX series extended with regression	12.6

Comparison method	QMED estimate (m3/s)
Catchment descriptors only	7.7
Bervie at Inverbervie (13001) used as donor	9.1
Feugh at Heugh Head (12008) used as donor	8.9
Weighted combination of Bervie at Inverbervie (75%) and Feugh at Heugh Head (25%) used as donor	9.0

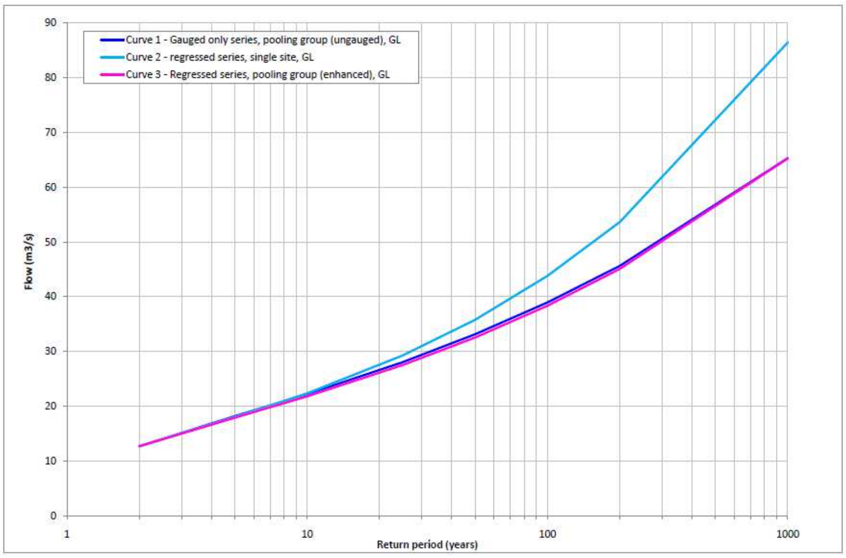
The estimates of QMED from the different methods are show good comparability. The estimate of QMED derived from the AMAX series extended with regression was chosen for use in this study. The strong relationship between the two gauges gives confidence in using this method to give a robust estimate and this also represents a conservative approach.

2.4.2 Creating growth curves

Given that the gauged record on the Carron is short, and the subsequent uncertainties over flow estimation, growth curves were developed for several approaches and compared. These approaches are listed below and Figure 2-7 shows the range of growth curves generated:

1. Ungauged pooling group analysis using the gauged Carron AMAX record only (Generalised Logistic (GL) distribution).
2. Single site analysis using an AMAX series derived from the gauged Carron record plus regression with the Bervie gauged record (GL distribution).
3. Enhanced pooling group analysis using an AMAX series derived from the gauged Carron record plus regression with the Bervie gauged record (GL distribution).

Figure 2-7: Growth curves for the Carron



In order to choose which growth curve is most appropriate, the context must be considered as well as the theoretical methodology. To help inform the decision, a review of historical flood events in Stonehaven was undertaken to determine the frequency with which different magnitudes of event have occurred.

2.5 Historical event review

The most significant historical flood events from the River Carron for which newspaper reports were available have been described in Section 1.8 above. These, together with other instances when the Carron was known to have been at a notably high level, were compiled into a historical flood record and estimates of flow for each event made using descriptions of the extent of flooding coupled with results from the hydraulic model. These estimates are given in Table 2-3 below:

Table 2-3: Historical flow estimates

Date	Brief description	Flow estimate at gauge (m3/s)
11/1873	Flooding of properties to 'considerable' depth	29
12/1882	Carron in 'high state of flood', flooding of properties to depth of 2-3ft	35
11/1905	Carron in spate	10
10/1906	Carron in spate	10
06/1907	Carron in spate	10
10/1907	(11th) Carron in spate and flooding of properties	26
10/1907	(18th) Carron in spate	10
06/1938	Carron in spate and causing concern to householders	16
11/1946	Carron in spate and at or above thresholds of properties on Cameron Street	26
03/1947	Carron in spate and causing concern to householders	16
09/1956	Carron in spate and causing concern to householders	16
08/1958	Carron in spate and causing concern to householders	16
10/1979	Carron out of bank and flooding properties on Cameron Street and Barclay Street	29
12/1985	Carron out of bank and flooding properties on Cameron Street and Barclay Street	27
04/1998	Carron in spate and flooding gardens on Cameron Street	12
10/2002	Carron in spate and reaching soffit of Green Br	20
03/2006	Carron in spate and reaching soffit of Green Br	12
10/2009	Carron in spate and approaching thresholds of properties on Cameron Street	20

Date	Brief description	Flow estimate at gauge (m3/s)
11/2009	Carron out of bank and widespread flooding to properties including those on Carron Terrace, Cameron Street, Barclay Street, Allardice Street, Low Wood Road, Dunnottar Avenue, Bridgefield, High Street and Arbuthnott Place	37
01/2010	Carron in spate and reaching soffit of Green Br	12

The return period of the most significant of these events was then estimated using the three potential growth curves described above. These are shown in Table 2-4 below:

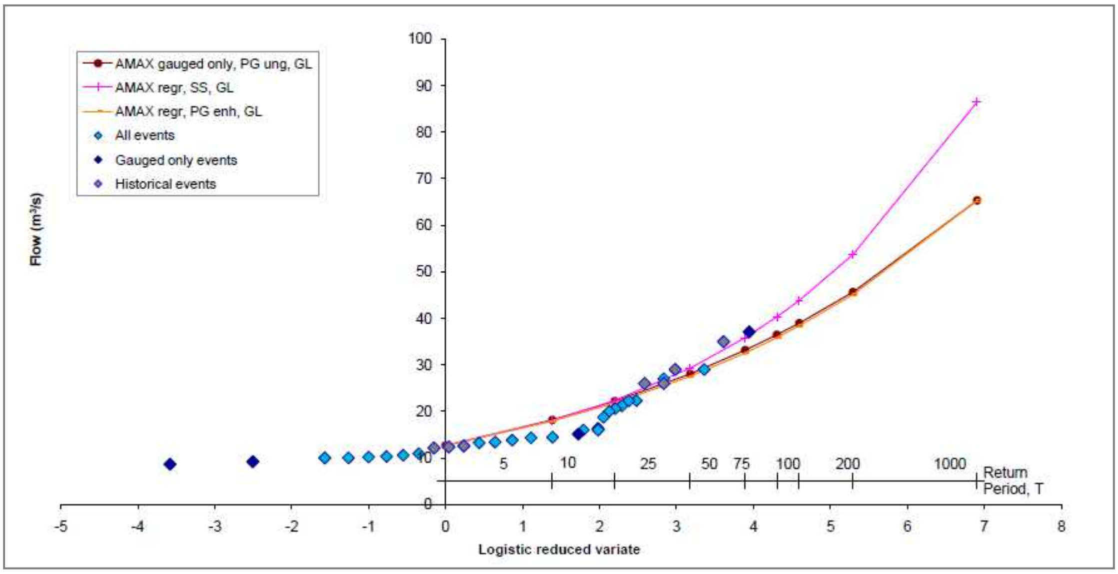
Table 2-4: Historical return period estimates

Date	Flow estimate at gauge (m3/s)	Return period estimate		
		Gauged only series, pooling group (ungauged), GL	Regressed series, single site, GL	Regressed series, pooling group (enhanced), GL
11/1873	29	30	24	32
12/1882	35	66	47	71
10/1907	26	20	18	21
11/1946	26	20	18	21
10/1979	29	30	24	32
12/1985	27	22	20	24
10/2002	20	7	7	8
10/2009	20	7	7	8
11/2009	37	84	58	89

Whilst all three growth curves give reasonable estimates of the return periods for the historical events, given that the November 2009 event is unmatched in approximately 140 years of historical reports and gauged record, this would suggest that a higher return period estimate is more appropriate. Higher estimates of return period are given by the ungauged pooling group approach using the Carron gauged record only and the enhanced pooling group approach using the Carron gauged series supplemented by the regression series.

A further way to verify the growth curves using historical information is using the Bayliss Reed method[27]. This method allows historical flood events to be plotted against growth curves using calculated plotting positions. The series of known flood events for the Carron at Stonehaven are shown with the three growth curves in Figure 2-8 below.

Figure 2-8: Plot of historical data and growth curves using Bayliss & Reed (2001) method



[27] A. Bayliss & D. Reed, 2001. The use of historical data in flood frequency estimation. Report prepared for MAFF by CEH.

This analysis again points to the two pooling group approach growth curves being the best fit for the data available. The single site analysis growth curve shows a poorer match to the data.

2.6 Design peak flows

In light of the above analysis and consideration of the theoretical methodologies, the choice of growth curve to be used for design flows for the Carron at Stonehaven is the enhanced pooling group approach based on the Carron gauged series supplemented by the regression series derived from the Bervie.

This was chosen as the most appropriate method from both a theoretical and evidence-based standpoint. From a theoretical viewpoint, the regression of the Carron and Bervie datasets showed a reasonable correlation and therefore use of an AMAX series derived from regression is considered a robust approach to extend the short gauged record on the Carron. A pooling group approach, using data from a range of similar catchments to create a growth curve, is preferable over single site analysis as it is generally more robust than relying solely on data from the single site. The enhanced pooling group approach ensures that the results are weighted towards the record available at the subject site for increased relevance.

Considering the historical evidence, the chosen growth curve matches well with historical estimates of flooding in Stonehaven and gives reasonable estimates of return period for the most significant historical events recorded. This gives confidence in the growth curve as being appropriate in context as well as in theory.

It should be noted that as the period of gauged record increases for the Carron and with the inclusion of future flood events experienced in Stonehaven, this analysis and the resulting growth curve should be updated which may result in changes in the design flows.

River Carron

As a result of the above analysis the design flows derived for the Carron at Stonehaven are:

Table 2-5: Design peak flows for the River Carron at Stonehaven

Annual probability	Return period (years)	River Carrion peak flow (m3/s)
50%	2	12.7
20%	5	17.9
10%	10	21.8
4%	25	27.5
2%	50	32.6
1.33%	75	35.9
1%	100	38.4
0.5%	200	45.1
0.1%	1000	65.3

Glaslaw Burn and Cheyne Burn

The Carron gauge was used as a donor for the estimation of flows on the two ungauged tributaries in the model: the Glaslaw and Cheyne Burns. An adjustment factor was applied to give an estimate of QMED on each of the burns and the growth curve applied to upscale the flows to the design events.

Table 2-6 below gives the design flows for the Glaslaw and Cheyne Burn.

Table 2-6: Design peak flows for the River Carron at Stonehaven

Annual probability	Return period (years)	Glaslaw Burn peak flow (m3/s)	Cheyne Burn peak flow (m3/s)
50%	2	1.5	0.7
20%	5	2.2	1.0
10%	10	2.7	1.2
4%	25	3.4	1.6
2%	50	4.1	1.9
1.33%	75	4.6	2.1
1%	100	5.0	2.2
0.5%	200	5.9	2.7
0.1%	1000	9.0	4.0

2.7 The November 2009 event in context

The calibrated hydraulic model was used to estimate of the magnitude of the 2009 event at approximately 37 m^3/s (as shown in Table 2-3 above). The growth curve calculated for the Carron places this estimate on the scale of flood event return periods at a return period of approximately 89 years.

Figure 2-9 below shows the gauged AMAX series for the Carron, plotted against the gauged AMAX for the Bervie at Inverbervie, Feugh at Heugh Head and Dee at Woodend. This helps to contextualise the magnitude of the November 2009 event in the Carron and nearby catchments.

Figure 2-9: AMAX series for the Carron, Bervie, Feugh and Dee

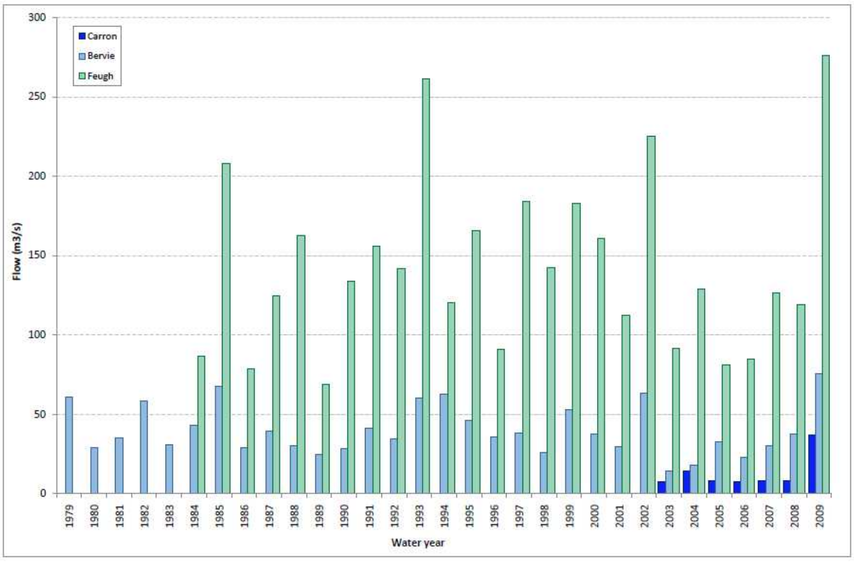
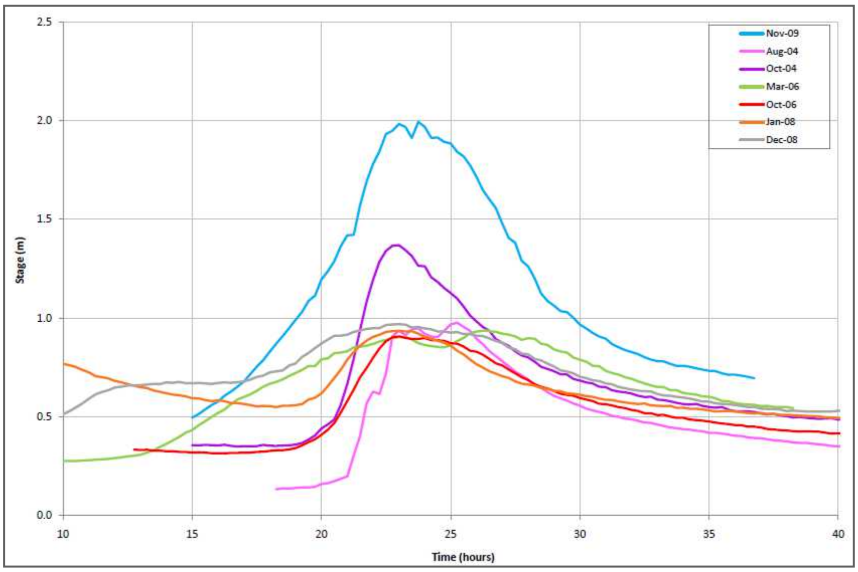


Figure 2-10 below shows the gauged level during 7 recent flood events on the Carron at Stonehaven. This demonstrates not only the magnitude of the peak flow in November 2009 but also the volume of floodwater that was conveyed along the Carron during this event, as the high levels are sustained for a long period of time.

Figure 2-10: Shape of historical event hydrograph for Carron at Stonehaven



2.8 Developing a standard hydrograph shape

River Carron

The shape of the hydrograph used to represent a flood event is important as well as the peak flow, as this will affect the character of the event including the volume of water being conveyed and the time to peak.

In developing a standard hydrograph shape for the Carron at Stonehaven it is important to consider flood volume and hence hydrograph width. To this end, the methodology described in Archer *et al* (1999)[28] was used to give a standardised hydrograph shape. This is based on averaging the shape of 19 gauged flood events over a threshold flow magnitude.

The standardised hydrograph derived can then be scaled to the design peak flows; this is shown in Figure 2-11 below.

Glaslaw Burn and Cheyne Burn

As these catchments are ungauged, the ReFH hydrograph shape was used and scaled to the design flows. This is shown in Figure 2-12 and Figure 2-13 below. The timing of the peak flows was matched between the Glaslaw Burn, Cheyne Burn and River Carron in order to be conservative.

2.9 Design hydrographs for the River Carron

The design hydrographs used in the model are shown below.

[28] D. Archer, M. Foster, D. Faulkner and J. Mawdsley, 2000. The synthesis of design flood hydrographs. In: Flooding Risks and Reactions. Proceedings of the Water Environment 2000 Conference, 5 October 2000. Institution of Civil Engineers, London.

Figure 2-11: Design hydrographs for the River Carron

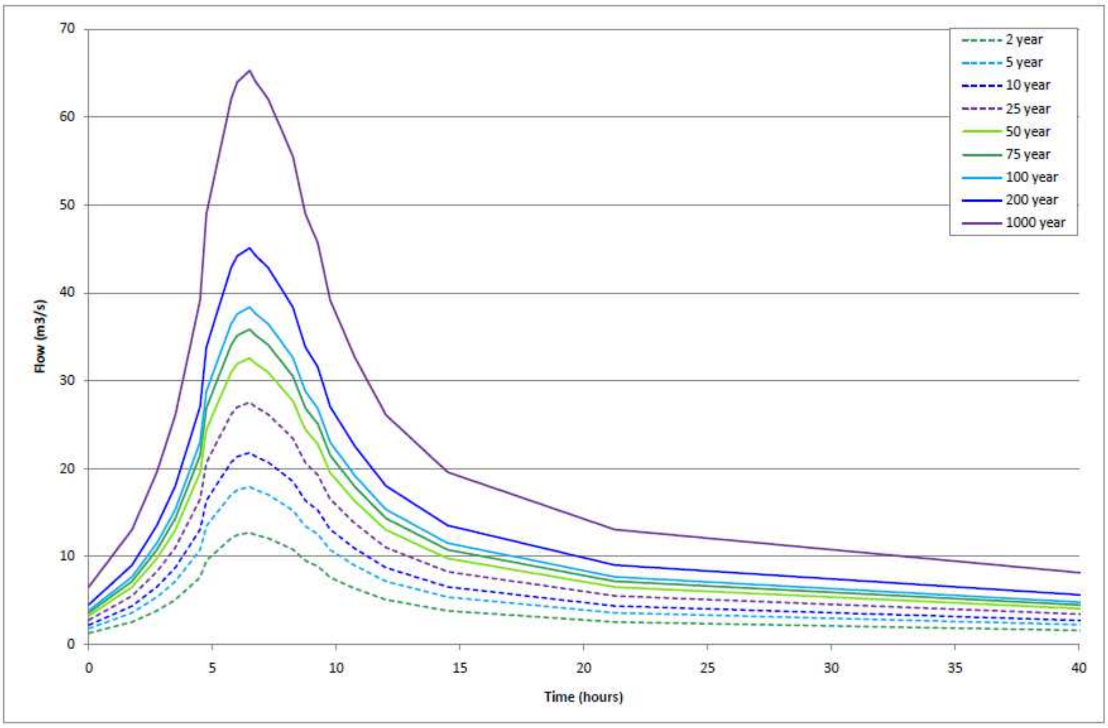


Figure 2-12: Design hydrographs for the Glaslaw Burn

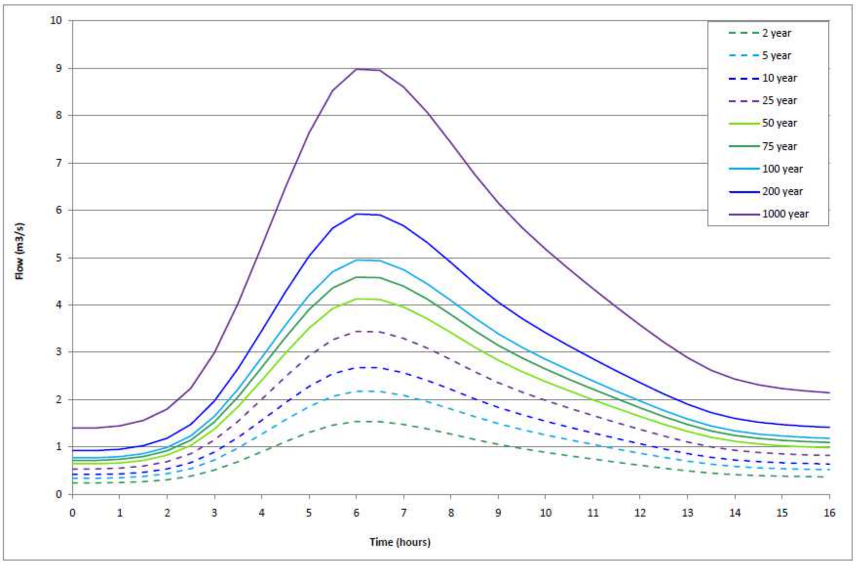
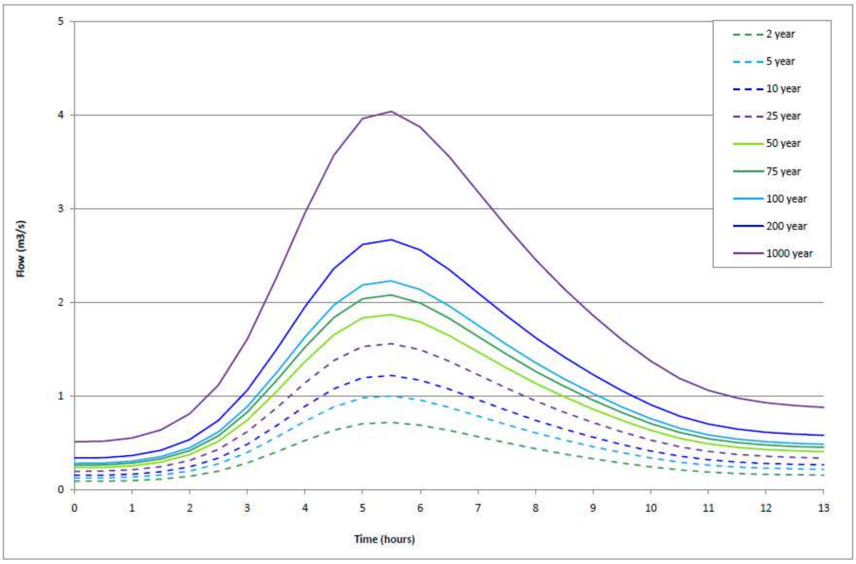


Figure 2-13: Design hydrographs for the Cheyne Burn



2.10 Summary

In summary the most up-to-date data available at the time of this study has been used to derive peak design flows within the River Carron, Cheyne Burn and Glaslaw Burn. The River Carron is gauged by SEPA at the Red Bridge while the Cheyne Burn and Glaslaw Burn's are ungauged.

As the River Carron gauge was first installed for water resources purposes and due to lack of safe access during high flow, the existing high flow rating was supplied by SEPA with caution. The hydraulic model constructed for this study has therefore been used to extend and verify the stage-discharge relationship at this location. The model rating has thus been used to convert the stage levels collected by SEPA into a flow series used for this analysis. Furthermore as the gauged data at the Carron gauge is relatively short this dataset has been extended using regression analysis from the Bervie data preceding the Carron. These estimates compare well with the historical data with respect to high flows and flooding instances available.

As with any flow estimate additional years of data collected in the future may result in changes to the data series, index flood (QMED) and flood growth curves and hence any future updates in flow data may result in changes in the design flows. The current estimate of the 0.5% AP (200 year) flow on the Carron is 45.1 m^3/s.

The Cheyne Burn and Glaslaw Burn's are ungauged and the River Carron gauge was used as a donor to adjust QMED, resulting in a 0.5% AP (200 year) flows of 2.7 and 5.9 m^3/s on the Cheyne Burn and Glaslaw Burn's respectively.

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3 Hydraulic modelling of the River Carron

A hydraulic model of the River Carron was required to assess flood risk to Stonehaven and to test proposed options for flood mitigation.

3.1 Modelling choices

The main choices for modelling are:

- Steady state 1 dimensional (1D) model: uses cross sections to represent the channel / floodplain geometry. Calculates water levels for a steady flow in a river, usually representative of a peak flow for a given return period. Takes account of watercourse structures.
- Hydrodynamic 1 dimensional (1D) model: uses cross sections to represent the channel / floodplain geometry. Models a flood "event," using a flood hydrograph, with the flow rising and falling before and after the peak flow. It is therefore more suited to volume sensitive calculations that involve washlands / floodplains (for example).
- Linked 1 dimensional / 2 dimensional (1D-2D) model: combines a hydrodynamic 1D model for the river channel with a 2D domain representing the floodplain, allowing time-varying flow in all directions. This is useful in situations where flow paths are complex or cannot be pre-determined.

For the River Carron at Stonehaven, a linked 1D-2D model is appropriate to ensure accurate representation of flow paths on the floodplain using detailed topographic information. This is important as flood risk to some areas of the town derives from flow escaping the channel further upstream before being routed across the floodplain.

3.2 Linked 1D-2D model

A 1D-2D InfoWorks-RS model was developed by JBA for this study. A 1D model had previously been constructed by JBA for the Channel Capacity Study undertaken in 2010[29] and was used as the basis for the linked model.

3.2.1 Model extent

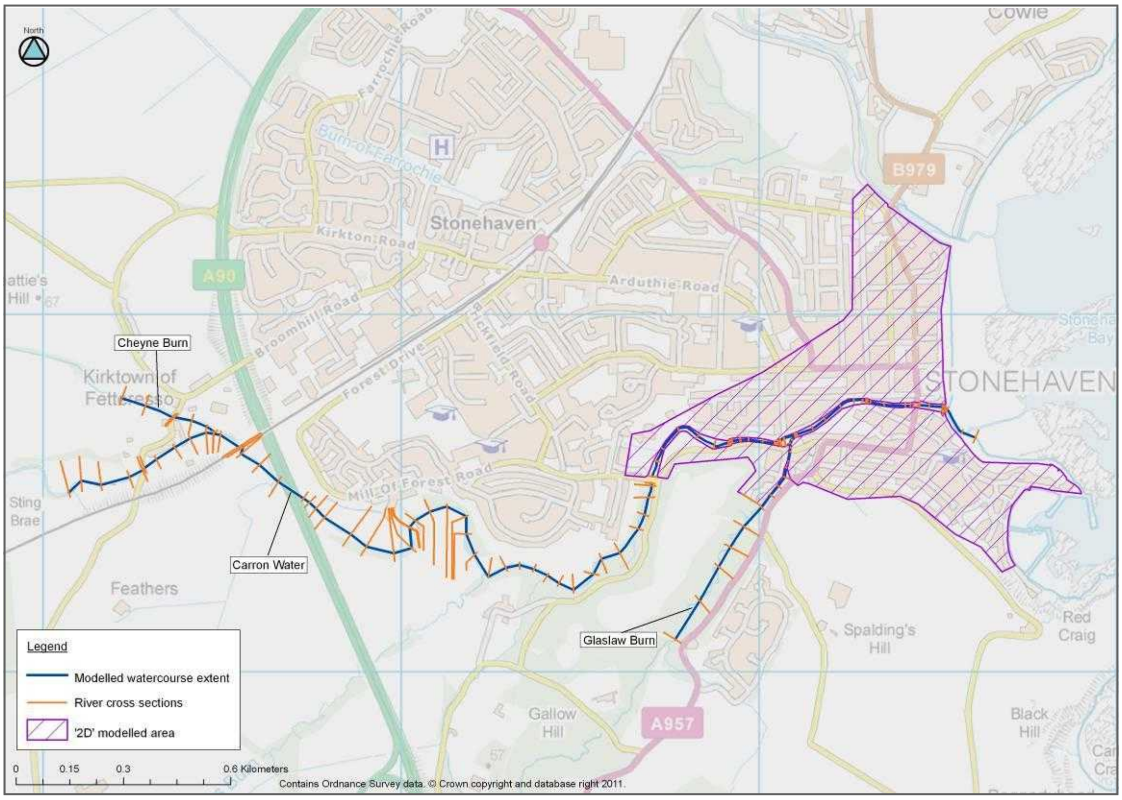
The model extends along the River Carron from Sting Brae (OS NGR 385071 785501) to the coastal outfall (OS NGR 387606 785657). It also incorporates the Cheyne Burn from Kirktown of Fetteresso (OS NGR 385218 785765) to its confluence with the Carron (OS NGR 385475 785669), and the Glaslaw Burn from Braehead Crescent (OS NGR 386767 785091) to its confluence with the Carron (OS NGR 387095 785658).

The upper part of the Carron to the Walker's Bridge (OS NGR 386689 785489) is modelled as a 1D reach, as are the Cheyne Burn and the upper part of the Glaslaw Burn. 1D modelling is appropriate for these reaches as the river valleys are well defined and therefore flood routing is relatively simple, being confined within the valley. The 2D model domain covers the areas of Stonehaven adjacent to the Carron from the Walkers' Bridge to the coast, incorporating the areas adjacent to the lower reach of the Glaslaw Burn. Here a 1D-2D linked model operates, with the channel (1D model component) connected to the floodplain (2D model component). Figure 3-1 below shows the model set-up.

The model does not include flood risk from the Touchs Burn (a right bank tributary of the River Carron), the Burn of Farrochie, the Maxie Burn or the Cowie Water.

[29] JBA Consulting, July 2010. Stonehaven Channel Capacity Study. Draft Report for Aberdeenshire Council. Updated in letter report to Aberdeenshire Council, 26 October 2010.

Figure 3-1: 1D-2D linked model set-up



3.2.2 Data available

The data available to construct the model comprised the following:

- Topographic survey of channel and structure cross sections on the River Carron from upstream of the Walker's Bridge to the coastal outfall (March 2010). This was used to construct a 1D InfoWorks-RS model of the Carron which was adapted for this study.
- Topographic survey of channel and structure cross sections on the River Carron between Sting Brae and the Walker's Bridge, and resurvey of the location of the log weir at the Green Bridge where the log was removed (March 2011).
- Topographic survey of channel and structure cross sections on the Cheyne Burn between Kirktown of Fetteresso and the River Carron confluence (March 2011).
- Topographic survey of channel and structure cross sections on the Glaslaw Burn between Braehead Crescent and the River Carron confluence (March 2011).
- LIDAR (Light Detection And Ranging) data for the Carron valley and Stonehaven town, flown by Infoterra in 2010. LIDAR data was provided to a 1m resolution and generally has a vertical accuracy of approximately ±0.2m.

3.2.3 Model geometry

River sections

River sections are taken from the topographic survey of the watercourses. In the reaches of the model where the 1D channel is linked to the 2D domain, the river sections extend the width of the channel to the top of bank level. Outwith the 1D-2D linked area, where the model is 1D only, the river sections extend onto the floodplain where this area is low and hence may convey floodwater.

Structures

Structures in the channel such as bridges, culverts and weirs were incorporated into the topographic surveys and dimensions and levels recorded. These structures were represented in the model.

2D domain

The 2D model domain was configured to cover the low-lying areas of Stonehaven in the proximity of the River Carron including those areas at risk due to overland flow. InfoWorks-RS triangulates a grid for the 2D domain using the LIDAR data which is loaded in directly. The maximum triangle size used (and hence the detail incorporated into the domain) is specified within the model parameters.

3.2.4 Boundary conditions

Boundary conditions are required at the model limits: the upstream point of each reach and at the downstream limit of the watercourse. The boundary conditions used for the River Carron model are as follows:

- Upstream limit of River Carron: Flow-time hydrograph
- Upstream limit of Cheyne Burn: Flow-time hydrograph
- Upstream limit of Glaslaw Burn: Flow-time hydrograph
- Downstream limit of River Carron: Stage-time hydrograph representing tidal harmonic.

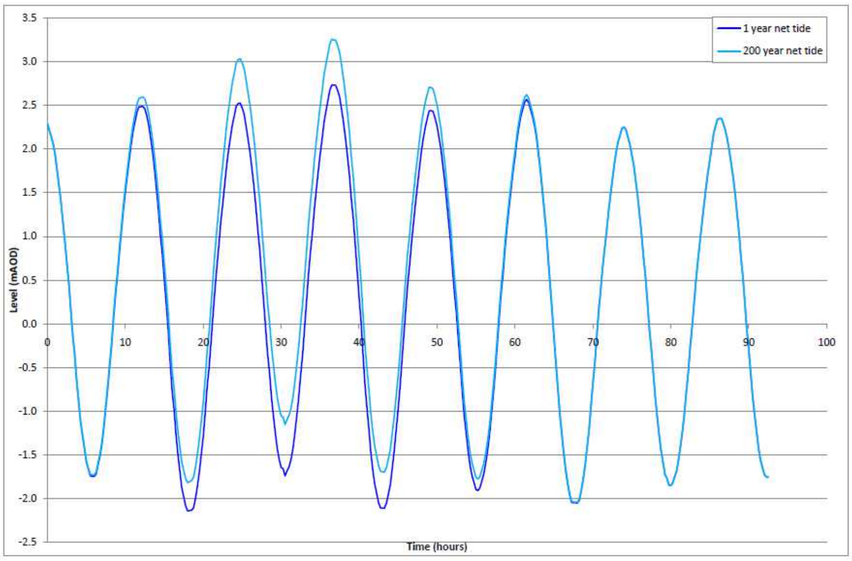
Upstream boundaries: flow hydrographs

The flow-time boundary conditions at the upstream limits of the three watercourses represent the design flows as described in Section 2.9.

Downstream boundary: tidal harmonic

The tidal harmonic used for the downstream boundary was derived using extreme sea levels taken from the Environment Agency's 2011 report on coastal flood boundary conditions[30] and also takes into account tidal surge. The 1 year and 200 year return period harmonics are shown in Figure 3-2 below.

Figure 3-2: Tidal harmonic at Stonehaven



The curve was timed so that peak sea level coincided with peak flows at the downstream limit of the model, in order to be conservative. The minimum water level was limited in line with the surveyed cross section.

[30] McMillan et al, 2011. Coastal flood boundary conditions for UK mainland and islands [project SC060064/TR2], Environment Agency report.

3.3 Model calibration

The model has been calibrated using information from the 1st November 2009 event. This event is within the gauged record of the SEPA gauge downstream of the Red Bridge and there is good documentary and photographic evidence of the flood extents.

This model includes the log weir downstream of the Green Bridge which was subsequently removed.

3.3.1 Calibration data available

The following data were available to calibrate the model:

1. Surveyed wrack marks - locations of deposits of debris and mud were marked following the event by Aberdeenshire Council and surveyed by JBA Consulting in 2010. These were found both within the town and in the river valley upstream of Stonehaven and were used to check that the modelled peak water levels are representative. Wrack marks should be treated with caution as they may be deposited as levels fall rather than at the peak of the flood.
2. Sketched flood outline - Aberdeenshire Council sketched the approximate extents of the out of bank flooding from November 2009 within the town. This was used to check that the modelled flood extents were realistic.
3. Photographs and videos - a number of photographs and videos were provided by the Council and local residents, as well as pictures and videos from news websites.

3.3.2 Methodology

The model was calibrated iteratively using the following methodology:

1. The model in its uncalibrated state was used to give a rating at the location of the gauge (Carron chainage 757) and hence to give an initial estimate of the flow during the November 2009 event equating to the flow required to reach the known gauged level of 2.07 mALD.
2. The model was run using this flow and the extent and levels reached noted.
3. Adjustments were made to the model parameters to achieve the closest possible approximation of the known outline and levels.
4. Once a reasonable calibration was achieved, the rating was extracted from the new model at the gauge location and a revised estimate made of the November 2009 flow.
5. The process was repeated to finalise the calibration.

The following parameters were considered and adjusted as required to improve the calibration:

Table 3-1: Calibration parameters

Parameter	Final value / type used
Channel roughness (Manning's 'n')	Open channel = 0.04 - 0.045 Vegetated islands = 0.1
General floodplain roughness in 2D model elements (Manning's 'n')	0.03
Road areas roughness in 2D model elements (Manning's 'n')	0.015
Method of representing buildings within the floodplain	Roughness polygons Manning's 'n' = 0.99
Bank spill levels (accuracy of LIDAR representation)	Surveyed river section bank levels used where LIDAR levels inconsistent
Bank spill weir coefficients	0.5 - 1.0 *
Bank spill modular limits	0.3 - 0.6
Weir coefficient for log weir at Green Bridge	1.0 *
Element size used in 2D model elements	5 m^2
* Note: Weir coefficient ranges are efficient: 1.0-1.7; inefficient : 0.3-1.0.	

3.3.3 Results of calibration

Figure 3-3 to Figure 3-11 below show the result of the calibration process, comparing the modelled levels and flood extent to the calibration data. The model is shown to calibrate well, although the 'scatter' amongst wrack marks should be taken into account.

Figure 3-3: Long section showing modelled water levels and calibration levels for whole modelled reach

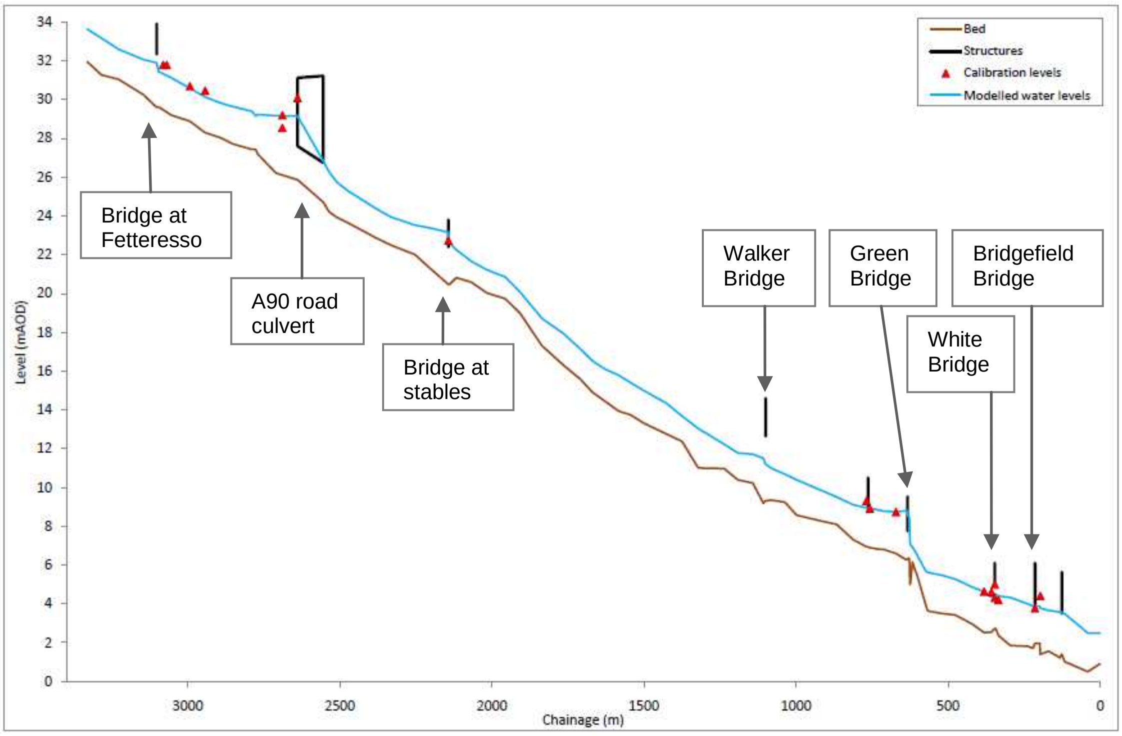


Figure 3-4: Long section showing modelled water levels and calibration levels for lower modelled reach

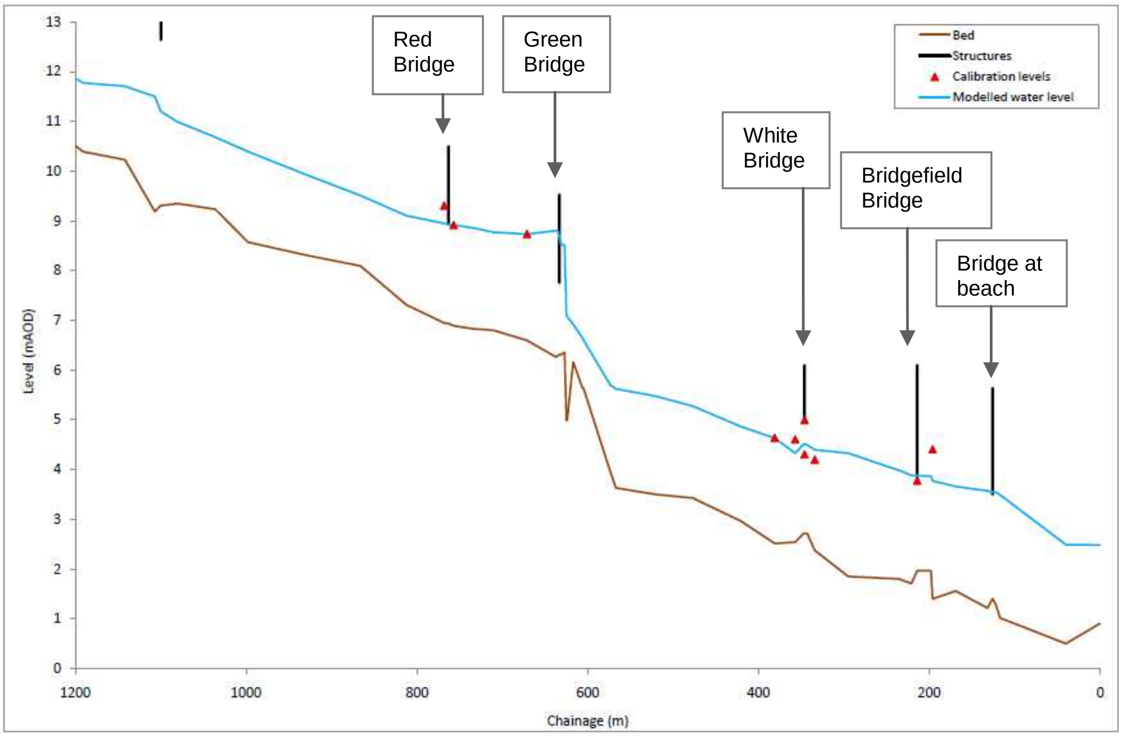


Figure 3-5: Plan showing modelled out of bank flood extents and sketched extent to north of River Carron provided by Council

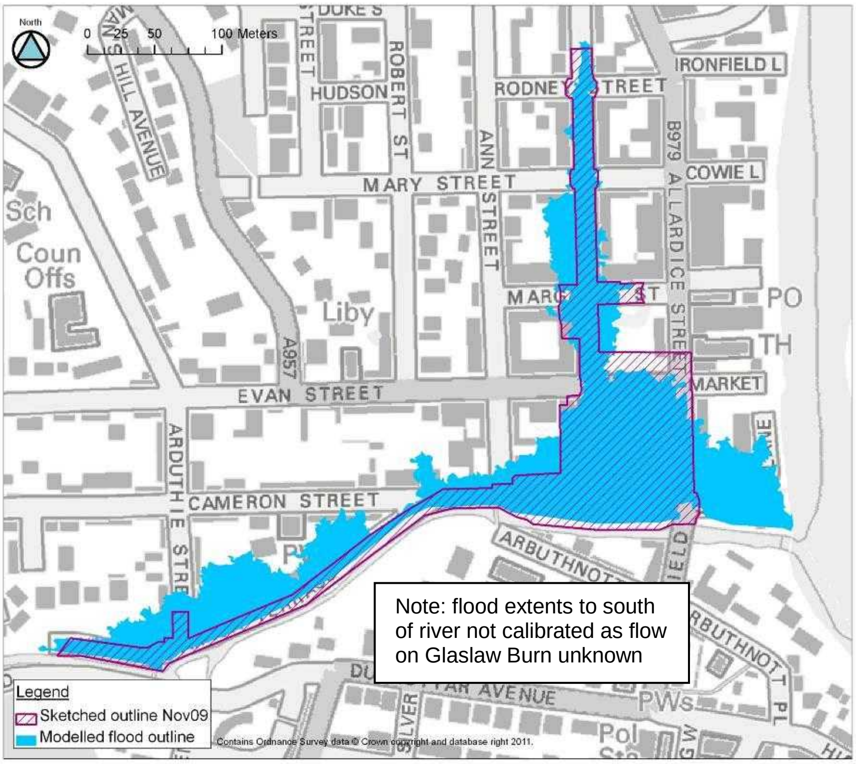


Figure 3-6: Modelled and documented flood levels at the Green Bridge

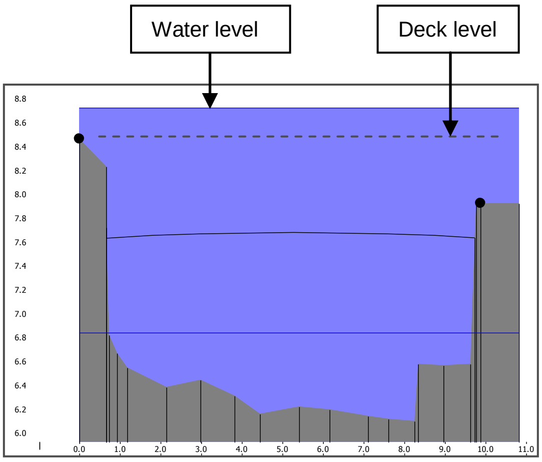
Documented	Modelled
 Downstream side of Green Bridge during the spate  Debris remaining on Green Bridge after flood event	 Model cross section at Green Bridge showing peak modelled water level

Figure 3-7: Modelled and documented flood levels at the White Bridge

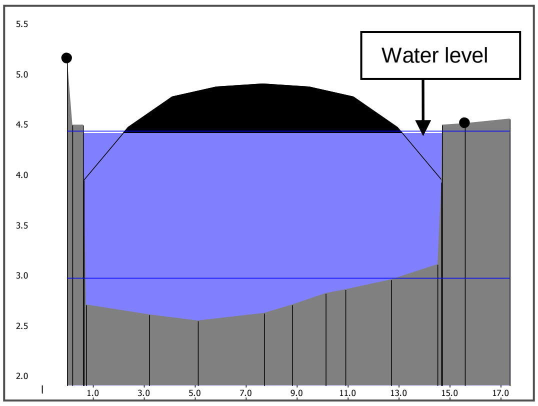
Documented	Modelled
 The White Bridge during the spate	 Model cross section at White Bridge showing peak modelled water level

Figure 3-8: Modelled and documented flood extents on Cameron Street east

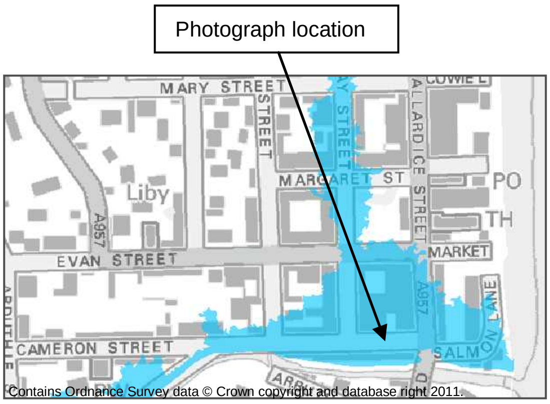
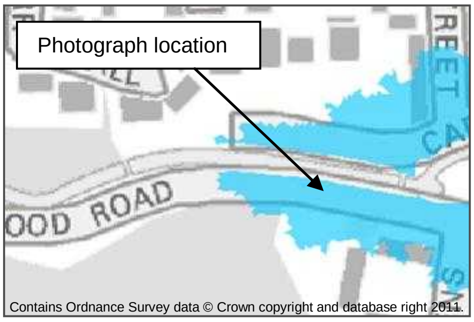
Documented	Modelled
 Flooding on Cameron Street  Flood debris on Cameron Street	 Modelled flood extents for Cameron Street area

Figure 3-9: Modelled and documented flood extents on Low Wood Road

Documented

Overbank flooding onto Low Wood Road during the spate

Modelled



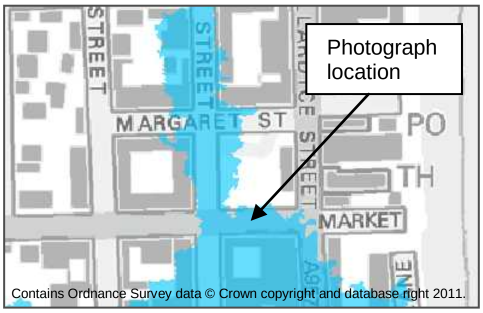
Modelled flood extents for Low Wood Road area

Figure 3-10: Modelled and documented flood extents at Market Square

Documented

Flooding on Evan Street at Market Square

Modelled



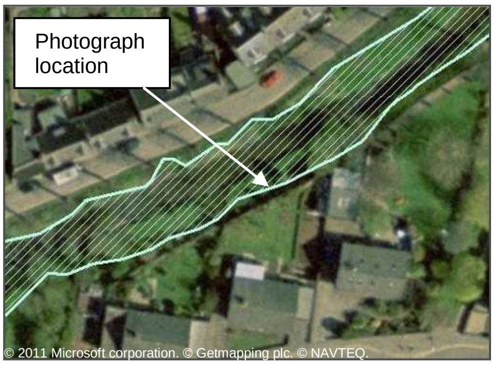
Modelled flood extents for Market Square area

Figure 3-11: Modelled and documented flood extents opposite Carron Terrace

Documented

Wrack mark in gardens of properties opposite Carron Terrace

Modelled



Modelled flood extents for area opposite Carron Terrace (showing channel flood extent only).

3.3.4 Further verification

A walkover was undertaken (16th June 2011) of the draft flood outline for verification, to check that the shape of the outline was consistent with observations on the ground and to verify choices made in the model schematisation.

3.4 Sensitivity testing

3.4.1 Introduction

Sensitivity testing was undertaken on the model to determine the impact that changes to the model parameters used would have. The following sensitivity tests were undertaken, based on the 0.5% AP (200 year) baseline scenario model:

Table 3-2: Sensitivity test ranges

Model parameter	Test range
Manning's 'n' of channel sections	± 10%
Weir coefficients (in-channel weirs and bank spills into 2D domain)	± 0.1
Downstream boundary condition	± 0.1m*
Flow	± 20%+
* As provided in Environment Agency's 2011 report on coastal flood boundary conditions[31] + Upper limit of 95% confidence interval for QMED calculated as +17.5% (based on methodology given in FEH Vol3)[32]	

3.4.2 Results

The results of the sensitivity tests for the 0.5% AP (200 year) event were as follows:

Table 3-3: Sensitivity testing results

Parameter	Change	Maximum increase (m)		Maximum decrease (m)	
		Amount (m)	Location	Amount (m)	Location
Manning's n	+ 10%	0.16	CAR_812	0.02	CAR_635
	- 10%	0.02	CAR_635	0.11	CAR_1036
Weir coefficients	+ 0.1	0.03	CAR_567	0.07	CAR_627
	- 0.1	0.09	CAR_671	0.05	CAR_573
Downstream boundary condition	+ 0.1	0.10	CAR_000	0.00	-
	- 0.1	0.00	-	0.10	CAR_000
Flow	+ 20%	1.12	CAR_2639	0.00	-
	- 20%	0.00	-	1.21	CAR_2639

These results suggest that the model is sensitive to flow, but with relatively low sensitivity to Manning's 'n', weir coefficients and the downstream boundary condition. The significant change in peak water level for the flow sensitivity tests occurs upstream of the A90 culvert, where at high flows the water backs up substantially, and this location is therefore particularly sensitive to a change in flow.

[31] McMillan et al, 2011. Coastal flood boundary conditions for UK mainland and islands [project SC060064/TR2], Environment Agency report.

[32] Institute of Hydrology, 1999. Flood Estimation Handbook, Volume 3.

3.5 Model assumptions

The use of this hydraulic model involves a number of assumptions.

Table 3-4: Model assumptions

Assumption	Comment
Model type	The model is a linked 1D-2D hydrodynamic InfoWorks-RS model.
Model geometry	The boundary between the 1D and 2D domains of the model is taken as the high point of the bank as defined using survey and LIDAR data. Bank levels along the boundary have been taken from LIDAR except where this has been deemed inaccurate compared to known features in surveyed cross sections such as walls and banks. A standard roughness value has been used across the 2D domain except for the footprint areas of buildings and roads. Roads have been modelled as low roughness polygons as they are likely to form flow routes. Buildings have been modelled as increased roughness polygons as water may occupy the building (since many have no raised threshold) but flow through them will be inefficient. The framework under the Green Bridge has been modelled as being 100% blocked, i.e. the base of the framework represents the underside of the bridge.
Boundary conditions	The model has three inflow points located at the upstream limits of each watercourse (River Carron and tributaries). The downstream boundary is a tidal harmonic.
Range of model application	The model is a linked 1D-2D hydrodynamic model and hence is applicable to modelling a range of scenarios including assessing floodplain storage and attenuation as well as changes to the channel geometry such as channel modification and alteration of structures.

3.6 Model outputs

The model outputs include results at each river cross section in the 1D domain, including time-varying water level, flow and velocity, and data for each element (triangle) in the 2D domain including depth and velocity.

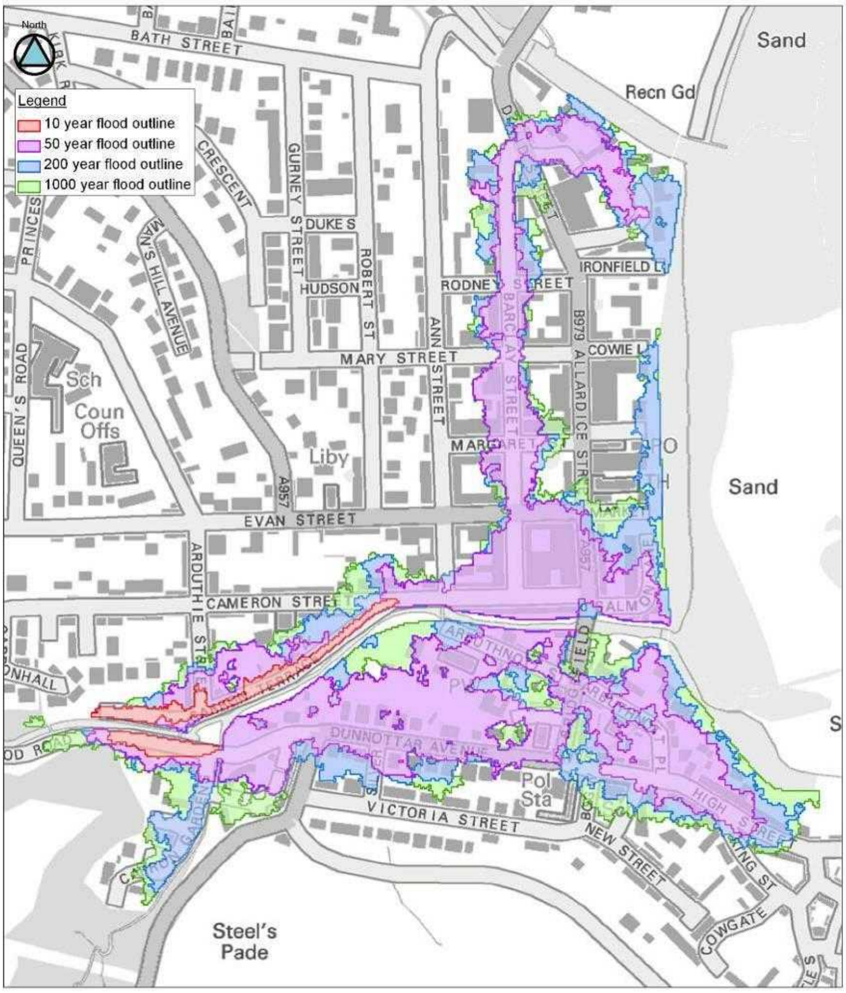
4 Flood risk from the River Carron

4.1 Model results for 'as existing' scenario

Appendix A and Figures 1 to 4 at the back of this report show the model results for the as existing scenario on the River Carron.

The figures below show the model results in terms of the extent of flooding in the 2D domain (Figure 4-1) and peak water levels (Figure 4-2) respectively. The model suggests that the River Carron will first overtop its banks during the 10% AP (10 year) event.

Figure 4-1: Existing scenario flood outlines

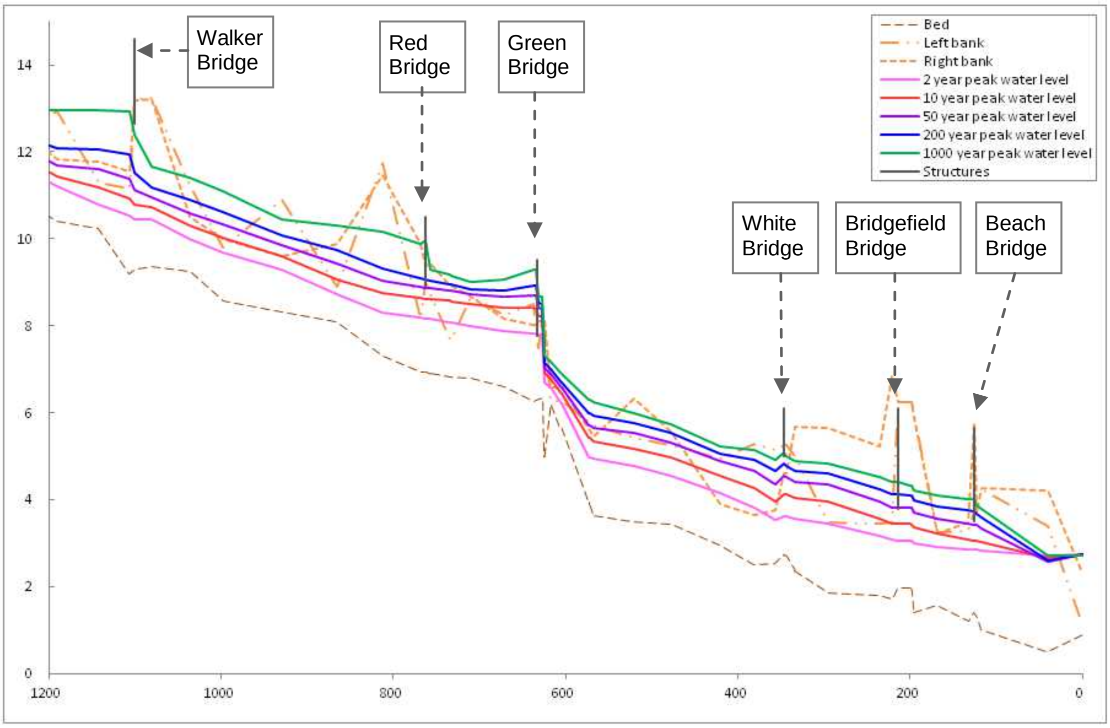


Modelled channel capacities at channel sections through the town are shown below in Table 4-1 below.

Table 4-1: Existing Modelled Channel Capacity

Node	Left Threshold Level (m AD)	Right Threshold Level (m AD)	Min flow at which threshold level reached (m3/s)
998	11.26	14.00	>47
929	10.91	13.73	>47
866	12.40	13.26	>47
812	11.97	11.88	>47
768	9.34	10.10	>47
763	9.34	9.93	>47
Red Bridge			
757	9.49	9.51	>47
734	9.36	8.93	43
710	8.66	8.66	30
671	8.41	8.17	17
637	8.49	8.01	16
635	8.54	8.00	16
Green Bridge			
631	8.50	8.10	18
627	8.24	8.11	18
Log weir			
624	7.86	8.13	>47
605	6.99	7.25	>47
567	6.30	6.38	>47
521	5.44	5.94	33
477	5.24	6.20	35
381	5.32	4.66	37
357	5.16	4.66	45
346	5.26	4.61	39
White Bridge			
334	5.03	5.07	>47
295	5.77	5.66	>47
236	3.45	5.22	23
221	3.48	6.83	28
214	6.23	6.24	>47
Bridgefield Road Bridge			
196	3.85	5.86	43
169	3.27	3.53	29
132	3.29	5.75	35
126	3.73	3.72	47
117	4.23	4.26	>47
40	3.40	4.22	
0	1.15	2.33	
Note: cross sections highlighted in bold are those sites which have a capacity less than that of the November 2009 event.			

Figure 4-2: Existing scenario peak water levels long section



4.2 Key flooding mechanisms

During the 10% AP (10 year) event on the Carron, the model suggests that the first location to experience overtopping of the banks is between the Red Bridge and Green Bridge. The left bank is shown to overtop first at the far west end of Carron Terrace, and the right bank would overtop along a considerable length of Low Wood Road between the two bridges. Out of bank flow is shown to be routed east along Carron Terrace and Low Wood Road. This is a key flooding mechanism as the model suggests that up to the 2% AP (50 year) event this is the only location of overbank flow which leads to flooding of property, but due to overland flow it is capable of causing widespread flooding north and south of the river, spreading to Barclay Street and the Market Square area as well as Arbuthnott Place and the High Street.

The model suggests that at the 1.33% AP (75 year) event, out of bank flow begins further east in the town, on the left bank at the junction of Carron Terrace and Cameron Street, and on the right bank immediately downstream of the White Bridge. Bank overtopping becomes more widespread here during the 0.1% AP (1000 year) event.

At the 0.5% AP (200 year) event out of bank flooding commences on the Glaslaw Burn at the far southern end of Carron Gardens. This floodwater is routed north via the road to join floodwater from the Carron.

The modelling suggests that the A90 culvert has a capacity of c. 23.9m^3/s without debris blockage.

4.3 Target areas for alleviation works

As a result of this analysis, the critical areas for alleviation works to reduce the peak flow or increase channel capacity are:

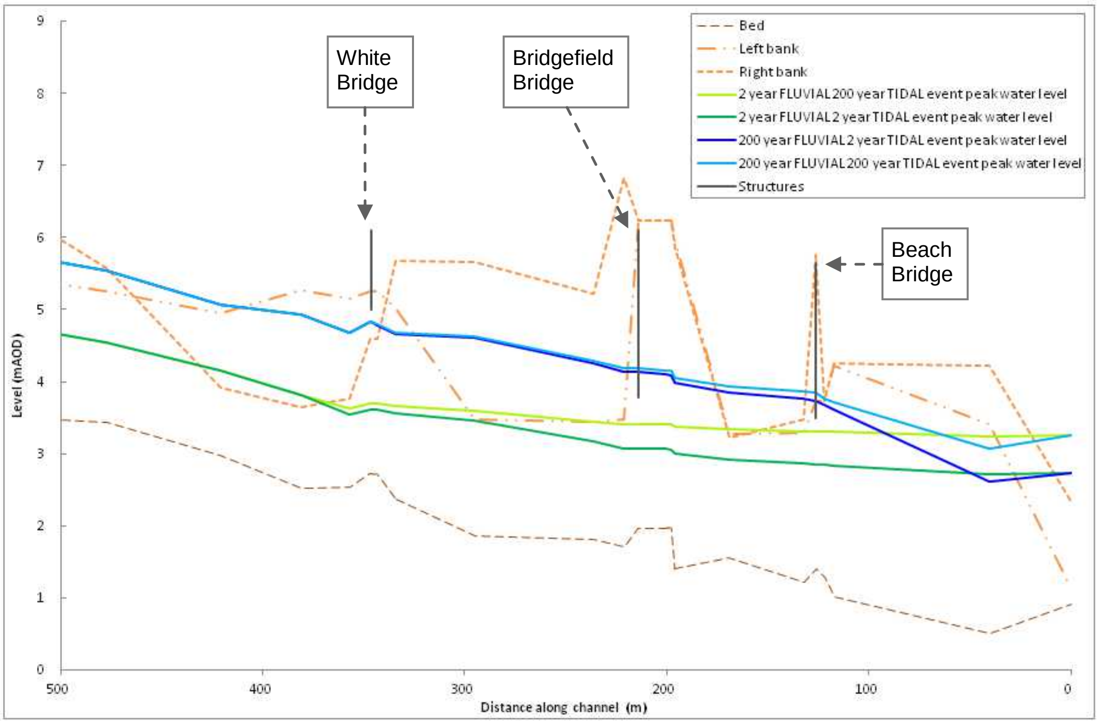
- Between the Green and Red Bridges;
- Along Carron Terrace / Cameron Street;
- Around the White Bridge; and

- At the south end of Carron Gardens.

4.4 Tidal influence on water levels

In order to provide an indication of the impact of extreme tidal levels on water levels in the River Carron, the model was run for each combination of the 50% AP (2 year) and 0.5% AP (200 year) fluvial flows on the Carron and tidal levels at the downstream boundary.

Figure 4-3: Tidal and fluvial 200 year peak water levels



This analysis suggests that the limit of the tidal impact on water levels is around the White Bridge for low return period events, and between the White Bridge and Bridgefield Bridge for the design 0.5% AP (200 year) event. The difference in water levels between the two tidal scenarios (0.5% AP (200 year) and 50% AP (2 year)) for the 0.5% AP fluvial flow is approximately 60 mm at Bridgefield Bridge.

This suggests that joint probability scenarios between fluvial and coastal flooding should be considered during the detailed design phase to determine the combined flood risk. Joint probability analysis relates to the potential for two (or more) variables (such as tidal levels and fluvial flows) taking high values at the same time. Thus a 0.5% AP event may be represented by a number of different combinations of relatively extreme conditions on both the River Carron and in terms of the tidal levels[33].

Thus different joint probability scenarios of fluvial and coastal flood risk should be assessed to determine the maximum required height of defences in the tidally-influenced reach downstream of the White Bridge. However, the above analysis using the very extreme 0.5% AP fluvial / 0.5% AP tidal (and thus very small overall annual probability) suggests that it is unlikely to be significantly different to the defence heights derived from the fluvial analysis which follows.

[33] More details are given in: SEPA, 2005. Use of Joint Probability Methods in Flood Management. R&D Technical Report FD2308/TR2.

5 Surface water flood risk to Stonehaven

5.1 Introduction

Surface water flooding is flooding as a direct result of rainfall onto the ground surface and its subsequent runoff via overland flow routes leading to pooling in topographically low-lying areas.

Surface water flood risk was mapped in this study using JFLOW+, 2D raster-based modelling software developed by JBA Consulting. The inputs to the model are rainfall data and topographical information for Stonehaven. The model produces a map of surface water flood depths across the study area which will provide a tool to assist with assessing surface water flood risk and developing options for mitigation.

5.2 Rainfall characteristics

The east coast of Scotland is in the rain shadow of the generally wetter west and the FEH CD-ROM (v3) suggest that the Standard Average Annual Rainfall (SAAR) within the study area is in the region of 870 mm.

A range of rainfall return periods were modelled to give a full understanding of the areas of Stonehaven at surface water risk at different magnitudes of event: 25 year (4% AP), 75 year (1.33% AP), 100 year (1% AP), 200 year (0.5% AP) and 1,000 year (0.1% AP).

Rainfall depths used in the model were derived using methods from the FEH and distributed over a standard 'summer' storm shape, which has a pronounced peak representing an intense convective storm likely to produce surface water flooding. See Appendix B for more details.

5.2.1 Effect of urban drainage

Drainage systems in urban areas remove some surface water runoff volume from the ground surface. Within an urban area such as Stonehaven, the capacity of the drainage system will vary substantially between locations and therefore it is appropriate to apply a standardised reduction in rainfall to account for drainage, in this case the average of the 20% AP (5 year) event. See Appendix B.

5.3 Digital Terrain Model

Surface water modelling uses a 2D raster approach to simulate rainfall runoff over the topography of the study area. For this purpose a Digital Terrain Model (DTM) is required.

The DTM for Stonehaven was created from LIDAR data (high resolution) which covers the town and main valley of the River Carron, supplemented by NextMap (lower resolution) for outlying areas. The DTM was edited to remove unrealistic obstructions to flow paths (such as bridges crossings) and to represent the impact of buildings and roads on surface water routing. See Appendix B.

5.4 Surface water modelling

5.4.1 Description of model

Surface water modelling utilises JFLOW+ modelling software, a specialist tool for assessing surface water flood risk. JFLOW+ is a 2D flood routing model which uses a raster-based approach driven by the underlying Digital Terrain Model. Water movement between cells is driven by gravity and depends on the ground level and water depth in adjacent cells. Velocity is also influenced by the roughness coefficient specified for the cells. Thus blanket rainfall applied across the study area will be routed according to the topography to low-lying areas, where it will pond until the water level is high enough to spill to surrounding cells. JFLOW+ incorporates full implementation of the Shallow Water Equations providing reliable flood depth and velocity modelling.

5.4.2 Model assumptions

The following assumptions apply to the JFLOW+ model:

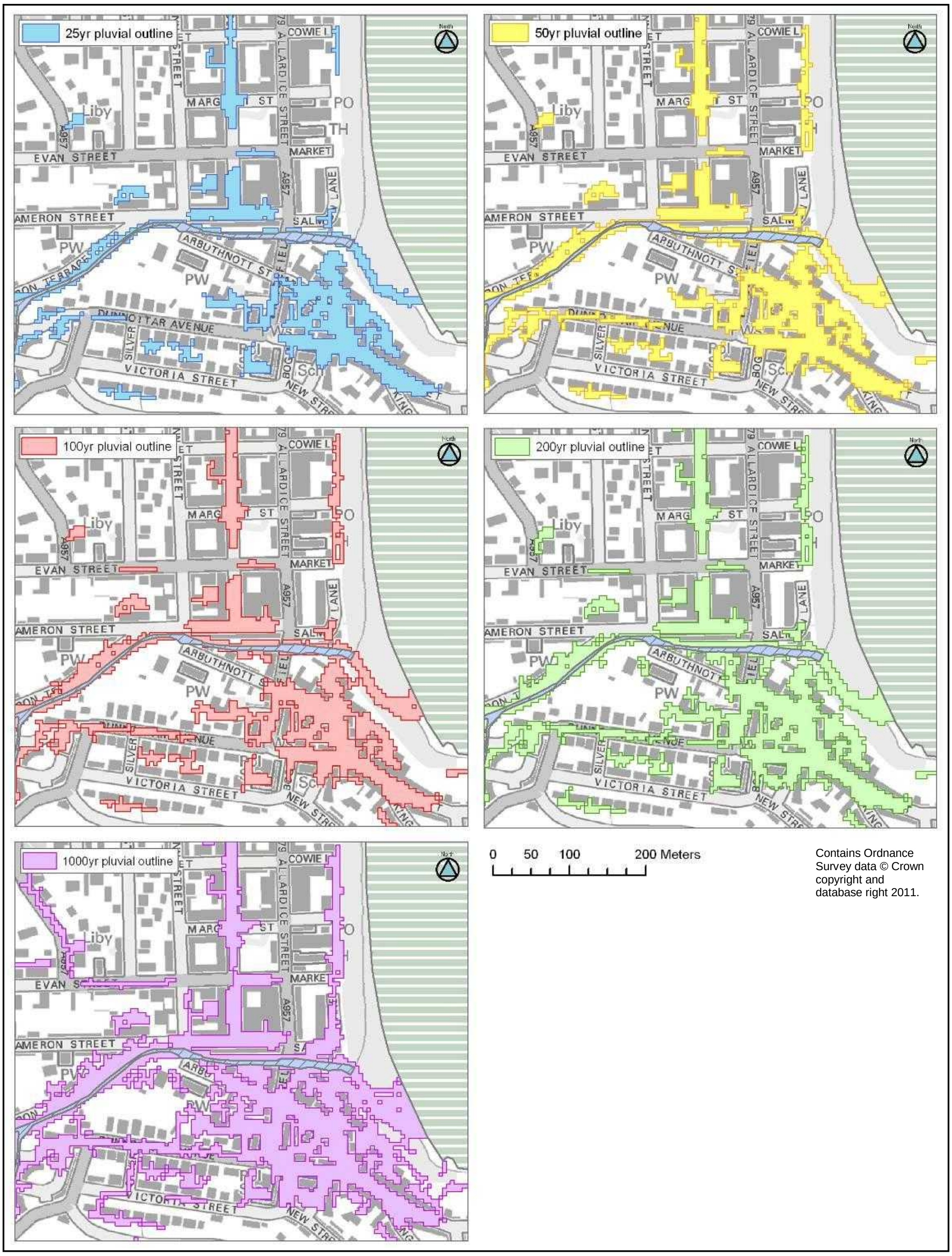
- Filtered LIDAR and NextMap data used in the DTM gives an accurate representation of the ground surface and presence of streamlines and low topography;
- Flow will pass around buildings rather than 'through' them (no volume accommodated within buildings);
- Flow along roads is constrained by kerbs of approximately 0.1 m height;
- A Manning's 'n' coefficient of 0.1 is used as a blanket surface roughness;
- Water is lost from the model at the edges of the DTM;
- The model run time extends beyond the end of the input hydrograph in order to allow water to continue to run off across the ground surface to create final flood depths. The model run continues for 6 times the hyetograph length (standard multiplier for JFLOW+).
- Urban drainage capacity can be represented by a reduction in rainfall equating to the average of the 20% AP (5 year return period) event.

5.5 Results

See Figures 5 to 9 in the Figures section at the back of the report for surface water flood mapping covering the Stonehaven urban area.

Figure 5-1 below shows the surface water flood outlines in Stonehaven town centre for each return period (with the outlines from the two durations merged for each).

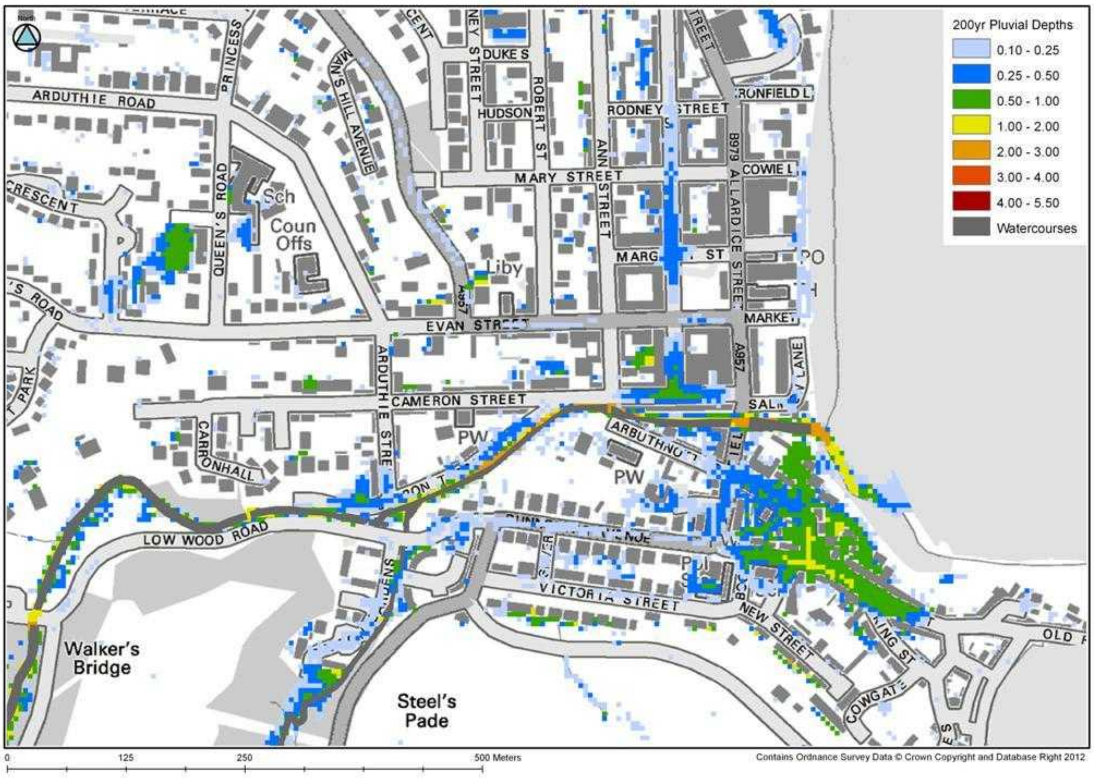
Figure 5-1: Surface water outlines for Stonehaven town centre



This suggests that the key areas of risk in the centre of town include Cameron Street near the junction with Barclay Street, Barclay Street around the junction with Margaret Street and the area around Arbuthnott Place / High Street. Both the former and latter are areas which historical reports have suggested are at risk.

Figure 5-2 shows surface water flooding depths for central Stonehaven for the 0.5% AP (200 year) surface water event.

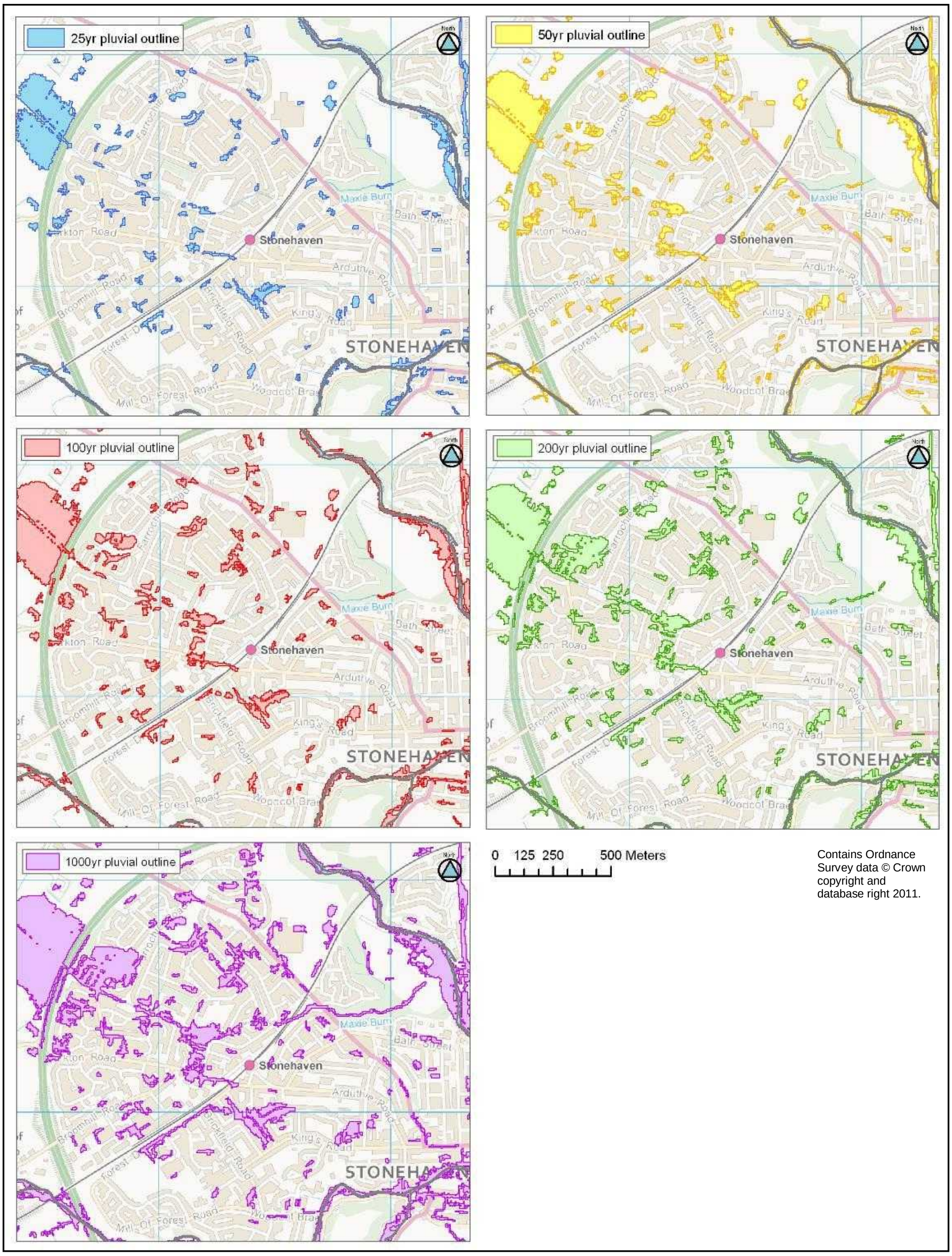
Figure 5-2: 0.5% AP (200 year) surface water depths for Stonehaven town centre



This suggests that surface water flooding poses a significant risk to properties in Stonehaven, with potential depths during the 0.5% AP (200 year) surface water event reaching approximately 0.7 m in the Cameron Street / Barclay Street area and approximately 1.1 m in the low-lying area of High Street. Works to reduce fluvial flood risk are unlikely to mitigate against surface water flooding unless they comprise individual property defences. Additional measures may thus be required to reduce the risk to properties from surface water flooding.

Figure 5-3 shows the surface water outlines for a wider area of Stonehaven. This suggests that in the wider town the areas of flooding are more scattered, as would be expected with a more variable gradient. There are some larger areas of surface water flooding during higher return period events, along the route of the Farrochie Burn with its associated topographic depression.

Figure 5-3: Surface water outlines for Stonehaven



Another key location which is shown on the maps to be at surface water risk is in the vicinity of the Cowie Leisure Centre and Caravan Park. These lie in a topographic depression at the coast and are therefore highly susceptible to surface water flooding.

5.6 Mitigating surface water flood risk

This study does not propose options for mitigating surface water flood risk. However, the Council in corroboration with Scottish Water may wish to consider options such as improving the capacity of the surface water combined sewers, retrofitting of SuDS (Sustainable Drainage Systems) and pumping in the future to help alleviate this risk or construction of new storm water relief systems.

SuDS systems work by reducing the rate at which surface water reaches the drainage system, through methods such as storage and infiltration. Further study would be required to identify whether this is feasible and possible locations for retrofitting to be undertaken.

Pumping is a reactive option to alleviate surface water flooding by removing ponded water in key locations. This may be of particular benefit where outfalls into the river are locked due to high water levels.

6 Ecological Survey

6.1 Introduction

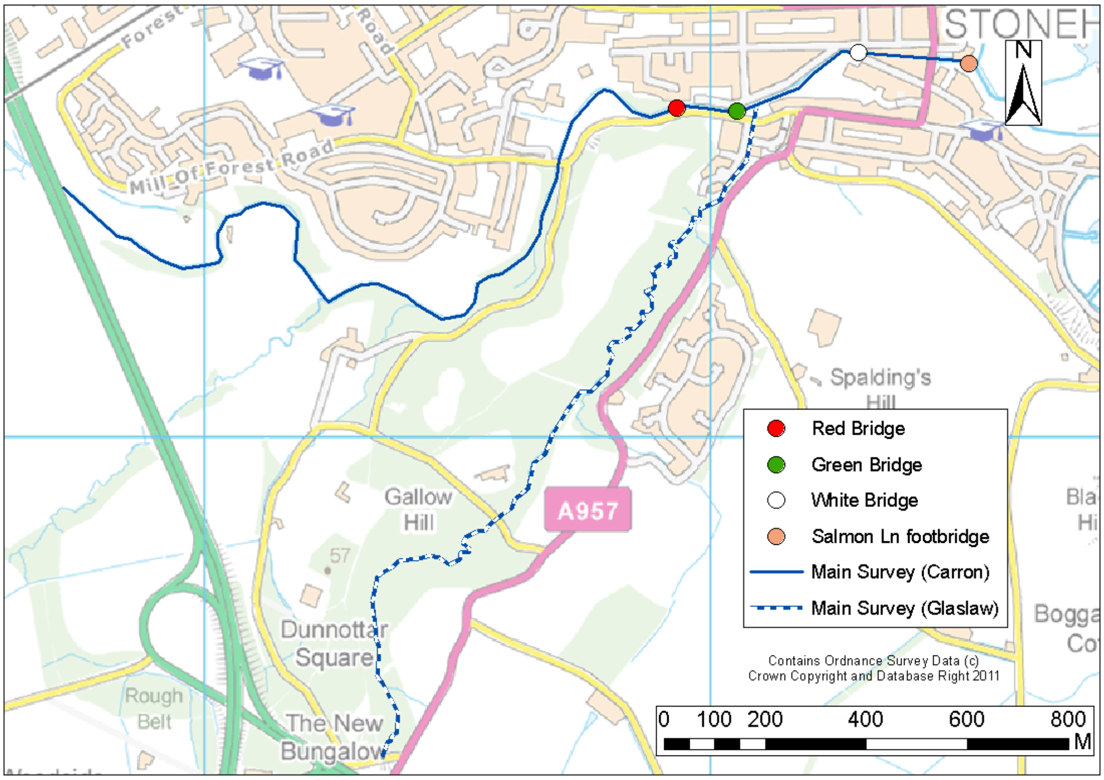
6.1.1 Background

As part of the development of flood alleviation options for Stonehaven, this chapter considers the environmental constraints and opportunities along the River Carron, with particular emphasis on the downstream reach between the A90 and the estuary.

6.1.2 Location

Figure 6-1 shows the reaches of the Carron and Glaslaw along which the ecological survey was undertaken.

Figure 6-1: Ecological survey location along the River Carron



6.1.3 Methodology

The survey has two main components; a desk-based survey examining existing records held by the local biological records centre and various web-based databases, and a walkover site survey. The desk-based survey covers the catchment while the walkover survey is constrained by the A90 and includes the Burn of Glaslaw, a significant right bank tributary. The total surveyed length of river is 4.5 km and the survey took place on 6th April 2011. A brief bat activity survey was carried out on the evening of 5th April using a Batbox Duet bat detector.

Websites used to gather information include Scottish Natural Heritage (SNH) Sitelink, National Biodiversity Network (NBN) Gateway, Magic, Scottish Environmental Protection Agency (SEPA), Stonehaven and District Angling Association (SDAA), Aberdeenshire Council, North East Local Biodiversity Action Plan (NELBAP) and the Scottish Ornithological Club (SOC). Records were obtained from the North East Scotland Biological Records Centre (NESBRC).

6.2 Desk-based survey results

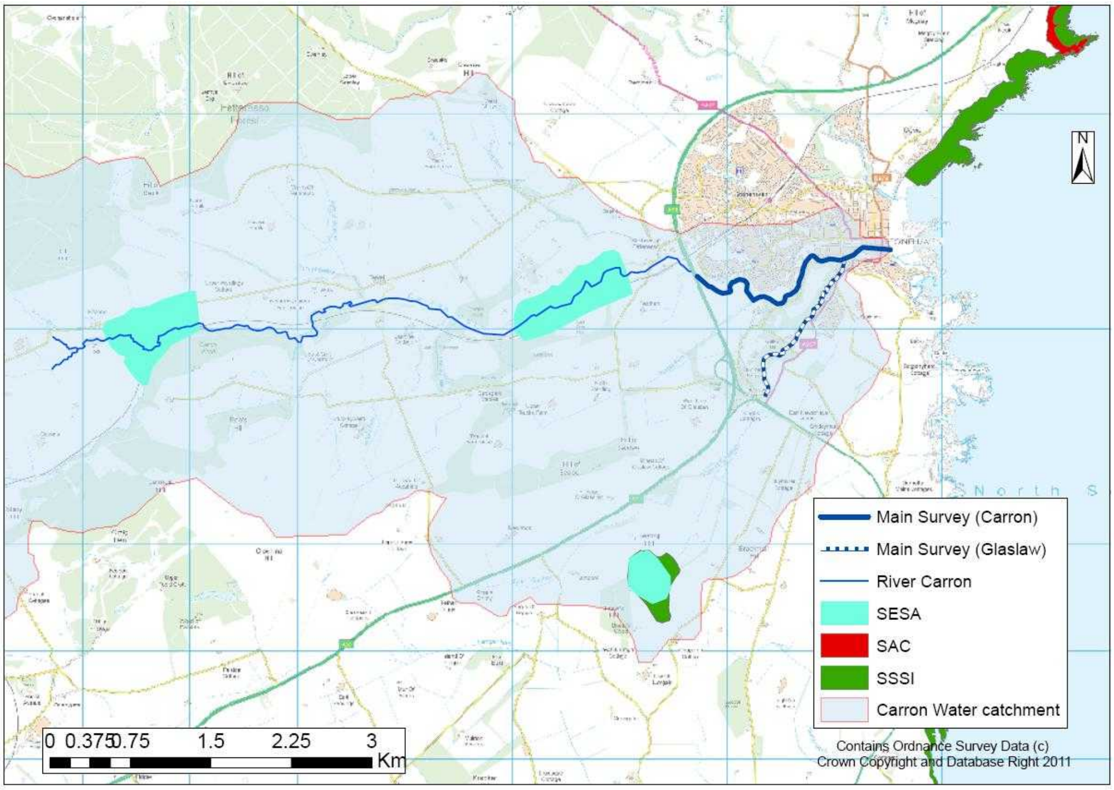
6.2.1 Designated sites

Within the catchment of the Burn of Glaslaw is the Loch of Lumgair Site of Special Scientific Interest (SSSI), which is one of the best examples of basin mire in eastern Scotland (SNH SSSI citation, undated). The remaining statutory nature conservation sites are all outside the catchment. The closest is the Garron Point SSSI. This is designated as a geological SSSI and is approximately 0.7 km northwards up the coast. The closest nature conservation site is the Garron Point Special Area of Conservation (SAC) which is 2.4 km up the coast from the estuary and Fowlsheugh SSSI is 3.1 km to the south along the coast.

The Carron Water itself is designated locally under the Study of Environmentally Sensitive Areas (SESA) for its interesting riverside vegetation, the boundary of this site is approximately 0.8 km upstream from the surveyed section. SESA is Aberdeenshire's local, non-statutory nature conservation designation. Also within the broader catchment: Elfhill is designated as a SESA site for its native population of Bluebell *Hyacinthoides non-scripta* and the Loch of Lumgair is also a SESA site.

The designated sites are shown below in Figure 6-2.

Figure 6-2: Environmental Designations



6.2.2 Habitats and land-use

The river rises in the conifer plantations of Fetteresso Forest before flowing through an area of mixed plantation and agricultural land. For much of this section the river shadows the railway line and the narrow land between has been planted for timber. The agricultural land is predominantly pasture but on the less steep valley slopes there are some arable fields.

Once across the A90 the general habitat is unchanged, however this soon enters a narrower valley with steeper wooded banks. With the Woods of Dunnottar above the right bank, the left bank becomes more urban. The final 550 m of the river is completely urban in nature, from just upstream of the Burn of Glaslaw to the sea, and much of this is artificially channelled through the town.

6.2.3 Protected species

The river is renowned as a salmonid stream with good numbers reported to use the upper reaches to spawn (SDAA). Atlantic Salmon *Salmo salar*, Sea Trout *Salmo trutta*, European Eel *Anguilla anguilla* and River Lamprey *Lampetra fluvialis* have all been recorded. Otter *Lutra lutra* is present throughout the catchment. Water Vole *Arvicola amphibius* are present on the Carron Water.

Daubenton's *Myotis daubentonii* and Common Pipistrelle *Pipistrellus pipistrellus* bats have been recorded and with nearby records of Soprano Pipistrelle *Pipistrellus pygmaeus* and Brown Long-eared *Plecotus auritis* bats, these are also probably present.

6.2.4 Non-native invasive species

The Wildlife and Countryside Act 1981 (as amended) Schedule 9 plant species Japanese Knotweed *Fallopia japonica*, Giant Hogweed *Heracleum mantegazzianum* and Himalayan Balsam *Impatiens glandulifera* are all recorded from the site. Rhododendron *Rhododendron ponticum* is also present within the wider catchment.

Grey Squirrel *Sciurus carolinensis* is recorded from the woodlands around Stonehaven.

6.2.5 Other environmental constraints

Several listed buildings on Cameron Street in Stonehaven back directly onto the river, these and the Glaslaw Bridge are Grade C(S) listed. Upstream of the A90 Fetteresso Bridge is a Grade B listed structure. Gallows Hill cairn is the only Scheduled Monument within the catchment.

The main town of Stonehaven is a built heritage conservation area.

6.3 Site survey results

6.3.1 Habitats and land-use

The habitat descriptions are divided into four broad types: River, Urban, Suburban and Woodland.

River

The River Carron is generally a medium to fast flowing watercourse over a rocky, pebbled substrate. The river varies in depth considerably, but was on average, at the time of the survey, approximately 0.3 m and averaged between 4 - 5 m in width. The surveyed length was 2.6 km and the lowest 0.7 km is urban in nature.

For most of the length from the A90 to approximately 200 m from the sea, the river has woodland on one or both banks. Through the farmland in the upper reaches this is generally restricted to a narrow fringe and, around Carron Terrace, the banks are planted with ornamental Limes *Tilia x europaea*. There are pockets of scattered scrub, mostly Gorse *Ulex europaeus* near the A90 and Woodcot Brae.

Figure 6-3: Confluence of Burn of Glaslaw and River Carron

Most in-channel vegetation was restricted to algae and mosses attached to the rocks, mosses included *Brachythecium rivulare, Fontinalis antipyreticum, F. squamosa* and *Platyhypnidium riparioides*, with occasional Reed Sweet-grass *Glyceria maxima*, Floating Sweet-grass *Glyceria fluitans* and Creeping Buttercup *Ranunculus repens* along the margins. Much of the banks have been planted, especially through the town, with horticultural plants, but there is also widespread Giant Hogweed and Himalayan Balsam growth throughout the surveyed section.

Small islands in the channel also hold Reed Canary-grass *Phalaris arundinacea*. Below the White Bridge footbridge near St James's church a small island contains a large population of Giant Hogweed and this appears to be the downstream limit of this plant.

The Burn of Glaslaw is a much smaller watercourse, generally about 2 m wide and averaging approximately 0.2 m deep, although this has considerable variation. The total surveyed length was 1.9 km, with the lowest 190 m being urban.

The upper part of the Burn is easily divided into two based on gradient. The first 500 m occupies a narrow gorge and drops in height considerably with several small cascades. The mid-section has a much shallower gradient and meanders across a valley floor. Both upper and lower sections have a stony substrate while the middle has a much greater quantity of silt. The Burn flows through broad-leaved woodland for the majority of its length, becoming open only in the last 50 m. This woodland has many small coarse woody debris dams throughout the lower sections.

The two watercourses join at the artificial island and plunge pool weirs at Green Bridge. These were installed by the council in 2002 to replace a concrete weir to reduce flood risk and to facilitate migratory fish passage. At the upstream end of the survey area a fish pass was installed in the concrete culvert beneath the A90 in 2001, due to flood damage this has been subject to minor alterations on at least two occasions.

Urban

Through both the lower 700 m of the River Carron and 190 m of the Burn of Glaslaw the surrounding habitat is built up and the watercourses are heavily modified. The Burn of Glaslaw flows adjacent to Carron Gardens in a narrow channel with heavily eroded and undercut drystone walls. It then passes through low culverts at Woodview Court and Dunnottar Avenue / Low Wood Road before outfalling into the River Carron.

Figure 6-4: River Carron below Bridgefield

Although the River Carron is never truly remote from built up areas it only takes on an urban environment from the Red Bridge between Carronhall and Low Wood Road. Below this point the river banks tend to be planted and maintained. There is considerable artificial bank material, of varying standards and heights, from this point to the sea.

The site of a bank overtopping onto Carron Terrace during the 2009 flood has been levelled with an earthen bank protected by coir matting. This is upstream of the Green Bridge fish passage weir and appears to have covered the bases of the lime trees. Downstream of the weirs the right bank has residential gardens and publicly accessible green space to the end of Arbuthnott Street. The left bank is a stone retaining wall with Carron Terrace and Cameron Bank roads running along the top.

Between the White Bridge and Beach Bridge the river flows through a constrained channel between houses and commercial property. The left bank is mostly residential with a range of gardens approximately 1 m above the normal water level.

After Salmon Lane the river becomes much deeper as it is retained by the raised pebble beach marking the tide line. This section is defended by large rock armour along both banks and is probably affected by salt water intrusion with very little in-channel vegetation.

Suburban

Between the A90 and Red Bridge the River Carron has a more rural feel with larger areas of woodland, rough open grassland and grazed pasture. There are two areas of rough open land, the smaller of which is on the right bank between the river and Low Wood Road, downstream of Woodcot Brae, and a larger area is on the left bank below the Riverside Drive estate. Both areas of rough grassland have scattered Gorse scrub and occasional trees.

There is a large eroded cliff below the houses at the western end of Riverside Drive which has a large infestation of Giant Hogweed and appears to receive tipped garden waste from the houses above. The right bank here is a large floodplain of poor, improved grassland used primarily for grazing horses.

Beyond the Mill of Forest farm the floodplain is on the left bank and also appears to be used primarily for grazing and is semi-improved grassland. The right bank here is generally a short wooded scarp slope with a narrow fringe of often wet grassland, however the area around the culvert has been subject to periodic disturbance over the last decade due to works on the fish pass. This has resulted in a more open and scrubby river corridor, mostly of Gorse bushes.

Figure 6-5: Upstream of Woodcot Brae

Woodland

The woodland associated with the River Carron can be divided into three types; there are planted ornamental trees in Stonehaven itself, particularly along Carron Terrace, the section between Woodcot Brae and Touck's Burn where the right bank runs alongside the Woods of Dunnottar, a large area of mostly semi-natural broad-leaved woodland with some planted ornamental and forestry trees. The remainder of the river has a narrow fringe of riparian woodland; these are composed of Sycamore *Acer pseudoplatanus*, Ash *Fraxinus excelsior*, Beech *Fagus sylvatica*, Wych Elm *Ulmus glabra* and copses of Alder *Alnus glutinosa*.

The Burn of Glaslaw is completely different in character being almost entirely wooded throughout the survey length. The lower part of the valley is broad and shallow and this area has been extensively planted for forestry, with Sycamore, Ash, Poplar *Populus alba* and a range of coniferous trees including Lodgepole Pine *Pinus contorta*. The middle section of the Burn runs through the estates original plantings and includes large patches of Cherry Laurel *Prunus laurocerasus*, Beech and Horse Chestnut *Aesculus hippocastanum*. Further up the valley in the gorges Wych Elm and Ash begin to dominate in more natural areas.

Figure 6-6: Burn of Glaslaw in the Woods of Dunnottar

6.3.2 Protected species

During the walkover survey only a single Otter spraint was recorded throughout the entire length. This was located on a rock beneath the bridge at Bridgefield in the centre of Stonehaven. Otter is a European Protected Species given legal protection under the Conservation of Habitats and Species Regulations 2010.

Burrows were observed in several areas but these appeared to be in association with droppings of Brown Rat *Rattus norvegicus* and no latrines, feeding remains, footprints or sightings of Water Vole were made.

On the evening of 5th April a bat activity survey took place between Bridgefield and Woodcot Brae. Bats were recorded throughout this length but two distinct areas were recorded with high numbers of foraging bats. The river between Carron Terrace and St. James church had foraging Soprano and Common Pipistrelle's, while the area around the Green Bridge at the end of Carron Terrace had both Pipistrelle species and Daubenton's bat. Occasional bats were heard between and outwith these locations suggesting commuting bats, however none were heard in the town around Bridgefield. No survey was carried out upstream of Woodcot Brae bridge or on the Burn of Glaslaw. All bats are European Protected Species.

Table 6-1: Mammal Records

Common Name	Scientific name	Notes
Otter	*Lutra lutra*	Single spraint at Bridgefield
Daubenton's Bat	*Myotis daubentonii*	Feeding over river at Red Bridge
Common Pipistrelle	*Pipistrellus pipistrellus*	Frequent
Soprano Pipistrelle	*Pipistrellus pygmaeus*	Frequent along river
Brown Rat	*Rattus norvegicus*	Droppings and burrows within town
Grey Squirrel	*Sciurus carolinensis*	Drey near Red Bridge
European Mole	*Talpa europea*	Common in fields

A specific breeding bird survey was not carried out, however at least three pairs of Dippers *Cinclus cinclus* and two pairs of Grey Wagtail's *Motacilla cinerea* were recorded. In one location a Dipper was seen to display outside a row of gabions and the in stream rocks at this site showed evidence of widespread use indicating a potential nest site. Vegetation adjacent to the watercourses were suitable for a range of other breeding birds. Table 6-2 lists the bird species recorded during the walkover survey.

Table 6-2: Bird Records

Common Name	Scientific Name	Notes
Mallard	*Anas platyrhynchos*	Feral flock in Stonehaven
Grey Heron	*Ardea cinerea*	Upper reaches of Carron
Linnet	*Carduelis cabaret*	Occasional
Goldfinch	*Carduelis carduelis*	Common
Greenfinch	*Carduelis chloris*	Frequent
Siskin	*Carduelis spinosa*	Woods of Dunnottar
Treecreeper	*Certhia familiaris*	Woods of Dunnottar
Dipper	*Cinclus cinclus*	Both watercourses
Rook	*Corvus frugilegus*	Common
Blue Tit	*Cyanistes caeruleus*	Common
Robin	*Erithracus rubecula*	Common
Chaffinch	*Fringilla coelebs*	Common
Herring Gull	*Larus argentatus*	Common in wider area
Grey Wagtail	*Motacilla cinerea*	Both watercourses
Great Tit	*Parus major*	Frequent
House Sparrow	*Passer domesticus*	Common
Dunnock	*Prunella modularis*	Frequent
Starling	*Sturnus vulgaris*	Common
Wren	*Troglodytes troglodytes*	Frequent along both watercourses
Blackbird	*Turdus merula*	Common
Song Thrush	*Turdus philomelos*	Occasional

A specific fish survey was not carried out but a few Trout were observed incidentally during the walkover survey.

Figure 6-7: Otter Spraint

6.3.3 Non-native invasive species

Flora

There are considerable infestations of Giant Hogweed through the central part of the River Carron. This is especially prevalent on the eroding cliff and within the grassland upstream of Woodcot Brae. On the cliff Giant Hogweed appears to be the main pioneer plant, growing on small ledges. Further into the town, growths become sporadic but individual plants and small clusters are regularly spaced on both banks. The small island downstream of the White Bridge footbridge appears to be the downstream limit at present. No visible growth was recorded on the Burn of Glaslaw.

Himalayan Balsam is widespread throughout the survey area, however due to the time of year this was apparent only as swathes of seedlings and exact distribution is difficult to judge. The spread of Himalayan Balsam appeared to coincide roughly with that of Giant Hogweed. No Japanese Knotweed *Fallopia japonica* was observed.

The Dunnottar House estate also has several large stands of overgrown Cherry Laurel which in some places envelops both banks of the Burn of Glaslaw. There are many other horticultural shrubs planted alongside the River Carron from Woodcot Brae to the sea, these include Deutzia *Deutzia scabra* and Snowberry *Symphoricarpos alba*.

Fauna

Grey Squirrel were observed, and a drey spotted, on the edge of the Woods of Dunnottar near to the Green Bridge.

6.4 Appraisal

6.4.1 Designated sites

The Loch of Lumgair SSSI is the only statutorily protected nature conservation site within the catchment. The site is located along a tributary of the Burn of Glaslaw 2 km upstream from the survey limit. There will be no significant adverse impacts upon this site, depending upon the final proposed scheme there may be minor beneficial impacts by slowing drainage.

The length of the River Carron designated as SESA is also outside the survey area and is unlikely to be significantly affected by any future flood alleviation proposals.

6.4.2 Protected species

As the River Carron and its tributaries are prized Trout and Salmon nurseries, with additional records of European Eel and Lamprey any works affecting the channel will require careful planning. This must include timing to avoid spawning seasons and periods of migration. Damage to spawning sites must be avoided and ideally, should any channel blockage be necessary, less than half the channel width should be dammed at any one time. Silt management will be an issue to avoid affecting downstream gravel beds.

Despite the scarcity of Otter field signs during this survey, the suitability of the habitat dictates that this species should be given full consideration during the planning stage. As ever, a walkover survey only presents a snapshot of what species are present at that time and as Otters can be extremely mobile, further surveys are recommended prior to any works taking place. Should any Otter places of shelter be discovered, appropriate mitigation will be required. This may include the provision of artificial holts for up to a minimum of six months before works are programmed to start, if it is likely that existing holts will be destroyed. Further Water Vole surveys should also be carried out during any future Otter survey.

Bankside vegetation was often dense and there are many trees providing ideal bird nesting habitat. It is possible that at least one former section of bank protection may now also support breeding Dippers. All vegetation clearance should be carried out outside the bird breeding season (March to September). Any channel works taking place within the bird breeding season should be preceded by a survey of that section of river to ensure there are no active nests.

The bat activity survey only covered a small section of the River Carron, but highlighted some considerable levels of foraging activity associated with the river. It is advised that a fuller bat survey is carried out at the site of any proposed works. This will allow a complete assessment of the likely impacts upon bat populations. Obstructions placed within the river channel and the use of artificial lights at night should be avoided. Many of the riverside trees have the potential to support roosting bats and should not be removed without a prior survey.

6.4.3 Non-native invasive species

The non-native invasive species Giant Hogweed and Himalayan Balsam may be the principle environmental constraints on any proposed flood alleviation scheme for Stonehaven. Both species are included on Schedule 9 of the Wildlife and Countryside Act 1981 (as amended). This makes it a criminal offence to allow, or cause, it to spread. Japanese Knotweed is also included in this schedule, but recent efforts (2006) by SDAA appear to have been successful in eradicating it from the Carron.

Himalayan Balsam is an annual plant, dying back each winter and growing again from seed. The plant disperses its seeds via a process known as explosive dehiscence. As the seed head grows, a fibre on one side remains the same length and the resulting tension is sufficient to propel seeds for several metres when ripe. The seedhead will continue to develop even if the plant is pulled out of the ground once the flowers have been pollinated. The simplest method of control is to handpull Himalayan Balsam plants before they flower and pile them in situ allowing them to compost naturally. Alternatively, herbicide applications are usually efficient but additional licences are required from SEPA to spray near to a watercourse. Working in winter may appear to avoid impacts but soils should not be removed from the site in this period to avoid transporting seeds. If works take place in this period, stringent site hygiene practices must be in place to clean footwear, tools and machinery before leaving site.

Giant Hogweed is another annual plant growing each year from the seedbank. However mechanical or hand control is complicated by the toxic nature of the plants sap, this can cause extensive burns when skin in contact with the sap is exposed to sunlight. Appropriate protective clothing must be worn when carrying out this activity. Cutting of the stems must extend into the rootstock to be effective. Cut stems must again be left on site to compost. Herbicide applications are also effective against Giant Hogweed and require a licence from SEPA. Contaminated soils must not be removed from the site and good site hygiene practices should be implemented to prevent inadvertent spread via boot and tyre treads, tools and plant.

Any material containing the seeds or any viable vegetative material is considered to be hazardous waste and must be treated appropriately. It can only be transported by a registered hazardous waste carrier and only deposited in a hazardous waste tip. This can have considerable cost implications. Herbicide applications must take place over a period of years to determine that the seed bank is exhausted and establishing a dense vegetation cover on the site also helps restrict future regrowth.

Figure 6-8: Giant Hogweed (centre)

Although Grey Squirrel is also on Schedule 9, its presence is unlikely to have any significant impact on any future proposals.

6.4.4 Other environmental constraints

None of the features of cultural heritage interest or archaeology are likely to be affected by any flood alleviation scheme proposals. The C(S) buildings will be afforded additional protection and the grade C(S) bridge and scheduled ancient monument are considerably higher than the watercourses.

7 Flood Protection Options

7.1 Introduction

Flood risk management options were considered at two levels:

- Generic Options
- Specific Options

7.2 Generic options

The generic options considered at the strategic level were:

Table 7-1: Generic options

Approach	Option	General description
Improve maintenance	Channel maintenance	This includes vegetation clearance, bank maintenance and grass cutting. This keeps the channel and banks in good condition but is unlikely to significantly reduce flood risk.
Increasing the channel capacity	Bridge raising	Raising the deck of structures crossing the river can help alleviate restrictions to flow and to lower water levels.
	Channel modification	Altering the channel geometry such as creating two-stage channels and removing in-stream deposits can increase channel conveyance.
	Direct defences	Raising existing walls and embankments or constructing new ones will increase the capacity of the channel and raise the water level threshold at which out of bank flow occurs.
Resilience	Flood wardens	The Council are currently developing a scheme of flood wardens to assist in distributing warnings and assistance during a flood event.
	Flood warning	This entails the forecasting of flood events based on real-time and forecasted rainfall and river gaugings. SEPA are currently developing flood warning for the Carron at Stonehaven.
	Household protection	This includes flood guards, airbrick covers and other temporary defences for individual properties. The Council currently have a scheme to provide household protection at low prices to at-risk residents in Stonehaven.
	Temporary defences	Temporary defences can be put in place following a flood warning to provide an increase in channel capacity during a flood event.
Alter flow routes	Flood relief channel	Diversion of flood flows via an alternative route to the sea can take the pressure off an under-capacity channel during the peak of a flood.
Storage and attenuation	Upstream storage	Storage capacity can be provided in the upper catchment as either on-line (where the river channel passes through the storage area) or off-line (where the channel bypasses the storage area, but flow is diverted into it at high flows). This approach can be used to temporarily store water during a flood peak and thus attenuate flows in the river downstream, reducing the likelihood of flooding.
Natural flood management	Wider catchment management	This approach includes measures such as tree planting in the upper catchment to help reduce runoff rates and hence attenuate flood peaks. There is relatively little empirical data to quantify the impacts and as such it is unlikely to form a stand-alone solution.

The generic options are broad strategic solutions, which can be narrowed down to specific options. These identified specific options for Stonehaven were assessed using:

- Hydraulic modelling to determine their feasibility in terms of flood mitigation and impact elsewhere in the catchment;
- Benefit-cost analysis will also be used to evaluate the economic feasibility of each option;
- Environmental appraisal to assess their environmental impact; and
- Assessment of structural feasibility.

7.3 Specific options appraisal

From these options (identified in Table 7-1), a number of approaches have been developed towards flood alleviation. These fall into 4 main categories:

- Channel modification;
- Direct defences and bridge raising;
- Upstream storage; and
- Resilience.

Channel modification is not a stand-alone option for flood alleviation as it is unlikely to make a significant enough difference to flood levels. It has been assessed for its potential impact as a 'quick fix' to provide betterment but not as a full option.

The following measures have been tested:

- Option 1: Continuation of maintenance and repairs;
- Option 2: Construction of direct defences as a stand-alone solution;
- Option 3: Construction of direct defences combined with modifications to the channel and bridges;
    - raising of Green Bridge and removal of remains of weir at Green Bridge;
    - raising of Green Bridge and White Bridge and removal of remains of weir at Green Bridge;
    - raising of Green Bridge and lowering the river bed at the Green Bridge weir in conjunction with removing the remains of weir at Green Bridge;
- Option 4: Provision of upstream storage;
- Option 5: Construction of direct defences combined with upstream storage; and
- Option 6: Resilience approach.

Options 1-6 will be assessed for feasibility in this study. They represent a 'do something' approach, to be compared to the baseline 'do minimum' approach which comprises ongoing channel maintenance by the Council to maintain the watercourses in their present condition, but no specific flood alleviation works being undertaken.

Appendix H details the impact of additional scenarios which were suggested for testing by the Council and residents of Stonehaven but do not form part of the proposed Flood Alleviation Scheme options.

7.4 Design objectives

The following design objectives have been identified:

- To provide a long term flood alleviation scheme in Stonehaven to reduce the likelihood and impact of fluvial flooding from the River Carron;
- To enhance or maintain the existing environment; and
- To avoid adverse environmental or geomorphological impacts.

7.5 Standard of protection

Scottish Government guidance relating to Flood Protection Schemes[34] recommends that they should be designed to withstand a minimum of the 1% AP (100 year) flood. However, the design event for planning purposes in Scotland is the 0.5% AP (200 year) flood. A consideration of climate change is also appropriate.

In this study a range of return periods have been used to assess flood risk, from the 50% AP (2 year) to the 0.1% AP (1000 year) event. A target standard of protection for the flood alleviation measures of the 0.5% AP (200 year) event has been used.

7.6 Freeboard

There is not a Scottish national standard for the stipulation of freeboard for proposed flood defences. The Environment Agency published a guidance document to help determine freeboard. It suggests that values of 300 mm and 600 mm for walls and embankments respectively are typical and have been used in this study.

These values can be varied based on specific circumstances and engineering judgement. There may be room for modification of these levels at the detailed design stage.

It is not recommended that freeboard be used to protect against flood flows above the design standard. Therefore, whilst the additional flood defence height could protect against a greater standard, the freeboard is provided to take into account uncertainties and should not be used to rely on protection for above design events.

7.7 Inspection and Maintenance Requirements

Inspection and maintenance of new works should be incorporated into Aberdeenshire Council's maintenance regime.

For embankment works, if included in the scheme, it is anticipated that inspection and annual maintenance in the form of grass cutting and vermin control will be required 2-3 times a year. Grass cutting should be undertaken using strimmers and timed to minimise environmental impacts (i.e. after ground nesting) and ideally cuttings should be removed. Annual inspection should evaluate if the embankment has changed from its as-built condition. Detailed checks on the embankments to ensure they are fit for purpose will be required every 15 years. These should include checks made for subsidence, slope stability and holes. If necessary, survey should be undertaken to assess how levels differ from the as-built condition.

Temporary barriers/flood gates if included in the final scheme should be checked annually and inspected by those who will actually close them during a flood. Works to walls will be required, including the replacement of some sealants, around once every 4 years.

Defence assets should be inspected after any significant flood event on the Carron.

An operation and maintenance plan will be drafted during detailed design.

In due course, these works will be incorporated into local flood management plans and also flood maintenance schedules.

[34] Scottish Executive (2005) Flood Prevention Schemes: Guidance for Local Authorities.

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8 Feasibility and Impact: Permanent direct defences, bridge raising and removal of weir (Options 2 and 3)

8.1 Introduction

Direct defences are a highly effective and visible way of mitigating flood risk and protecting properties. They increase the channel capacity by accommodating flood water up to a higher level and thus reducing the risk of the river banks being overtopped. They can be designed to provide the required standard of protection, incorporating a freeboard allowance.

However, direct defences can be detrimental to the amenity value of the river if they prevent public access and obstruct views of the river. This is a potential risk in Stonehaven and it is therefore appropriate to consider them alongside measures to reduce peak water levels in the channel and hence the height of defences required.

These measures include removal of the remains of the weir immediately downstream of the Green Bridge which was shown above to offer a small reduction in water levels in this key location. Bridge raising was also considered since bridges across the Carron have a significant effect in causing a flow restriction leading to 'backing up' of water upstream, raising water levels. The following bridges cross the Carron in Stonehaven:

Table 8-1: Bridge raising options in Stonehaven

Bridge name	Bridge type	Comment
Walker's Bridge	Road bridge	Causes significant backing up of water. Complex to raise as is a substantial road bridge. No low-lying properties directly upstream - no significant benefit from raising. May be currently helping to retain water upstream.
Red Bridge	Footbridge	Causes limited backing up of water. Feasible to be raised. No low-lying properties directly upstream - no significant benefit from raising although would reduce risk of blockage which may exacerbate out of bank flooding.
Green Bridge	Footbridge	Causes significant backing up of water. Feasible to be raised. In key risk area and raising would offer significant benefit.
White Bridge	Footbridge	Causes limited backing up of water. Feasible to be raised. In key risk area and raising may offer some benefit.
Bridgefield Bridge	Road bridge	Causes limited backing up of water. Complex to raise as is a substantial road bridge.
Beach Bridge	Footbridge	Causes limited backing up of water. Feasible to be raised. No significant benefit from raising.

Therefore it is deemed that the bridges where raising is a feasible option and which offer the most potential benefit are the Green Bridge and White Bridge.

8.2 Approaches to be assessed

Four variations of 'direct defence' options are considered here. These are:

1. Direct defences as a stand-alone solution;
2. Direct defences coupled with raising of the Green Bridge and removal of the remains of the weir immediately downstream of the Green Bridge;
3. Direct defences coupled with raising of both the Green Bridge and the White Bridge and removal of the remains of the weir immediately downstream of the Green Bridge.
4. Direct defences coupled with raising of Green Bridge and lowering the river bed at the Green Bridge weir (by lowering the sewer) in conjunction with removing the remains of weir at Green Bridge.

8.3 Option 2: Direct defences as a stand-alone solution

8.3.1 Description of option

For direct defences to form a stand-alone solution they would be required along a considerable length of the River Carron through the town. This would require the construction of flood walls or similar on both sides along the majority of the channel between Bridgefield Road Bridge and the Red Bridge.

The height of these defences is likely to be considerable given the high water levels relative to bank levels experienced in some locations on the Carron during flood events. This has implications for both structural feasibility and the amenity value of the river.

8.3.2 Feasibility

The introduction of direct defences was tested in the model for its impact on water levels and flows. Retaining water in the channel rather than allowing it to flow out of bank results in a substantial increase in the peak water levels experienced. There is also an increase in peak flow in the channel.

The conjecture that direct defences would need to be very high was verified using the model to test the height of defences which would be required to protect against the 0.5% AP (200 year) event, taking into account a standard freeboard allowance of 300 mm for walls. Estimated height requirements at key locations are as follows:

- Wall of height 2.58 m above level of Carron Terrace on left bank in proximity of garages upstream of Green Bridge.
- Wall of height 2.82m above level of Low Wood Road on right bank immediately upstream of Green Bridge.

These walls are of substantial height and would therefore significantly impact on cost and on the amenity value of the River Carron in Stonehaven. This approach of direct defences as a stand-alone solution is therefore not considered to be a sustainable option.

The results suggest that the channel at the Green Bridge and weir remain a key restriction on flow capacity which causes out of bank flooding upstream of the Green Bridge. Therefore to provide a more feasible solution, direct defences were considered in tandem with further works at this point, as outlined below.

8.3.3 Summary of feasibility and impacts

This option has been shown to be undesirable from an amenity point of view once the structural requirements are taken into account and therefore will be discarded at this stage.

8.4 Option 3a: Direct defences, raising of Green Bridge and removal of remains of weir at Green Bridge

8.4.1 Description of option

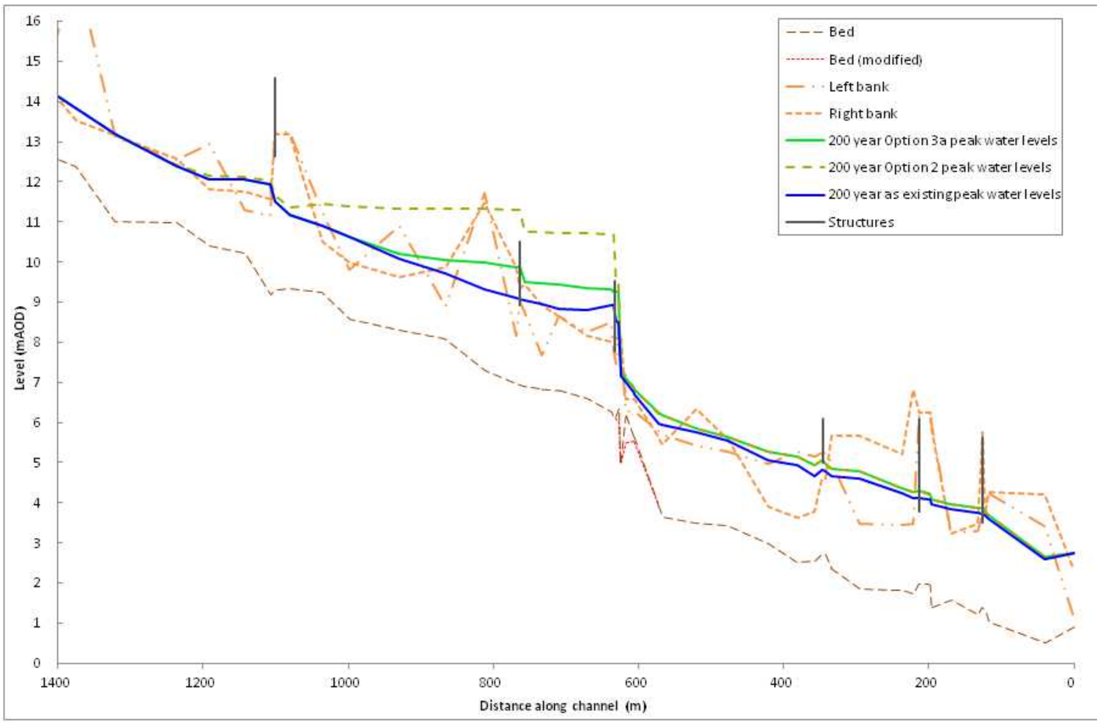
As the Green Bridge and weir have been identified as causing backing up of water levels during a flood event, an approach of channel improvement in this location was considered in tandem with direct defences. The improvement works proposed are raising of the Green Bridge to prevent it causing an obstruction to flow under flood conditions, and the removal of the remaining step in the channel at the location of the log weir described in Appendix H Section H.1.3. This leads to a reduction in peak water levels upstream of the Green Bridge and thus in the heights of direct defences required.

The effect of raising the Green Bridge and modifying the bed levels at the weir and downstream was tested in the model. The level of defences required throughout the reach to prevent out of bank flooding was then assessed.

8.4.2 Model findings and hydraulic feasibility

Figure 8-1 below shows the impact of Option 2 and Option 3a on the peak water levels during the 0.5% AP (200 year) event.

Figure 8-1: 200 year existing and Options 2 and 3a scenario peak water levels



The model results suggest that raising the Green Bridge and removing the remains of the weir offer a significant reduction in the peak water levels and hence the height of direct defences required. Therefore it is deemed a feasible option for reducing flood risk from this point of view.

8.4.3 Structural feasibility: flood defences

The locations and sections of the proposed flood defences are shown on Figure 10 in the Figures section at the back of the report. To implement this option the following approximate heights of defences are required:

Table 8-2: Height of flood defences

Location	Left bank defence height	Right bank defence height
Bridgefield to White Bridge	1.4 - 2.0 m	Not known as height of backfill behind existing stone wall not surveyed. Likely to be similar to left bank.
White Bridge to Green Bridge	0.0 - 0.9 m	0.0 - 0.8 m
Green Bridge to Red Bridge	0.0 - 2.5 m (above road level)	0.0 - 1.6 m

The built up nature of the river corridor means there is generally not enough room to construct flood embankments, therefore flood walls are the preferred solution. The superficial geology would tend to suggest mixed soils, including sands and gravels (see Appendix C, Section C.4.2), so a cut off below the wall is likely to be required to prevent seepage through the soil. Sheet piles may be combined with reinforced concrete walls clad in masonry as required. Installation of the sheet piles may be noisy and it is suggested that vibratory or press methods are used to limit sound levels. To prevent water from surface water flooding building up behind the defences strategically placed flap valves or similar may be incorporated into the walls to convey the water to the river channel when river levels are low.

Elsewhere where low level defences are required a concrete retaining wall with a cut off would be adequate.

Cameron Street Gardens (Bridgefield to White Bridge)

The height of the defences behind Cameron Street is likely to be up to 2.0 m, this could be oppressive to the property owners on the bottom floor as the rear walls are in some instances very close to the proposed defences. It is suggested that the surface treatment of the wall needs to be carefully considered in consultation with the residents and property owners.

To allow additional light through the barriers consideration may be given to providing areas of glazing. To provide a feeling of safety it is suggested that a 1 m high strip of glazing is installed on top of a 1 m high wall. Maintenance will be required to ensure seals etc. remain watertight. The use of self-cleaning glass should minimise costs associated with cleaning. The glass would need to be toughened laminated glass, to provide the required strength. The cost of providing a glazed strip along this stretch will increase project costs by about 10%. Whilst individual householders may benefit, it may be argued that this is a poor use of public funds as it would provide little additional benefit for the public good.

Figure 8-2: Example of glass flood barrier

For works carried out immediately adjacent to the river, work will be required from the river side, in which case a temporary working platform would need to be created on the river bed which could block at least half the river channel. To prevent wash off from any works in close proximity to the river an impermeable bund could be created alongside the platform. The runoff may be collected and treated, before being treated and disposed of in a safe manner.

Accessing the works will be difficult as the bridges are of restrictive height preventing access by vehicles. However an access point may be created with a ramp and temporary crossing point at the end of Arbuthnott Street.

Carron Terrace (White Bridge to Green Bridge)

Along Carron Terrace there is a line of mature trees at the top of the river embankment, behind which is a public road. A 600 mm diameter concrete sewer at shallow depth (Invert level 0.8 - 1.8 m below surface), is located in the road immediately behind the line of trees. Therefore the only place that the wall may be built without hitting services is along the existing fence line, which will mean the removal of the trees. To avoid diverting the sewer it is likely that some form of embedded cantilever retaining wall will be required. This could consist of sheet piling clad in masonry.

Given that the trees have a great amenity value, and are potential roosting sites for bats and other animals, their removal is likely to raise objections from the local community. As such the materials used to create the walls need to be sympathetic to the local surroundings. Additional planting and habitat creation measures will need to be thought about carefully, and presented appropriately.

Constructing a retaining wall on sheathed piles to avoid severing tree roots would be difficult for a number of reasons: a cut off would be required to prevent seepage, foundations would need to be hand-dug, the piles individually placed to avoid roots, and the combined sewer diverted. It is likely that this option would prove prohibitively expensive and has extra technical and constructional risk associated with adopting 'unproved' techniques.

From the junction of Carron Terrace and Cameron Street a wall extends along the left bank towards the White Bridge. This is not a flood defence wall and work would be required if it is to become a defence to ensure it is strong enough to withstand water pressure and is watertight.

Arbuthnott Street Gardens (Bridgefield to White Bridge)

In the 2009 flood it would appear that the existing masonry walls withstood about 1 m of water pressure, without adverse consequences. However the effect of building direct defences together with a 0.5% AP (200 year) event, could double the water pressure to a height of 2 m. The additional water pressure would increase bending stresses in the wall by a factor of 4. It is therefore likely that either these walls will need to be replaced or strengthened. Strengthening could be carried out from behind the wall in a number of ways, including:

- Adding masonry buttresses combined with a sheet pile cut-off, if necessary;
- Adding a reinforced concrete wall clad in masonry to match existing;
- Adding steel 'king posts' combined with a sheet pile cut-off, if necessary.

The last option is likely to be the most cost effective, whilst it may look visually unattractive from the garden side, their location at the end of the garden may mean that the residents do not object if it protects them from flooding.

Access to carry out the works will need to be gained through people's gardens, although certain items could be lifted over the wall from the temporary platform required for the works to Cameron Street gardens.

Public Space (White Bridge to Green Bridge)

It is suggested that a bund be created that goes from the end of the White Bridge to the existing boundary wall surrounding Abbeyfield House. This 'bund' may be extended to create Disability Discrimination Act (DDA) compliant ramps on both sides, as shown on Figure 10.

Alternatively a low height wall may be created together with an automated flood gate to allow access to the public space. However this is a less robust solution as the gate would need to be maintained, to ensure it was kept operational.

The existing boundary wall is unlikely to have a 'cut off' to prevent seepage. Therefore the wall will need to be rebuilt with a reinforced concrete base and cut off, re-using the stone to match the original wall. It is suggested that the stonework is reconstructed using traditional materials and techniques.

Carron Terrace (Green Bridge to Red Bridge)

The defences will be at their highest along this section. At 2.54 m the wall could seem oppressive if it starts from road level. It is therefore suggested that the existing embankment is extended, and a new reinforced concrete wall supported on sheet piles is constructed. In this case the height of the wall would appear much less at about 1.25 m.

A set-back wall could be considered but this may restrict access to the properties.

Low Wood Road (Green Bridge to Red Bridge)

The height of the defences on this side will be lower at about 1.63 m. The existing concrete wall may be extended, although at a height of 1.63 m this will represent a loss of amenity. Other options such as setting the wall back to maintain a footway along the river, are not practical due to site constraints such as services and the need to keep the water within the main channel.

8.4.4 Structural feasibility: bridge works

Green Bridge works

The Green Bridge provides access to the town centre from Carron Gardens. It has high amenity value providing recreation opportunities for local residents and tourists.

The bridge is currently not Disability Discrimination Act (DDA) compliant. If altered by the proposed scheme, it would be sensible to take the opportunity to improve access for all potential path users, including cyclists and disabled users, by making 'reasonable adjustments'. It is suggested that all proposals should be subject to a formal DDA assessment and be reviewed by the 'Local Access Panel' to incorporate any comments they may have. It may be argued that work to the existing structure to make it DDA compliant should be funded by a different mechanism to the flood defence works, since the flood protection scheme will not necessarily make the situation any worse. Other funders such as 'Sustrans' may be interested in contributing to an enhanced scheme, which could help stimulate recreation and tourism, and have health and social benefits.

The bridge will need to be raised by approximately 1.81 m. This is a substantial amount. To construct DDA compliant ramps would require them to be a minimum of 27 m long, both sides. In addition services are present in the area. Two 11kV cables are hung below the existing bridge, which would need to be rerouted. A sewer crosses below river bed level, and a medium pressure gas main is located on the south side of the bridge.

The amount of raising required as stated above takes into account the present trellis work below the bridge deck as this would need to be raised above the flood level to reduce risk of blockage. To reduce the amount that the bridge deck needs to be raised, and hence ramp lengths, it would be possible to construct a new bridge in the same position without the trellis and current deck support but with the deck suspended from ‘upstand’ girders on both sides. This would mean the bridge deck would be raised by about 1.3 m, which would cause less visual intrusion, and make the bridge more accessible.

Given the site constraints at this location it may be better to build a new footbridge further downstream below the weir. Two areas have been identified one about 30 m downstream, spanning onto the island and one about 65 m further downstream (see Figure 10 at the back of this report). The precise crossing point would need to be determined based on more detailed surveys and discussions. This would avoid the need for long ramps, and would cause less visual intrusion. It would also avoid the need to move or protect services in the road. Work to create the abutments could be carried out away from the river channel, and a new structure could be lifted into position. An opportunity to commission a unique and distinctive structure that would add to the local community would be created.

Figure 8-3: Example of a type of footbridge that may add interest to the area

White Bridge works

Although this option does not include raising of the White Bridge, minor works will be required to provide enough of a freeboard to stop water overflowing the deck, and escaping out the sides.

The White Bridge connects Arbuthnott Street with Cameron Street, and provides access to the town centre and associated public services for the residents in Dunnottar Avenue and surrounding areas. It has high amenity value providing recreation opportunities for local residents and tourists.

At its current level, during a flood event water will be flowing above soffit level which could impose substantial lateral loads on the bridge. The bridge consists of two steel girders between which have been infilled with concrete, and the ends are built into masonry walls. Therefore it is unlikely to move when subject to flooding.

The flood level with freeboard is marginally above deck levels at both ends. However this may be remedied by adding concrete up-stands to the deck edges to prevent water escaping down the sides of the bridge.

8.4.5 Environmental feasibility

Raising the Green Bridge

Raising the level of Green Bridge has very limited environmental impacts. To allow access on the left bank it may be necessary to undertake some small-scale pruning of the tree nearest the bridge. On the right bank the installation of a larger access ramp or steps will increase the footprint of the bridge. However, Low Wood Road is sufficiently wide to allow for this. Bats forage over the channel at this point and night-time working or obstructing flightlines should be avoided during construction in order to prevent disturbance.

Removing the Green Bridge

There has been a bridge on the site of the Green Bridge since the late 19th Century and the removal of a bridge from this location will have some cultural heritage impacts. Two options have been presented for the site of the replacement of Green Bridge: the first of these is approximately 30 m downstream and crosses via the island created as part of the cascades construction; the second is approximately 65 m downstream.

The ‘island’ crossing will form a continuous route between Arduthie Street and Carron Gardens and should have less impact as this area was disturbed during construction of the cascades. An additional benefit may be that this bridge could utilise the island and therefore may not require a long single span which would reduce the size of the footprint at the north end of the structure on Carron Terrace. Although this will disturb the habitat on the island, this is currently already easily accessible across the drier section of channel.

The downstream option would create a new 'off-line' crossing route and would require connecting paths to be constructed on the right bank. This would cross an area not currently well-frequented by members of the public. In order to avoid significant impacts a single span would be preferred but this would require larger abutments at either end. In particular the north side is directly onto the road and would require considerable impact upon the highway to allow access.

Both locations will create an additional obstruction to foraging bats, but the downstream location is much closer to the main foraging site. Additionally for both sites Giant Hogweed is common and careful mitigation will be required.

Direct defences at identified locations on River Carron

Direct defences are proposed for the river through Stonehaven and these are dealt with geographically between bridges upstream to downstream.

Between Red and Green bridges there is an existing small embankment on the left bank and it is proposed to formalise this defence by raising and extending this bank and constructing a flood wall to a height of approximately 1.53 m. This will entail the removal of some mature trees, chiefly Beech and Lime and re-planting with the same species will be a requirement. The existing embankment was created by piling material around the bases of these trees and it is likely that this will already be causing damage to these trees. Without removal it is not likely to be possible to raise the defences at this location. The loss of the trees will remove bird nesting sites and possible bat roosting sites. There is considerable bat activity in this area and further survey will be required to determine the roost locations. Even if the bats may be roosting within the nearby buildings, the removal of the trees will disturb the foraging behaviour of this population, although this is a small area and further suitable habitat can be found adjacent to the site. If the roosts are in the trees themselves there will be serious adverse impacts which will require in-depth mitigation.

On the right bank between Red and Green Bridges, the proposal is to replace the existing roadside fence with a new flood wall to a height of 1.63 m. The only likely adverse impact here will be visual in nature through the change of appearance.

Between the Green and White bridges it is proposed to increase the height of, and formalise, the walls on the left bank to approximately 0.95 m. This will begin approximately 60 m below Green Bridge and 35 m below the bottom cascade and extend to White Bridge. The construction of a flood wall will have limited environmental impacts with visual issues being the major long-term effect together with some construction phase constraints. The right bank includes construction of a flood wall which will enclose the pedestrian access from Dunnottar Avenue to the White Bridge. This will be at a height of 0.75 m. The wall will tie into a ramp to be constructed at the south end of the White Bridge. This ramp will ensure access can be maintained to Abbeyfields Care Home. This area has a high level of bat use and care will be needed during construction to avoid disturbing foraging bats. Again there are considerable amounts of Giant Hogweed within this section.

Between the White Bridge and the Bridgefield Bridge (A957) road crossing it is proposed to construct a flood wall along the rear of the properties on Cameron Street. This will provide a standardised defence to a height between 1.4 - 2.0 m. On the right bank the existing walls will be reinforced. The principle environmental issue here will be the need to carry out works from within the watercourse. This will result in risks of silt mobilisation and other potential pollution sources (plant etc). This may impact upon fish populations and works are likely to require specific timing. There may also be impacts upon the local residents amenity and the visual change will be taken into consideration.

8.4.6 Summary of feasibility and impacts

This is a feasible option to be taken forward for benefit-cost analysis.

8.5 Option 3b: Direct defences, raising of Green Bridge and White Bridge and removal of remains of weir at Green Bridge

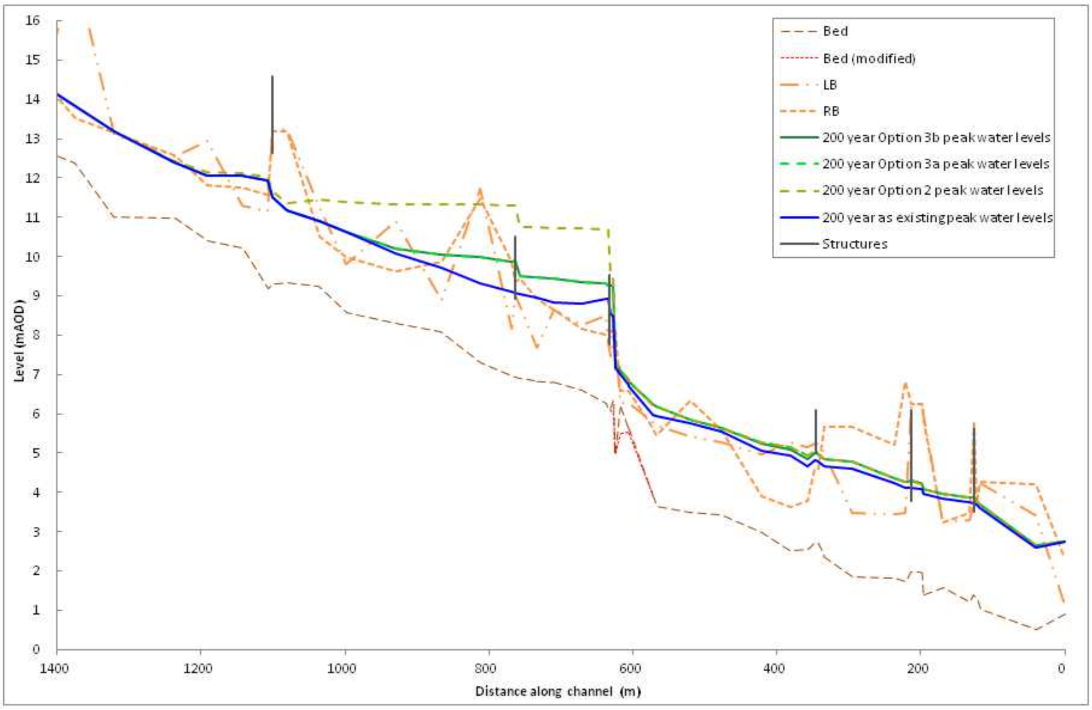
8.5.1 Description of option

As bridge raising has been identified as a possible means to reduce flood levels and thus the height of direct defences, the model was used to test whether raising of the White Bridge as well as the Green Bridge would provide significant additional benefit.

8.5.2 Feasibility

Figure 8-4 below shows the impact of Option 3b on the peak water levels during the 0.5% AP (200 year) event.

Figure 8-4: 200 year existing and Options 2, 3a and 3b scenario peak water levels



The model suggests that compared to Option 3a, the reduction in water levels achieved by raising the White Bridge is minimal. Water levels are reduced by a maximum of 100 mm. Therefore the cost of raising this bridge would increase costs out of all proportion to the anticipated benefit.

The implications of constructing direct defences and raising the Green Bridge will be similar to Option 3a. The effect of raising the White Bridge is very slight with respect to flooding, but the cost of pursuing this option is likely to be considerable.

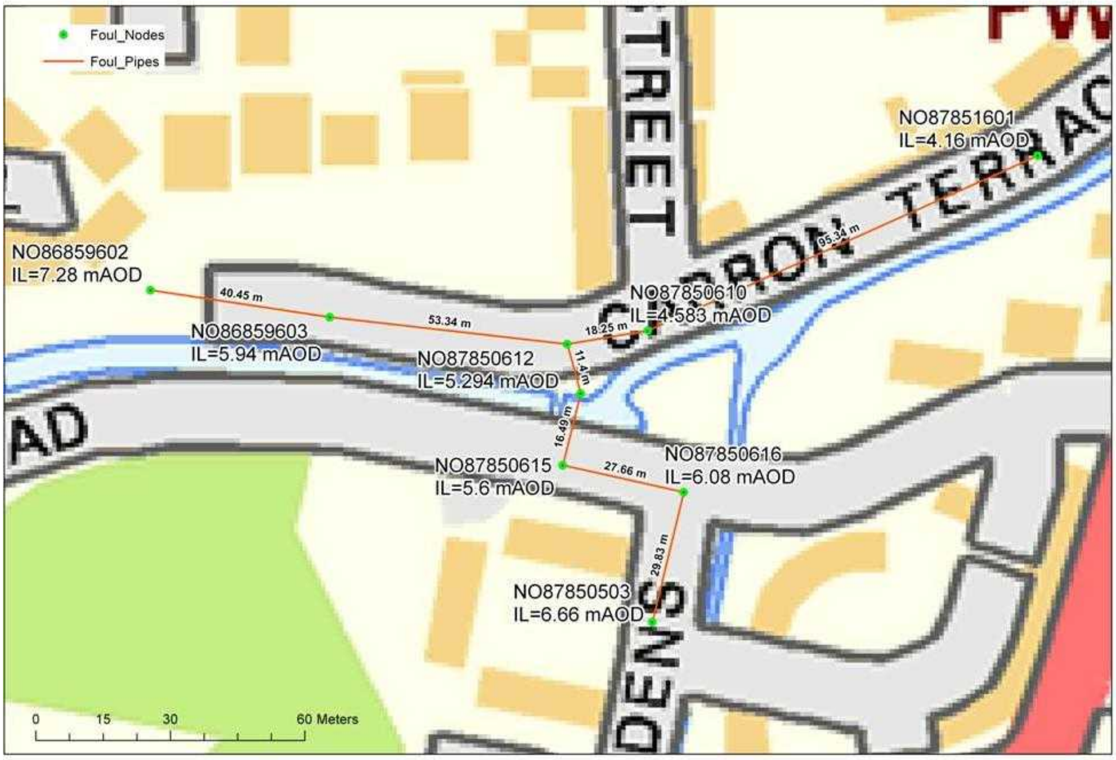
8.5.3 Summary of feasibility and impacts

This option has been shown to provide very little benefit in terms of flood mitigation over Option 3a and will therefore be discarded at this stage.

8.6 Further consideration to lowering the weir at the Green Bridge through modifying the Scottish Water sewer (Option 3c & 3d)

Consideration of the Scottish Water InfoWorks CS model (provided by Scottish Water) shows that the Scottish Water sewer has an invert ranging from 5.6mAOD on Low Wood Road to 5.391 mAOD on the left bank of the Carron immediately downstream of the Green Bridge and then on to 5.294 mAOD on Carron Terrace (see Figure 8-5). The sewer is 300mm in diameter and connects with a 600mm diameter sewer on Carron Terrace. This sewer system is a gravity system.

Figure 8-5: Extract from Scottish Water Model



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An initial analysis of the local sewers including:-

- Diverting the sewer from the manhole on the left bank invert 5.391mAOD directly to manhole NO87850610 (IL 4.583 mAOD)
- Reducing the slope to minimal acceptable levels
- Relaying the sewer to NO87850616.

This would suggest that a new weir/bed level invert of 5.25-5.35m could be achieved. Lower levels could be achieved by re-routing the sewer or pumping the sewage from the south side of the river.

Table 8-3 below shows the reduction in maximum defence height required between the Red Bridge and the Green Bridge weir comparing direct defences alone (Option 2) with direct defence combined with the removal of the Green Bridge and the lowering of the weir to 6.00, 5.35 and 5.00 mAOD respectively. It can be seen that the ability to lower the weir assists in reducing the required direct defences and bringing these down to a more achievable height.

Table 8-3: Consideration of further weir lower

Option	Max Defence Height between Red Bridge and the Green Bridge weir (Left Bank)	Max Defence Height between Red Bridge and the Green Bridge weir (Right Bank)	Difference from Option 2
Option 2 - Direct Defences as stand alone	3.9	3.0	
Option 3a - Direct Defences, Removing Green Bridge and lowering weir to 6.00mAOD	1.7	0.8	-2.2
Option 3c - Direct Defences, Removing Green Bridge and lowering weir to 5.35mAOD	1.3	0.4	-2.6
Option 3d - Direct Defences, Removing Green Bridge and lowering weir to 5.00mAOD	1.0	0.1	-2.9

8.7 Direct Defence on the Glaslaw Burn

The Glaslaw Burn immediately upstream of its confluence with the Carron is confined between the Carron Gardens on the left bank and gardens of Woodview Court on the right bank. The burn also passes beneath a low access road culvert (access from Carron Gardens to Woodview Court) and the Low Wood Road culvert.

Blockage risk of these structures is potentially high given the wooded nature of the catchment and banks.

While the complete feasibility of these defences has not been included at this stage, this would need to be included at detailed design. This should include the consideration of raising the access roads and hence increasing culvert capacities. Defences within this area would also be likely to include a wall along the left bank of the watercourse from Low Wood Road upstream past the commencement of Carron Gardens. A wall or embankment would also be required along the right bank, thus preventing potential overland flow from the Glaslaw Burn out across Woodview Court and down into the main town. The ground around the Woodview Court is notably lower than the Glaslaw Burn however the flatted properties would appear to have floor levels which are raised up significantly above the existing ground level.

The Glaslaw Burn is likely to have been historically straightened in this area and it is also noted that the Glaslaw Burn along this reach is starting to erode the right bank alongside the Woodview Court as the watercourse, as the watercourse is trying to follow a more sinuous route. In the long term this erosion will also reduce the standard of protection currently afforded to the area and hence increase flood risk.

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9 Feasibility and Impact: Upstream storage (Options 4 and 5)

9.1 Introduction

The creation of flood storage areas can help to mitigate flooding by storing water during the peak of a flood event and releasing it at an attenuated rate as water levels start to recede. In Stonehaven, storage areas could be created in the Carron valley upstream of the Walker Bridge where there are suitable areas of low-lying land.

There are two types of storage areas:

1. 'On-line': the river channel passes through the storage area. Water is retained in the storage area for example by the construction of an embankment at the downstream end and the outflow is controlled by a structure such as an orifice, hydrobrake, gate or similar to allow water to be discharged at the required time / rate.
2. 'Off-line': the river channel bypasses the storage area but a connection between the two exists. The storage area is formed for example by excavating or embanking an area, and flow into the pond is facilitated by the introduction of a side weir or spill, gate or similar. Outflow from the storage area may take the form of a pipe or orifice, gate etc which controls the outflow rate.

9.2 Approaches to be assessed

Upstream storage will be assessed in outline terms as appropriate to this study by looking at the indicative volume of water required to be stored, and the volumes available in each of several identified possible storage areas.

Four areas were identified using LIDAR data as possible sites for upstream storage; these are likely to form in-line storage areas given the narrow geometry of the valley. Constraints to the level of water which could be stored in each of the areas were also identified, such as nearby properties, road and structure levels.

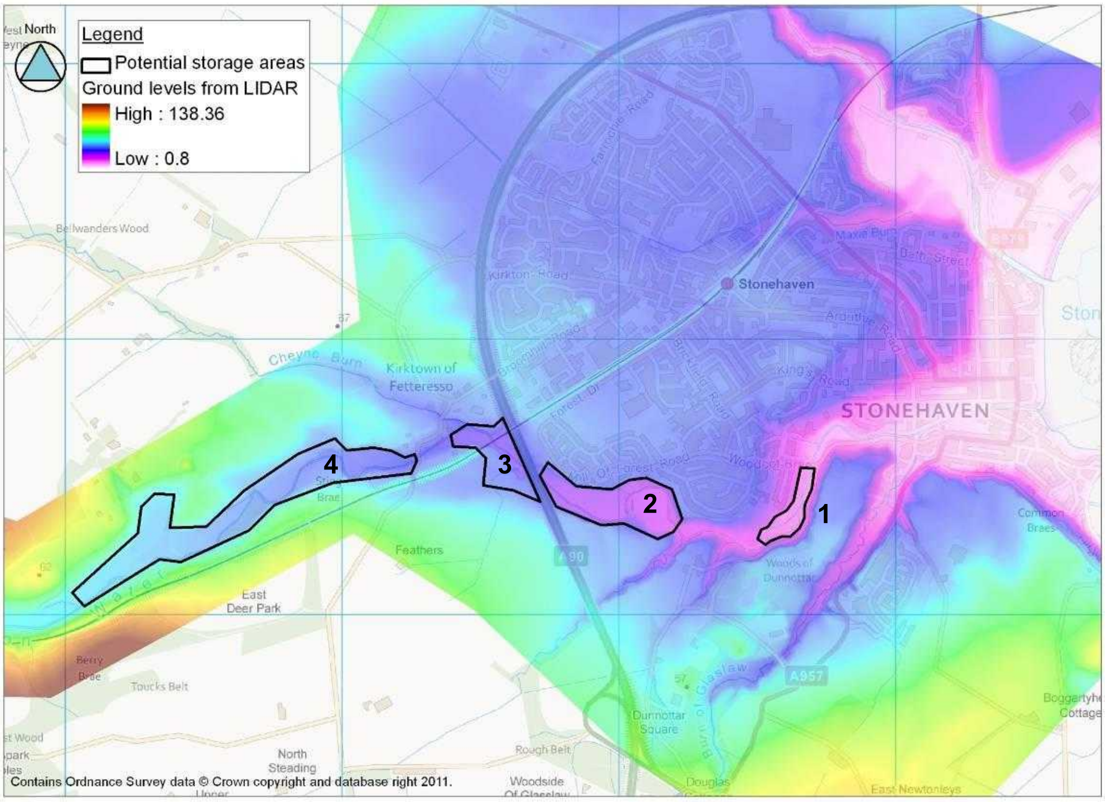
9.3 Option 4: Upstream storage

9.3.1 Description of option

In order to alleviate flood risk in Stonehaven as a stand-alone solution, upstream storage would need to be sufficient to reduce the design event (e.g. 0.5% AP (200 year)) flow down to a flow which does not result in out of bank flooding. It has been identified that in Stonehaven out-of-bank flooding first occurs at the 10% AP (10 year) event. Therefore the design event peak flow would need to be reduced to that of the 20% AP (5 year) peak of approximately 18 m^3/s.

The identified possible storage areas are shown on Figure 9-1 below.

Figure 9-1: Identified possible areas for upstream storage



During the November 2009 event there was potential c. 49, 000 m^3 of water within these four floodplain areas, estimated as:

Table 9-1: Estimated Floodplain Volumes November 2009

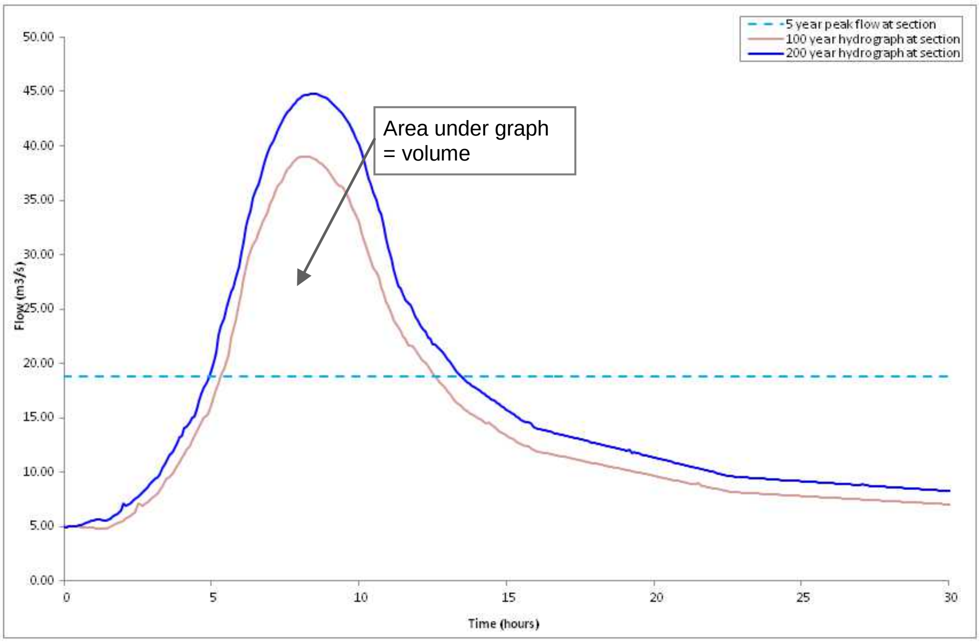
Location	Estimated Volume (m3)
1 - Walker Bridge	3,000
2- Mill Of Forest	14,000
3 -A90 Upstream	11,000
4- Sting Brae - total	21,000

9.3.2 Hydraulic feasibility

Volume of storage required

To estimate the amount of storage which would be required to reduce the design events to the 20% AP (5 year) flow peak, the hydrograph at a cross section near the Green Bridge was extracted. The volume of storage required is equal to the area under the graph between each hydrograph and the 5 year peak level, as shown in Figure 9-2 below.

Figure 9-2: 100 year and 200 year hydrographs on River Carron near Green Bridge, compared to 5 year peak flow



The volumes derived are as follows:

Table 9-2: Storage volumes required

Design event	Storage volume required (m3)	Comment
0.5% AP (200 year)	446,800	Target volume to be provided
1% AP (100 year)	303,300	
1.33% AP (75 year)	253,600	
2% AP (50 year)	192,500	

Volumes available

LIDAR data for each storage area was interrogated to determine the level constraints and volumes available in each area.

Table 9-3: Storage area constraints

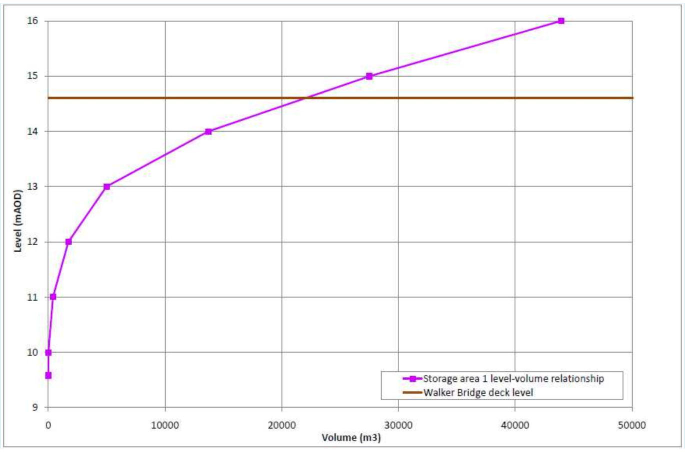
Area	Minimum ground level (mAOD)	Constraints
1	9.6	Walker Bridge deck level = 14.6 mAOD
2	17.4	Estimated property 1 level = 23.7 mAOD Estimated property 2 level = 22.3 mAOD A90 deck level = 31.1 mAOD
3	26.5	A90 deck level = 31.1 mAOD
4	30.5	Kirktown of Fetteresso bridge deck level = 33.9 mAOD Estimated property level = 38.5 mAOD

Given that Area 4 is extensive it will be divided into smaller areas for analysis and as such a stepped storage area would be created.

Analysis of the LIDAR demonstrated the level-volume relationships for each storage area shown on the following pages.

Area 1

Table 9-4: Storage area 1 level-volume relationship

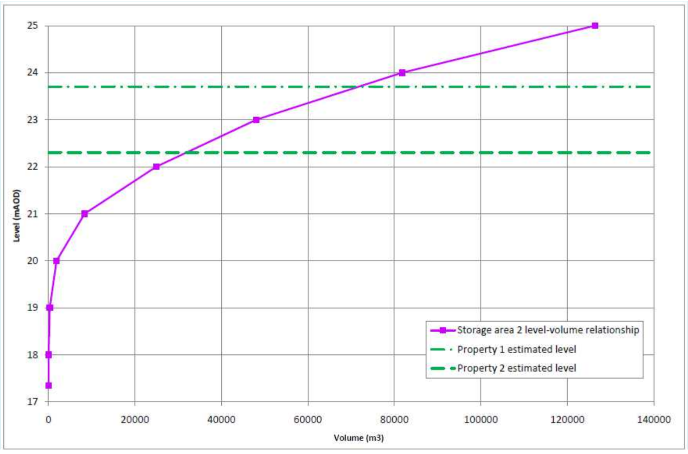
Level (mAOD)	Volume (m3)	Chart
9.6	0	
10	10	
11	40	
12	1720	
13	4980	
14	13700	
15	27510	
16	43920	

The constraint of the Walker Bridge deck level suggests that a maximum retained water level of approximately 14 mAOD may be appropriate. This would give a storage volume of approximately 13,700 m^3. Figure 9-3 below shows the approximate route of the 14 mAOD contour within Area 1 and hence the area that would be flooded.

Figure 9-3: Storage area 1 approximate flooded area

Area 2

Table 9-5: Storage area 2 level-volume relationship

Level (mAOD)	Volume (m3)	Chart
17.4	0	
18	10	
19	280	
20	1840	
21	8350	
22	24920	
23	48070	
24	81740	
25	126330	

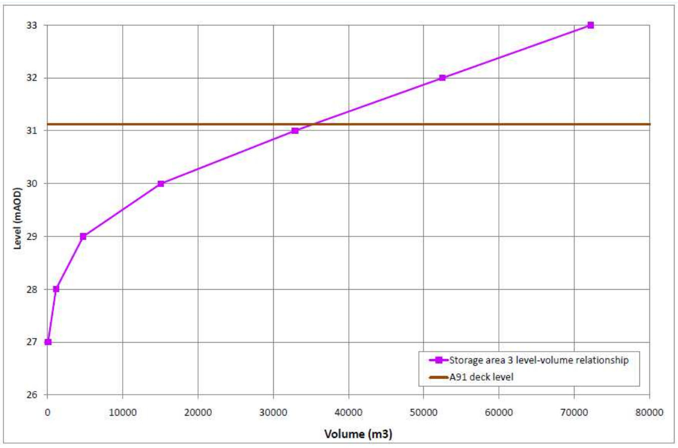
The presence of two properties at Mill O'Forest within the proposed storage area means that the maximum retained water level will need to be restricted. A level of approximately 23 mAOD may be appropriate. This would require property defences to be installed. This would give a storage volume of approximately 48,070 m^3. Figure 9-4 below shows the approximate route of the 23 mAOD contour within Area 2 and hence the area that would be flooded.

Figure 9-4: Storage area 2 approximate flooded area

Area 3

Table 9-6: Storage area 3 level-volume relationship

Level (mAOD)	Volume (m3)	Chart
26.5	0	
27	50	
28	1100	
29	4740	
30	15060	
31	32880	
32	52480	
33	72230	

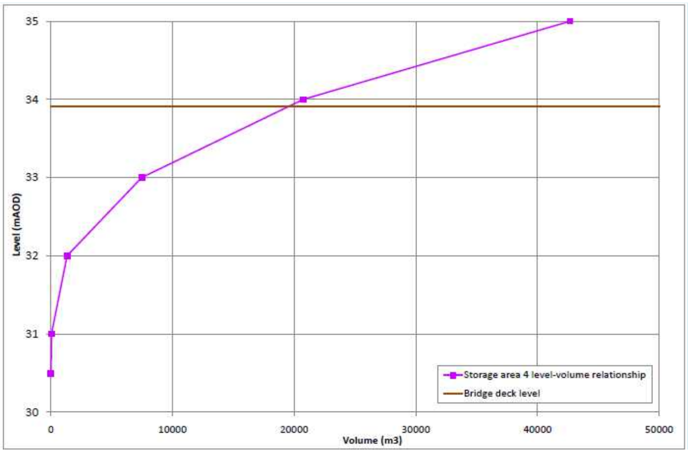


The road level on the A91 adjacent to the proposed storage area suggests that the maximum retained water level may need to be restricted; a level of approximately 31 mAOD may be appropriate. This would give a storage volume of approximately 32,880 m^3. Figure 9-5 below shows the approximate route of the 31 mAOD contour within Area 3 and hence the area that would be flooded.

Figure 9-5: Storage area 3 approximate flooded area

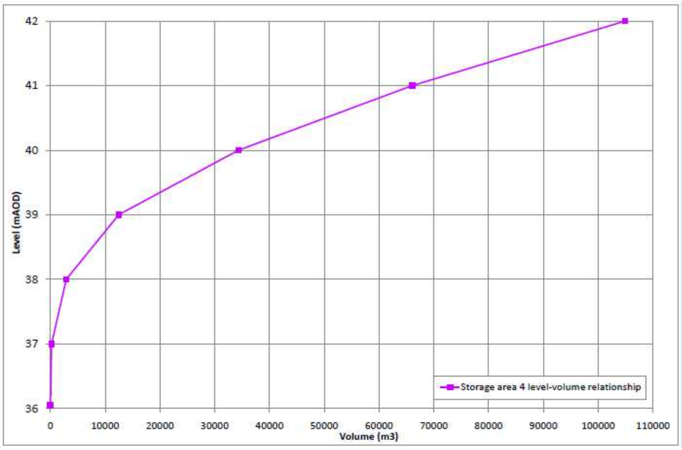
Area 4

Table 9-7: Storage area 4 (lower area) level-volume relationship

Level (mAOD)	Volume (m3)	Chart
30.5	0	
31	50	
32	1330	
33	7470	
34	20730	
35	42670	

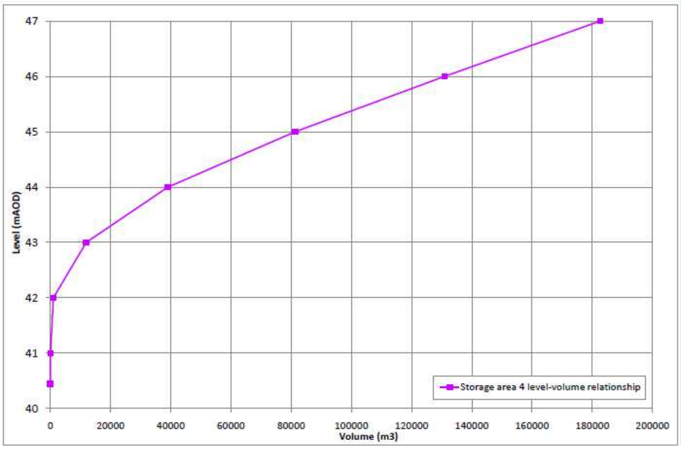
The road level on the road bridge adjacent to the proposed storage area suggests that the maximum retained water level may need to be restricted; a level of approximately 34 mAOD may be appropriate. This would give a storage volume of approximately 20,730 m^3. Figure 9-6 below shows the approximate route of the 34 mAOD contour within the lower area of Area 4 and hence the area that would be flooded.

Table 9-8: Storage area 4 (middle area) level-volume relationship

Level (mAOD)	Volume (m3)	Chart
36.05	0	
37	220	
38	2870	
39	12470	
40	34340	
41	66020	
42	104920	

Bank levels at the downstream end of the storage area envisaged as the location of the outflow retention structure are approximately 37-38 mAOD. Thus a retained water level of approximately 40 mAOD may be appropriate with reference to the height of an embankment or structure required. This would give a storage volume of approximately 34,340 m^3. Figure 9-6 below shows the approximate route of the 40 mAOD contour within the middle area of Area 4 and hence the area that would be flooded.

Table 9-9: Storage area 4 (upper area) level-volume relationship

Level (mAOD)	Volume (m3)	Chart
40.44	0	
41	20	
42	990	
43	11900	
44	39010	
45	81320	
46	130890	
47	182660	

There is an existing embankment at the downstream end of the proposed area which has a level of approximately 43 mAOD. Thus a retained water level of approximately 45 mAOD may be appropriate with reference to the height of an embankment or structure required. This would give a storage volume of approximately 81,320 m^3. Figure 9-6 below shows the approximate route of the 45 mAOD contour within the upper area of Area 4 and hence the area that would be flooded.

Figure 9-6: Storage area 4 approximate flooded areas

Summary

Table 9-10 below summarises the volumes available using the assumptions made above.

Table 9-10: Total volume available

Storage area	Volume available (m3)
1	13,700
2	48,070
3	32,880
4 lower	20,730
4 middle	34,340
4 upper	81,320
TOTAL	**231,040**

This suggests that even with all storage areas used to a maximum feasible capacity, the total storage volume available falls significantly short of that required to reduce the 0.5% AP (200 year) event peak flow to that of the 20% AP (5 year) event. As a stand-alone solution, upstream storage could be used to mitigate flood risk from the 2% AP (50 year) event, but above this flow, flooding would still occur in the town.

It may be possible to use upstream storage in combination with another approach to offer some attenuation of the peak and hence, for example, reduce the height and extent of direct defences required in the town.

9.4 Option 5: Upstream storage plus direct defences

9.4.1 Description of option

As upstream storage as a stand-alone cannot provide mitigation to the design flow, a further option would be to couple upstream storage with direct defences in the town to give a 0.5% AP (200 year) standard of protection. The height and / or extent of defences required would be reduced compared to Option 1 as the 0.5% AP (200 year) flow would be attenuated by the available storage to a reduced flow.

9.4.2 Hydraulic feasibility

Attenuated peak flow

During the 0.5% AP (200 year) event, the storage available could be utilised to reduce the peak flow on the River Carron. With the available storage filled to capacity (as described in Table 9-10 above), the 0.5% AP (200 year) peak flow could be reduced to an estimated attenuated peak flow of approximately 28 m^3/s.

Modelling has shown that a flow of approximately 28 m^3/s is sufficient to cause flooding in Stonehaven, with bank overtopping occurring between the Red Bridge and Green Bridge. Thus defences would still be required within the town but limited to the left and right banks in this location. Modelling suggests that the level of the defences required would be very similar to those proposed in Option 2 for this section (since the present option does not propose the raising of the Green Bridge).

This analysis suggests that upstream storage plus direct defences is a feasible solution for flood mitigation in Stonehaven.

9.5 Summary of feasibility of Options 4 and 5

9.5.1 Structural feasibility

To construct flood storage areas would involve damming sections of river and constructing flow control structures. Four in-line flood storage areas have been identified, requiring four structures, which are likely to consist of a concrete headwalls, together with flow control devices, such as a 'hydroslide' or other float activated gate. Earth embankments either side will be required to create a 'dam' across the valley. Construction of such a scheme will involve disturbance of the river channel and will need to be carefully planned to reduce its environmental impact. One option may be to create temporary diversion channel to construct the flow control structures. The final structures will need to incorporate features to enable migration of animals up and down the river.

The structural feasibility of the direct defences required has already been covered in Section 8.4.3.

9.5.2 Environmental feasibility

Area 1

This area of narrow floodplain has a large and widespread population of Giant Hogweed throughout the reach including some extensive stands. The right bank is steep and planted with forestry trees, while the left bank also rises but is mostly open rough grassland with patches of Gorse scrub. There are unlikely to be any significantly adverse ecological impacts as water is unlikely to be attenuated for any significant period of time in this location.

Area 2

This is an area of open rough grazing land, which although forming a floodplain appears to only be inundated during exceptionally high flood events. There are visible remains of low floodbanks parallel to the river and farm buildings have also been constructed within this area. There may therefore be some adverse impacts on this area should it be flooded more often as a result of this scheme. A change in the flora and fauna currently found in this area could result from more frequent and longer periods of flooding. The left bank at the downstream end of this proposed area is formed by a large, unstable sandstone cliff which may not be suitable for floodwater retention. Currently this cliff is vegetated by the non-native invasive species Giant Hogweed. This appears to be providing some stability, but may actually be weakening the cliff as Giant Hogweed is an annual plant and so the root system dies back each year leaving voids in the surface of the cliff face.

Area 3

This area, immediately upstream of the A90 culvert has limited available space but, during flood events already acts as an unofficial storage area as water cannot flow through the culvert. Formalising this situation will present no additional adverse impacts upon the environment that do not already occasionally occur.

Area 4

This is the most upstream area and the largest of the four and sits within the floodplain of the River Carron in the Fetteresso Estate. Much of this area is historically active floodplain and it would be relatively easy to hold water within the area for longer. The existing habitats are wet grassland and wet woodland and as such are unlikely to be adversely impacted by occasional inundation. The land use may cause some issues as much of the land is used for grazing horses. There would need to be an outflow designed to allow any entrained fish to escape following the retreat of floodwaters.

9.5.3 Summary of feasibility and impacts

Option 4 is a feasible option for partial mitigation of flood risk up to the 2% AP (50 year) return period standard, beyond which flooding would occur although at a reduced magnitude.

Option 5 is a feasible option for full mitigation of flood risk up to the 0.5% AP (200 year) return period design standard.

These options will be taken forward for benefit-cost analysis.

9.6 Constraints of methodology

The constraints of this outline analysis should be taken into consideration. If upstream storage is to be pursued as an option it would require more detailed investigation to assess its feasibility both in terms of the volumes available and the operation of any inflow / outflow structure.

Note that should this option be pursued it would need to be modelled in detail at the next stage of the process to test its effectiveness. During modelling, it should be taken into account that with storage incorporated into the catchment, the critical duration of the design storm would increase as a lag would be incorporated into the hydrological response. This change in critical duration is likely to result in a larger overall volume of storage being required as the hydrograph length and thus the area under the hydrograph increases. This should be investigated in detail at the next stage.

During further investigation it should be determined whether off-line storage areas are feasible, as these are likely to cause less disruption to the dynamics of the river system. SEPA's guidance on pond creation highlights the risks associated with the creation of on-line ponds connected to streams: the risk to fish passage, the downstream pollution risks when the ponds are de-silted and the risk of dam creation, particularly in a location such as this, upstream of a conurbation[35].

It is also noted that upstream storage on the River Carron would reduce the overall flood peak but the risk of flooding on other watercourses remains. For example, high flows on the Glaslaw Burn would not be attenuated by the storage areas described above.

[35] SEPA, 2000. Ponds, pools and lochans. Guidance note.

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10 Feasibility and Impact: Resilience approach (Option 6)

10.1 Introduction

A 'resilience' approach to mitigating flooding from the Carron in Stonehaven was envisaged as comprising suitable flood warning coupled with individual temporary property defences to all properties identified to be at risk. Thus when a warning was triggered, residents and business owners could install their property defences in time to protect from the rising waters.

The temporary property defences envisaged include door guards, airbrick covers and non-return infrastructure for property drainage systems. As part of this option, more detailed survey of properties would be required, and there would be ongoing costs associated with costs incurred during flood events and maintenance requirements.

This approach would fit well with Aberdeenshire Council's 'flood warden' scheme to help disseminate information and provide assistance to local residents during a flood. Household defences would also provide protection against surface water flooding although the provision of an effective flood warning would be more difficult for a surface water event.

10.2 Approaches to be assessed

The resilience approach will be assessed in terms of its impact on flood extent and its relative benefits and costs. It is assumed that flood warning with a viable lead time will be available through telemetry and SEPA's ongoing Flood Warning developments for the Carron.

An allowance will be made for the number of properties which manage to have a defence effectively installed in time to protect from flooding. Although every effort would be made by the Council in this situation to provide prior training as well as ample warning, it is inevitable that some property owners would be absent or unable to install a defence for other reasons and hence this will be taken into account in the calculation of economic benefits.

10.3 Option 6: Resilience approach

10.3.1 Description of option

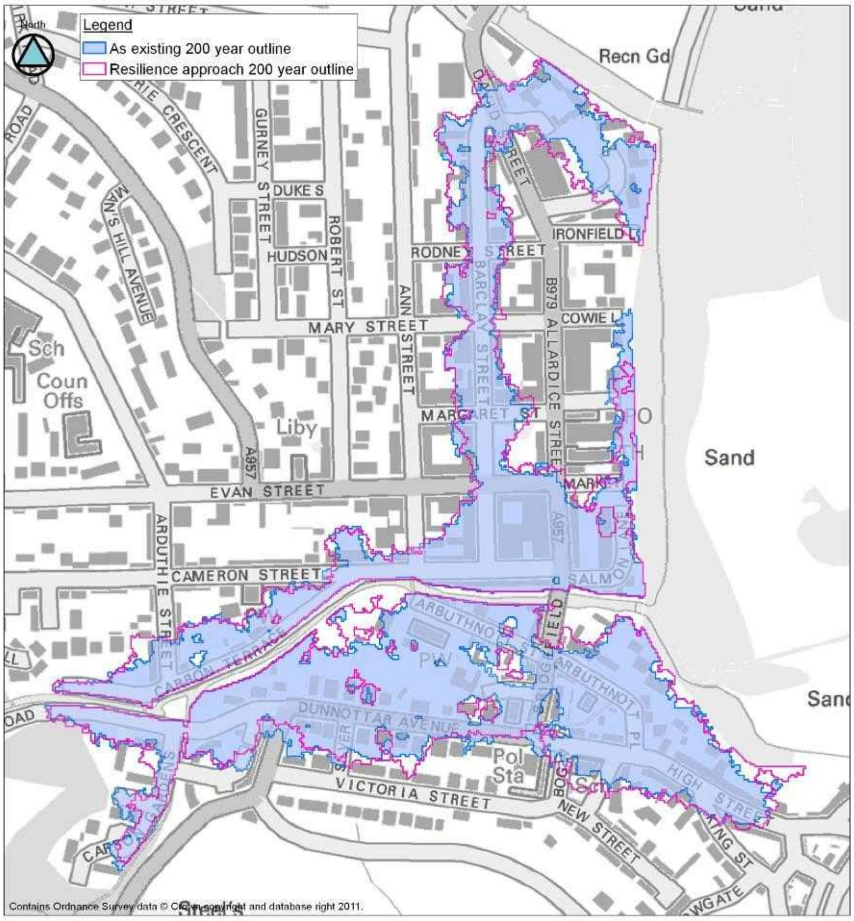
This option would allow out of bank flooding to occur as it does presently, but would reduce the flood risk to properties by defending individual buildings against the incursion of flood water. Roads and open ground would still be inundated.

10.3.2 Feasibility

The resilience approach identified is not expected to cause considerable changes to the hydraulics of the river as out of bank flooding would be permitted as in the existing scenario. The effect on the flood outline was tested using the model, with the representation of building footprints changed to low porosity polygons to inhibit water flow.

The modelling results suggest that with less permeable buildings there are likely to be small changes in the flood extents as routing of water across the floodplain is affected. However the changes are relatively small.

Figure 10-1: 200 year event flood as existing and resilience scenario outlines



10.3.3 Summary of feasibility and impacts

This is a feasible option to be taken forward for benefit-cost analysis.

11 Economic Appraisal

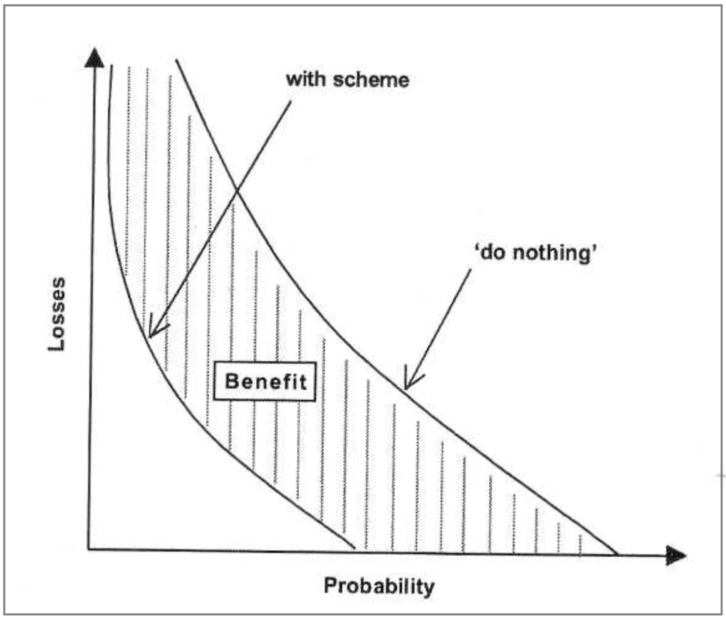
11.1 Introduction

It is recommended that a range of options are considered in the early stages of the analysis to identify possible approaches to the solution, alternative alignments, and different standards of protection. This enables the identification and prioritisation of the best solution in terms of environmental, economic and social aspects to reduce the range of technically feasible options for detailed analysis.

11.1.1 Principals of benefit-cost analysis

The process to estimate the benefits of an intervention option is to plot the two loss-probability curves: that for the situation now, and that with the proposed option (Figure 11-1). The scale on the y axis is the event loss (£); the scale on the x axis is the probability of the flood events being considered. When the two curves are plotted then the difference in the areas beneath the curve (the Annual Average Damage) is the annual reduction in flood losses to be expected from the scheme.

Figure 11-1 Schematic of loss probability curves



These are compared with the whole life cost of the capital and maintenance works associated with the option, expressed as present value. If the benefits exceed the costs for the option, the scheme is deemed to be cost effective and worthwhile for promotion.

11.1.2 Study area

The area particularly affected by flooding in Stonehaven is defined by the flood outlines prepared for this study and includes properties flooded up to the 0.1% AP flood. Both residential and industrial properties are at risk.

Flood damages have been assessed from fluvial flooding only. Coastal flood damages, wave overtopping and damages from surface water flood risks have not been assessed at this time.

11.2 Scenarios and option selection

The aims of the flood mitigation in Stonehaven are to protect the town from fluvial flood risks.

11.2.1 Guideline standards

Scottish Government guidance[36] states:

'…it is expected that flood prevention schemes in Scotland will continue to be designed to withstand, at least, a 1 in 100 year flood event';

and:

'…. a 1 in 100 year standard is a reasonable starting point, and provides a practical benchmark to assist with the administration of the grant scheme.'

The aim of the scheme was to provide a scheme that provided at least a 1% AP, but preferably a 0.5% AP flood standard. Climate change has not, at this stage, been assessed.

11.2.2 Options appraised

Of the 6 options assessed within this report, the following are deemed to be feasible and have been taken forward for an economic appraisal. These include:

- 'Do minimum' (baseline against which to review the options);
- Direct defences, raising of Green Bridge and removal of remains of weir at Green Bridge;
- Upstream storage;
- Upstream storage plus direct defences; and
- Resilience.

These options are referred to in the rest of this section as 'Do Nothing', 'Direct defences', 'Flood storage', 'Storage plus defences' and 'Resilience'.

11.3 Option costs

Whole life costs including all enabling, capital and long term inspection and maintenance costs are required for each option. Indicative scheme costs for the design options have been determined; a summary of what is included is provided here. A breakdown of the capital costs is provided in Appendix D.

11.3.1 Methodology

Costs have been derived from a number of sources suitable for this level of assessment, together with unit costs from previous studies and general guidance. Unit rates for flood walls were taken from the Environment Agency Flood Risk Management Estimating Guide[37]. Indicative rates for the costs of resilience measures were taken from a study by Defra[38]. Unit rates for storage were obtained from a previous report on floodplain storage[39].

In addition to the construction costs the following items were added:

- Professional fees (10% of civil works; 20% for storage options due to the disparate nature of the available storage);
- Site investigation (1.5% of civil works; 2.5 % for the storage options);
- Statutory fees (2.5% of civil works);
- Optimism bias (see below).

[36] Scottish Executive (2005) Flood Prevention Schemes: Guidance for Local Authorities. Chapter 5, Paragraph 6.4.

[37] Environment Agency (2010). Flood Risk Management Estimating Guide. (Unit Cost Database).

[38] Defra/Environment Agency (2008) Developing the evidence base for flood resistance and resilience: Summary Report. R&D Technical Report FD2607/TR1.

[39] Morris, J., Vivash, R., Alsop, D., Lawson, C., Leeds-Harrison, P. & Bailey, A. (2002). Economic basis and practicalities of washland creation on the Somerset levels and moors. A Report For: Somerset Levels and Moors, The Wise Use of Floodplains Project in Somerset.

11.3.2 Price base date

The price base date is July 2011; benefit calculations have therefore been updated to the same date in order to compare the benefits and costs on an equal basis. The costs have been discounted over the 100 year life of the scheme to determine present values.

11.3.3 Optimism Bias

An optimism bias of 60% has been applied and is representative of a scheme at the design stage of development. This provides a significant safety factor for cost implications and risks.

11.3.4 Operation and maintenance costs

The maintenance and operation costs for each option have been estimated separately. Annual operation and maintenance costs have been estimated the assumptions listed in the table below.

Table 11-1: Annual maintenance costs and assumptions

Option	Annual maintenance cost assumption	Annual cost (£k)
'Do minimum'	No costs assumed	0
Option 2: Direct defences	£670 per year based on Environment Agency guidance for concrete wall annual maintenance costs per km.	0.67
Option 4: Flood storage	1% of the capital costs for structural maintenance plus £2,500 for statutory inspections and flood plan maintenance.	5.30
Option 5: Storage plus direct defences	£300 per year based on Environment Agency guidance for concrete wall annual maintenance costs per km. 1% of the capital costs for structural maintenance plus £2,500 for statutory inspections and flood plan maintenance.	6.40
Option 6: Resilience	Costs assume that council operatives would be required during flood events to provide training/annual practice events and to provide ongoing project management and community liaison	6.34

11.3.5 Scheme costs summary

A summary of the scheme costs is presented in the table below.

Table 11-2: Scheme cost summary

Scheme cost	Total PV capital cost (£k)	PV operation & maintenance costs (£k)	PV other (£k)	Total PV scheme costs (£k)	Optimism bias (60%) (£k)	Total PV costs (£k)
'Do minimum'	0	0	0	0	0	0
Option 2: Direct defences	2,094	19	0	2,114	1,268	3,382
Option 4: Flood storage	2,752	151	0	2,904	1,742	4,646
Option 5: Storage plus direct defences	3,617	185	0	3,802	2,281	6,083
Option 6: Resilience	1,992	183	131	2,305	1,383	3,689

11.4 Benefits of flood mitigation

11.4.1 Guidance

Guidance on assessing the benefits is provided in the Scottish Government FPS guidance document[40] in chapters 5 and 6. Supplementary guidance is also provided by the Flood and Coastal Erosion Risk Management - Appraisal Guidance (FCERM-AG)[41]. Damages were

[40] Scottish Executive (2005) Flood Prevention Schemes: Guidance for Local Authorities.

[41] Environment Agency (2010) FCERM- Appraisal Guidance

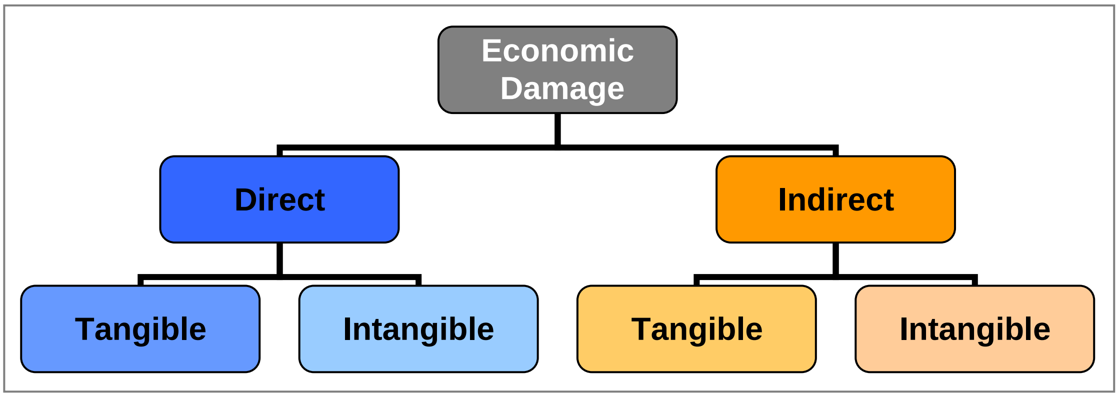
calculated in accordance with the Benefits of Flood and Coastal Risk Management[42] (the Multi-Coloured Manual (MCM)).

11.4.2 Methodology

JBA use standard spreadsheets to calculate direct and indirect flood damages for a number of options to calculate the benefits of flood mitigation and ultimately the cost effectiveness of each option. Damages are calculated by cross referencing modelled flood level / depth information with property information and standard MCM depth damage curves.

Flood damage assessment can include direct, indirect, tangible and intangible aspects of flooding, as shown in the figure below. Direct damages are the most significant in monetary terms, although the MCM and additional research provide additional methodologies, recommendations and estimates to account for the indirect and intangible aspects of flood damage.

Figure 11-2: Aspects of flood damage



Damages estimates have been derived for direct and indirect flood damages, together with an allowance for intangible impacts such as increased stress and health effects as a result of flooding.

Items included:

1. Direct damages to residential properties;
2. Direct damages to commercial and industrial properties;
3. Indirect damages (emergency services);
4. Intangible damages associated with the impact of flooding; and
5. Indirect flood damages (extra heating and electricity costs, temporary accommodation).

Items excluded:

1. Traffic disruption costs;
2. Risk to life;
3. Indirect damages to commercial properties; and
4. Socio-economic equity.

11.4.3 Direct property damage methodology and data

The standard MCM methodology was followed to estimate direct property flood damages for residential and non-residential properties (commercial and industrial properties). Estimation of damages essentially links property information and flood depths with defined depth damage curves to derive flood damages for each property. The key datasets include the following:

[42] E. Penning-Rowsell et.al. (2005). The Benefits of Flood and Coastal Risk Management: A Manual of Assessment Techniques.

- Property dataset provided by Aberdeenshire Council;
- Depth damage curves provided by the MCM (2010 version); and
- Flood level/depth data from the hydraulic model at each property.

The following statistics are provided for information.

Table 11-3: Number and type of properties assessed

Variable	Number	Percentage
Total number of properties in appraised area	914	
Number of properties removed from analysis (upper floor flats, duplicates, non property)	353	
Number of properties included in analysis	561	
Number of residential properties	438	78%
Number of commercial/industrial properties	123	22%

Table 11-4: Proportion of residential property types in the property database

Property type	Number	Percentage
Detached	47	11%
Semi-detached	58	13%
Terraced	165	38%
Flat	168	38%
Total	*438*	

Table 11-5: Proportion of non residential property types in the property database

Property type	Number	Percentage
(High Street) Shop	40	33%
Bank	3	2%
Betting Shop	2	2%
Café / Food Court	13	11%
Church	4	3%
Community Centres / Halls	6	5%
Hairdressing Salon	6	5%
Hotel	1	1%
Laundrette	2	2%
Law court	1	1%
Miscellaneous (Weighted mean)	2	2%
Offices (non specific)	19	15%
Petrol Filling Station	1	1%
Police Station	1	1%
Pub / Social club / Wine bar	5	4%
Residential Home	1	1%
Restaurant	2	2%
School / College / University / Nursery	5	4%
Showroom	3	2%
Surgery / Health Centre	3	2%
Vehicle Repair Garage	1	1%
Workshop	2	2%
Total	*123*	

Flood damages have been determined using the following steps:

1. Properties identified from within fluvial flood zone.
2. Property dataset amended to include property MCM codes, property areas, threshold levels and market values.
3. Walkover survey undertaken on the 16 June 2011 in order to check property details.
4. Predicted flood levels obtained from hydraulic modelling are assigned to each property and flood depths derived.
5. Estimation of property flood damages for all return periods assessed using flood depths and property depth-damage curves.

The following assumptions and additional data were used to improve and provide the necessary information to supplement the above datasets. Comments on the quality of the data and future improvements have also been listed.

Table 11-6: Assumptions

Data type	Data used	Quality (MCM categories)	Improvement
Threshold level	No threshold values used. Site visit assessed number of steps and level of threshold above ground level. LiDAR + 150mm per step.	Data with known deficiencies	Survey threshold levels
Basements	Basements identified on site and threshold from LiDAR adjusted and reduced by 2m. Depth damage curves without sub-floor level damages used.	Data with known deficiencies	Property survey to identify all basements.
Upper floor flats	Upper floor flats have been excluded from the analysis based on site visit information.	Best of breed	N/A
Residential property types	Defined by property types (Detached, Semi-Detached, Terraced, Flat) based on site survey. Age and social types excluded.	Data with known deficiencies	Define by property age
Non residential property types	MCM property types defined using property dataset and site visit.	Best of breed	N/A Site surveys for key beneficiaries if required
Property areas	Defined by Mastermap and count of properties per Mastermap polygon	Best of breed	N/A
Residential market values for capping	Estimated from current median property valuations obtained from www.home.co.uk for each property type in Stonehaven.	Data with known deficiencies	Define property values by street
Non residential market values for capping	Market value = (100 / equivalent yield) x rateable value. Equivalent yield obtained from report on National Property Dataset[2]. Rateable values (£) by property class per m^2 based on DCLG values for North East[3].	Data with known deficiencies	Obtain rateable values from SAA[1]
Flood duration	Assumed to be less than 12 hours based on historic flooding and flood hydrographs.	Best of breed	N/A
Updating of MCM damage data	Retail Price Index	Best of breed	N/A
Distributional Impacts	Not included	Data with known deficiencies	Assess using Census data

[1] Scottish Assessors Association
[2] Environment Agency (2004). National Property Dataset: Property Data for England and Wales.
[3] Department for Communities and Local Government. Floor space and rateable value of commercial and industrial properties, 1 April 2008.

The MCM data is based on January 2010 prices, and therefore needs to be brought up to date in order to accurately compare against the costs. The Scottish Government recommends that this is carried out using the Retail Price Index (RPI). Damages have thus been updated to the July 2011 price base; this represents an increase in damages of approximately 8%.

11.4.4 Indirect flood damage methodology

The MCM (2005) recommends the inclusion of indirect loss data into the benefit appraisal process. The following quantifiable impacts that can be included in the analysis are:

1. Extra heating costs;
2. Electricity costs of de-humidifiers (cost of renting the equipment is included in MCM damage curves);
3. Temporary accommodation costs; and
4. Costs of emergency services.

The damages at each return period and for each option, together with the number of residential properties flooded at different depths are included in Appendix E. The damages are summarised in Section 11.5.

Table 11-7: Indirect flood damages

Data type	Assumption/Guidance
Extra heating costs	Extra heating costs resulting from post flood inundation were added to each property when inundation depths exceed the property threshold value as recommended in the MCM. The additional heating cost is estimated to be £170 per property inundated[43].This has been updated to a 2011 value of £190.
Electricity costs of de-humidifiers	The cost of renting de-humidifiers is included within the clean-up costs of the MCM depth-damage estimates. Domestic clean-up costs do not, however, include the additional electricity costs of running the de-humidifiers, which are included here as recommended by the MCM. For flood depths less than 100 mm the total cost is £604.80 per house, £1,209.60 for flood depths greater than 100 mm. These have been updated to 2011 values of £676 and £1,353 respectively.
Temporary accommodation costs	The MCM recommends that for properties flooded to a depth above 300 mm, 64% of households will rent alternative accommodation for an average of 22 weeks. The estimated average weekly rental accommodation costs for Aberdeenshire are £150[44]. Therefore, the average cost for alternative accommodation per household is £3,300.
Emergency services costs	MCM recommends applying a multiplier of 1.107 to the total property damages to allow for the emergency costs that would be incurred during a flood event, that are not counted elsewhere in the benefit assessment[45].

11.4.5 Intangible flood damage methodology

Scottish Government guidance[46] indicates that the value of avoiding health impacts of fluvial flooding is of the order of £200 per year per household. This value is equivalent to the reduction in damages associated with moving from a do-nothing option to an option with an annual flood probability of 1% (100 year standard). A risk reduction matrix can be used to calculate the value of benefits for different pre-scheme standards and designed scheme protection standards. This is shown in Appendix F.

The intangible damages have been incorporated into the economic appraisal process by determining the standard of protection for each property and defining the intangible flood damages per property. Using the risk matrix the associated value of intangible damages for each option is derived. These are then summed and discounted to obtain the total intangible damage for each option.

[43] E. Penning-Rowsell et.al. (2005). The Benefits of Flood and Coastal Risk Management: A Manual of Assessment Techniques. Chapter 4.5.2, subsection 3.

[44] http://www.rentright.co.uk/aberdeenshire/2_rrpi.aspx.

[45] The Benefits of Flood and Coastal Risk Management: A Manual of Assessment Techniques. Chapter 3.4.7.

[46] Scottish Executive. Flood Prevention Schemes: Guidance for Local Authorities. Chapter 5, Paragraph 4.1.24.