Dumfries and Galloway Council

Carsphairn Flood Study

Final Draft

September 2015

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Table of Contents

List of Figures

List of Tables

Executive Summary

Dumfries and Galloway Council and Scottish Power commissioned Kaya Consulting Ltd. to undertake a study to assess flooding risk from the Water of Deugh and its tributaries within the village of Carsphairn.

The Water of Deugh overtopped its banks and flooded areas of Carsphairn in December 2013. This was thought to be one of the largest flooding events in recent memory. Subsequently, the village flooded again in January 2015, although to a lesser extent.

This study undertakes a detailed hydrological assessment for the Water of Deugh, develops a linked 1D/2D flood model of the river through Carsphairn, produces flood inundation maps for a range of return period flood events, assesses a range of possible flood alleviation measures and presents an initial cost-benefit analysis for the preferred flood alleviation options.

Design flows for the Water of Deugh for use in the study were developed using standard methodologies taking into account the impact of the Scottish Power Hydro Scheme. The 200 year flow for Water of Deugh downstream of Carsphairn at Liggat Bridge, was predicted as 330 m^3/s. This compares with an estimated peak flow of approximately 210 - 230 m^3/s for the December 2013 event, which has an estimated return period of around 1 in 10 to 50 years (average 1 in 25 years).

An integrated mathematical model of Water of Deugh and its tributaries through Carsphairn was developed using the ISIS 1D/2D software packages. The model was calibrated against recorded flood level and flood extent information from the December 2013 event. The model predicted flood extent matches reasonably well to the recorded flood extent during the 2013 event.

The calibrated model was used to simulate inundation during floods with a range of return periods (2, 5, 10, 25, 50, 100, 200, 200 plus climate change, and 1000 year return periods). Flood maps were prepared for each event, showing the extent of flooding and properties and infrastructure affected.

The model predictions showed flooding of large floodplains to the south, south-east, west and north-west of Carsphairn village, even during floods with low return periods (of the order of 1 in 2 years and above). Modelling indicated that flood waters overtop the east bank of the river upstream of the confluence with Carsphairn Lane, flow east and spill on the A713 and then flow towards Green head Strand. Flows running down Green head Strand and high flows in Water of Deugh combine and affect properties along the main road.

Liggat Bridge, located at the downstream reach of the village to the south-east is elevated high above the channel and was not predicted to surcharge.

The model results predicted that 31 properties would be affected during a 200 year flood, of which 27 are residential. The threshold return period at which flooding would affect properties is 2 to 5 years.

A number of flood mitigation options were considered, including; flood storage upstream; direct defences where flood risk areas could be protected by flood walls and embankments; natural flood management measures, and removal of sediment from the river. Modelling work indicated that only the direct defence option would be able to provide the desired level of protection to all affected properties in Carsphairn.

It was calculated that a total of some 500 m of flood walls and 850 m of flood embankments would be required to protect all the flood risk areas in Carsphairn from a 200 year flood. Wall heights would generally be up to 1 m above existing ground level, and embankments up to 1.5 m high. Options were also considered for defence schemes that provided lower levels of protection. In comparison, a scheme which would provide 10 year level of protection would require defence heights on average 0.2 m lower than the scheme required for 200 year protection.

An initial cost-benefit analysis was undertaken, based on the model results and conceptual level flood alleviation options. Hence, the cost-benefit analysis should be considered as initial only, with a high degree of uncertainty. A bias factor of 60% was added to cost estimates for the flood defence schemes as per standard practise for initial cost-benefit analyses.

The conclusions of the cost-benefit analysis were that the benefit-cost ratio for direct defence scheme is positive (1.27). This only includes direct flood damages and inclusion of environmental and social factors and intangibles would likely result in a higher ratio. This indicates that such a scheme would be economically feasible. However, Carsphairn village has not been designated a PVA (Potentially Vulnerable Area) by SEPA and therefore it may not, at least in the foreseeable future, attract grant aid from the Scottish Government.

Based on the outline cost-benefit analysis undertaken, a scheme consisting of direct defences and providing up to 200 year level of protection would appear technically and economically feasible and worth further consideration.

Although the 1D/2D mathematical model used for the study produced good correlation with the December 2013 flood data, it can be refined to increase its accuracy in some areas by collecting additional topographical survey. This would increase model confidence in particular in areas where limited or no survey data is available at present.

1 Introduction

1.1 Background

The village of Carsphairn in Dumfries and Galloway experienced flooding on 30 December 2013 when several properties were flooded and the main road through the village was closed. Upstream of Carsphairn on the Water of Deugh, the water level at the Brownhill level gauge reached the highest level ever recorded. The river level at Glenlochar, downstream of Carsphairn, was also the highest ever recorded by SEPA. During the same period, widespread fluvial and surface water flooding was reported within the Dumfries and Galloway Council area.

Following this event Dumfries and Galloway Council and Scottish Power commissioned Kaya Consulting Limited to undertake a detailed flood study for Carsphairn, focussing on flooding risk of the urban areas from the Water of Deugh and its tributaries close to the village.

1.2 Aims and Objectives

The main aim of the study is to identify the risk of flooding from the Water of Deugh and its tributaries within Carsphairn and to develop outline flood mitigation measures, including outline costs to implement the measures and a cost-benefit analysis of the measures. The findings of the study will be used by Dumfries and Galloway Council to make a decision on what further actions can be taken to mitigate flood risk in the village.

The Terms of Reference for the study identified 10 key tasks. The tasks are summarised in Table 1, which also identifies where in this report each of the tasks are addressed.

1.3 Extent of Study Area and Description

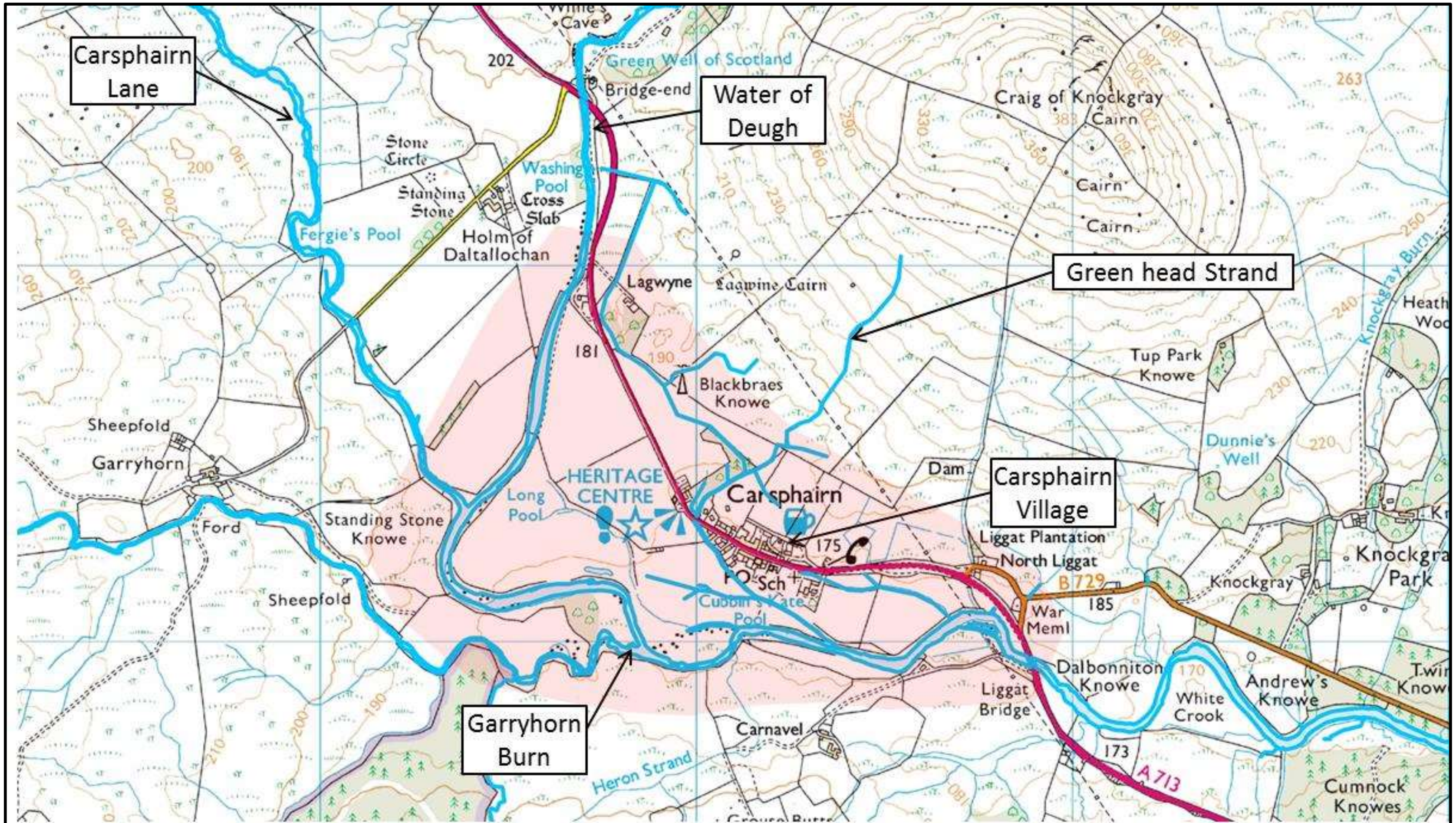
Carsphairn is located approximately 44 km north-west of Dumfries, in Kirkcudbrightshire, Dumfries and Galloway. The village is located on the main A713 road between Ayr and Castle Douglas and the village is situated to the east and north of the Water of Deugh which runs south adjacent to the village.

The study area for flood modelling extends along the banks of the Deugh and its tributaries (Carsphairn Lane, Green Head Strand and Garryhorn Burn) from National Grid Reference (255687,594002) close to Lagwyne Farm off the A713 and (256960,592884) downstream of the Liggat Road Bridge, as shown in Figure 1.

Table 1: Key Tasks

No.	Task	Where Addressed in Report
1	A review of historical flooding incidents in Carsphairn, including a door to door survey of properties identified as at-risk to flooding.	Chapter 2
2	Fluvial hydrological study of the Water of Deugh and tributaries as well as the small watercourses within Carsphairn;	Chapter 4
3	Annotated mapping showing the operational arrangements for abstraction and discharge within the upstream catchment.	Chapter 4
4	A review of Scottish Water GIS data for the wastewater network within the vicinity of river network and an indication of the effect of the 1:200 year flood levels on the network.	Chapter 8
5	Mathematical modelling and flood inundation mapping (for scenarios with and without hydraulic structures) for 1:2 , 1:5, 1:10, 1:25, 1:50, 1:100, 1:200, 1:200 + Climate Change and 1:1,000 year return periods;	Chapter 5
6	Outline Design: Identify three feasible options for flood protection schemes to achieve: a) A 0.5% AEP (including an allowance for climate change) level of protection b) A 2.0% AEP level of protection c) A level of protection for the greatest benefit/cost ratio of feasible options for an event return period between 1:1 and 1:200 + Climate Change.	Chapters 6 and 7
7	Economic analysis to develop preliminary Cost Benefit Analysis (CBA) for identified options for flood protection schemes;	Chapter 9
8	An assessment of potential mitigation measures which may have a degree of benefit in terms of flood risk management but which would not be considered a formal flood protection scheme.	Chapter 6
9	Assessment of suitability and implementation costs of flood warning scheme for Carsphairn;	Chapter 10
10	The benefits, in terms of flood risk management, of carrying out works of sediment management on the watercourses within Carsphairn.	Chapter 6

Figure 1: General Location Map for Carsphairn (extent of modelling study highlighted in red)



2 Review of Historical Flooding Incidents

In the past Carsphairn has been subject to numerous flooding incidents of differing magnitude. Information recorded from the events has been documented by the local council and published as part of the biennial reports which are a statutory requirement under the Flood Risk Management (Scotland) Act 2009.

Historical information on recent flood events was also obtained from local residents who witnessed the flooding first hand. Door to door surveys/interviews as well as a presentation to residents was undertaken as part of the assessment.

2.1 Historical Flood Information Received from Dumfries and Galloway Council

Historical flood records were provided by the council. The dataset contained flood records from 2007 to 2012.Additional information was also obtained from review of the council Biennial reports, see Table 2.

Table 2: Historic flood records provided by Dumfries and Galloway Council

Record date	Main source	Location	Description
1995-1997	1st Biennial report	Green head Strand	Overflow ditch cleaning
1997-1999	2nd Biennial report	Green head Strand	Overflow ditch cleaning
2001-2003	4th Biennial Report	Green head Strand	Watercourse was inspected in November and June. The area opposite and adjacent to the church is a high flood risk due to its very gentle gradient and thick vegetation. In extreme conditions flooding has extended to include the school and properties at Greystone and Kirklea. The pub is currently not at risk but may become one if the banking erodes at all.
2003-2005	5th Biennial report	Green head Strand	Overflow ditch cleaning
2003-2005	6th Biennial report	Green head Strand	Overflow ditch cleaning. Land Drains from pond above Glenelg flooding heritage driveway and garden at Glenelg. Washed out gravel from driveway
2007-09	7th Biennial report	Green head Strand	Watercourse was inspected in November and June

2.2 Other Historical Flood Information

As well as speaking directly to a number of residents, Kaya Consulting met with local residents in Carsphairn on Monday 17th November 2014 at the local village hall. The residents provided additional information related to historical flooding and especially related to the December 2013 event. This information included anecdotal data as well as photographic information of previous notable events which occurred in Carsphairn and the surrounding areas.

Based on historical information provided by the residents it appears that Carsphairn has experienced significant flooding (which has caused overtopping of the A713 and flooding to properties adjacent to the road) a number of times in the past:

- Month unknown 1926 - Flooding at Cairnview (north of village) and flooding at Kirklee (south of village); and
- January1995 – Flooding at Kirklee.

An overview of the December 2013 flood event is given in Section 2.3, with a brief discussion of the more recent January 2015 event in Section 2.4.

2.3 Overview of December 2013 Flood Event

Heavy rainfall from 29th to 31st December 2013 resulted in flooding in the village of Carsphairn, Dumfries and Galloway. This chapter presents an overview of flooding that occurred during this event (including a timeline) based on consultations with local residents affected by the flooding, discussions with Dumfries and Galloway Council flood officers and discussions with Scottish Power (SP) staff.

2.3.1 Timeline

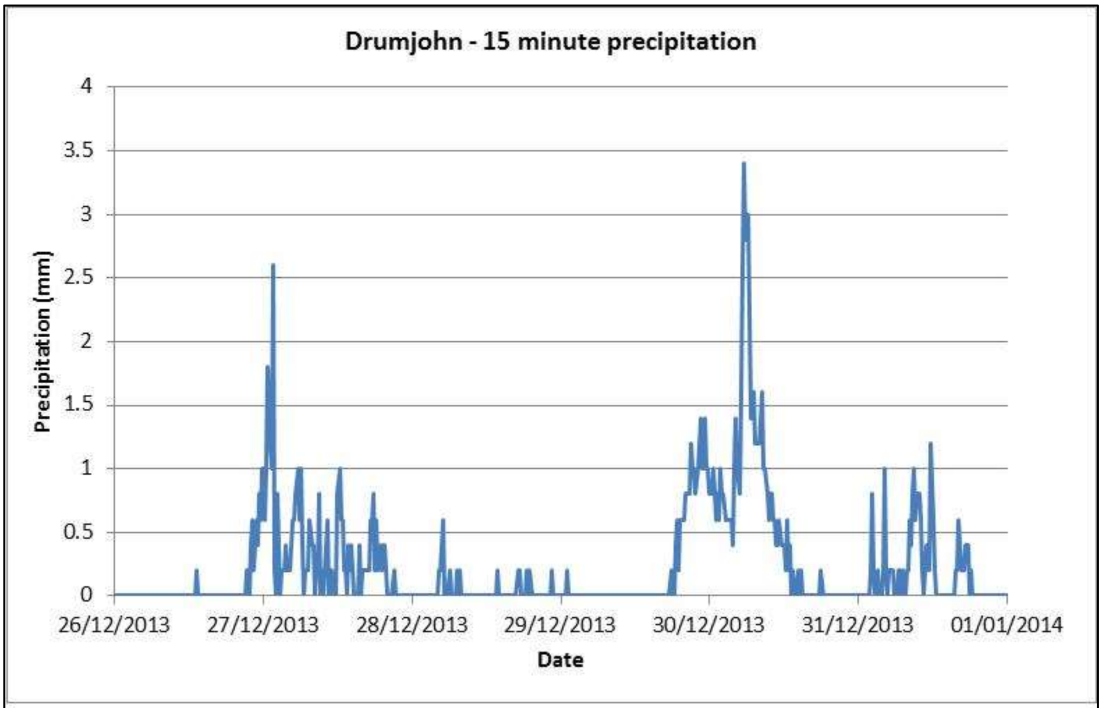
Recorded rainfall at the Drumjohn rain gauge (located at OS Grid Reference, (252494, 597541), close to the SP Drumjohn station) is shown in Figure 2. The data indicates there was reasonably heavy rainfall on 27th December, but limited rainfall on the 28th, through most of the 29th. Rainfall started to be recorded at Drumjohn at around 1600 hours on 29th December and continued for the next 21 hours, with two peaks in rainfall at 2315 on the 29th December and 0530 on 30th December. A full analysis of how this rainfall event compared to other historical rainfall events at Drumjohn and elsewhere is provided in Section 3.3.

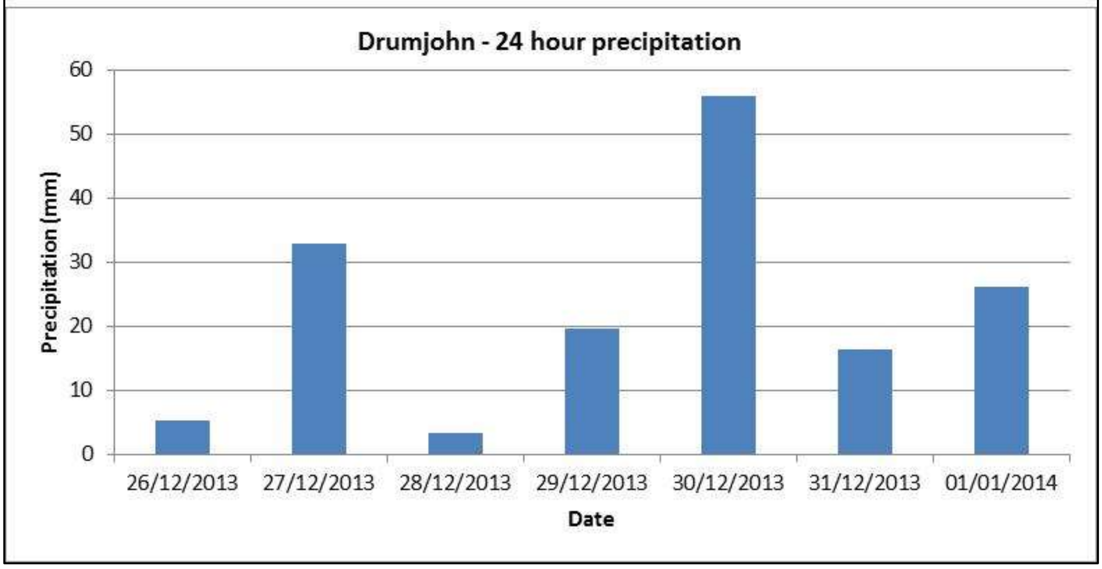
A general time table of observations and events during the 2013 event is provided in Table 4.

Table 3: General Timetable of Events during December 2013 Flood

Time	Observation	Source
29th December 1600	Rainfall starts to be recorded at Drumjohn monitoring station	Drumjohn rain gauge
29th December 2315	First peak in rainfall recorded at Drumjohn	Drumjohn rain gauge
30th December 0530	Second peak in rainfall recorded at Drumjohn	Drumjohn rain gauge
30th December 0800	First observations of flooding in Carsphairn (drains overflowing to north of village)	Observation by resident
30th December 0835	Dumfries and Galloway Council receive reports of flooding in Carsphairn	Dumfries and Galloway Council
30th December 0900	Peak water level observed at Brownhill gauge	Brownhill gauged data
30th December around 0900	Peak of flooding in northern part of Carsphairn reached just after 0900	Observation by local resident
30th December 0945	Water level on road in Carsphairn reported to be around 3 to 4 feet deep	SP
30th December 0948	Needle valve at Drumjohn is opened discharging water into Carsphairn Lane	SP
30th December 0959	Reports of flooding in Carsphairn received at Drumjohn	SP
30th December around 1010	Estimated arrival of Drumjohn water at Carsphairn	SP
30th December 2015	Record high water level reached at SEPA gauge at Glenlochar	SEPA data

Figure 2: Recorded Rainfall at Drumjohn in December 2013 Event





2.3.2 Observations of Flooding Extent and Flood Mechanisms

Kaya Consulting staff carried out an extensive site survey in Carsphairn as well as to the SP infrastructure upstream of the village. During the visit in June staff met SP managers and toured the SP facilities at Drumjohn, as well as visiting offtake structures at Bow Burn and the Water of Deugh Offtake structure. After this meetings were held with local residents affected by flooding.

Based on the information provided by the residents a flood map for the December 2013 event was created and is shown in Figure 3. Key observations and indicative flood depths are shown on the plan. Some flood levels (based on observations by local residents) were surveyed and are shown on the figure.

Key observations related to flooding mechanisms were made by local residents:

- Initial flooding at 8am on 30th December appeared to be from drains located on the road to the north of the village. Water then was seen accumulating near to the heritage centre before overtopping and flowing along the main road in the village, see Photo 1 in Appendix A;
- Property opposite the Primary School was described as having been flooded from water passing along the main road, see Photo 2 in Appendix A;
- Property opposite Knowe B&B was described as being flooded from a mix of water flowing from main road and from fields to the west of the property, see Photo 3 in Appendix A;
- Residents suggested that water levels within buildings fell rapidly after peak of flooding, 'like plug being removed'.

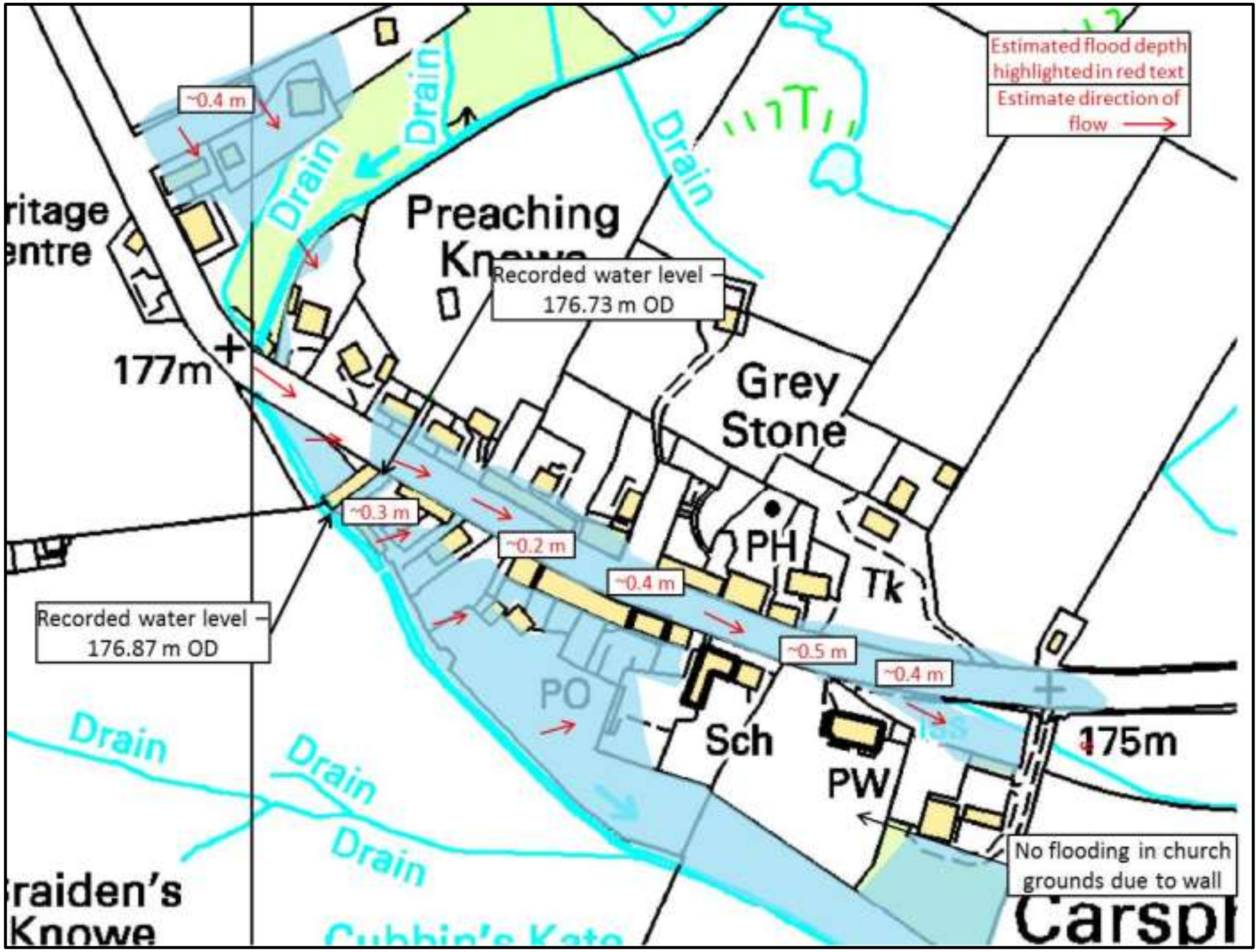
2.4 January 2015 Event

In the early hours of the 15th January 2015, Carsphairn was also subject to a flood of similar magnitude to the December 2013 event. Due to the timing of the event not a lot of information was recorded during the peak of the flood, however; Dumfries and Galloway Council attended the village the following morning and was able to capture photographs of the remnants of the flooding within the village.

Key observations which can be derived from the January 2015 event:

- Email communication from the community council indicated that around 10 or 11 properties had been flooded;
- Evidence of flood waters passing through properties on the south of the A713 and flowing on to the road, see photos 5 and 6 in Appendix A;
- Overtopping of the Deugh upstream of the watergate was noted (based on flattened vegetation on river bank). Flow pathways were also recorded within the adjacent floodplain see Photo 7 and 8 in Appendix A;
- Overtopping of the A713 upstream of the town was also recorded with standing water yet to recede from the event see Photo 9 in Appendix A.
- Flood waters reaching the north of the A713 entered the Green head Strand, passing through properties close to the post office.

Figure 3: Flood Map of December 2013 event based on local resident observations (flooding out with village not shown)



3 Data Collection and Review

Information from numerous sources has been obtained and analysed for the purpose of this study. Key data obtained for this assessment are described in the following sections.

3.1 Data Received from Dumfries and Galloway Council

Dumfries and Galloway Council provided the following Ordnance Survey mapping information for Carsphairn and the surrounding study area:

- 1:1,250 detailed maps;
- 1:10,000 maps; and
- 1:25,000 maps.

In addition to the above Dumfries and Galloway also provided Scottish Water infrastructure drawings which covered urban areas within Carsphairn.

Historical flooding details were also obtained from Dumfries and Galloway Council; these are described in Chapter 2.

3.2 Data Received from SEPA

3.2.1 Flood Maps

SEPA publish Indicative River and Coastal Flood Maps for Scotland (Third Generation) (http://www.sepa.org.uk/flooding/flood_extent_maps.aspx). The maps show the predicted extent of flooding for a 200 year flood event (0.5% chance of occurring in any year) in line with Scottish Planning Policy (SPP). As indicated by their name, these maps are considered Indicative only as they are based on relatively crude topographical data and mathematical modelling. The flood maps are designed to provide a community level assessment of flooding and its impacts. They model flooding at a national scale. As with any approach of this scale, there are limitations and assumptions made to enable modelling and a consistent approach to be applied across Scotland. Limitations arise from the data used to create the maps, the modelling techniques applied and the ability to incorporate datasets from local studies into a national approach. Therefore, they provide an overview of likely flood extents, but cannot be relied on for detailed assessments. For any specific study area, more accurate flood maps are typically required based on more detailed modelling work and site-specific topographical data.

Flood maps for the 10 year and 200 year for Carsphairn obtained from the SEPA website have been reproduced in Figure 4 and Figure 5 below. The maps indicate a significant area of flooding on both banks of the Water of Deugh and the Carsphairn Lane close to the study area; however the map does not show the urban area of the village to be at risk of flooding. The maps also show overtopping of the A713 upstream of the village with flood waters predicted to inundate low lying areas close to the Green head Strand.

The SEPA flood map also indicates flood waters overtopping the right bank of the Deugh and flowing westwards through Holm of Daltallochan. This area is located outside the study area; however, in any event the floodwaters would enter the Carsphairn Lane and re-enter the Deugh adjacent to the town.

Figure 4: Approximate extent of SEPA 1 in 10 year fluvial flood maps of Carsphairn (reproduced manually by Kaya Consulting)

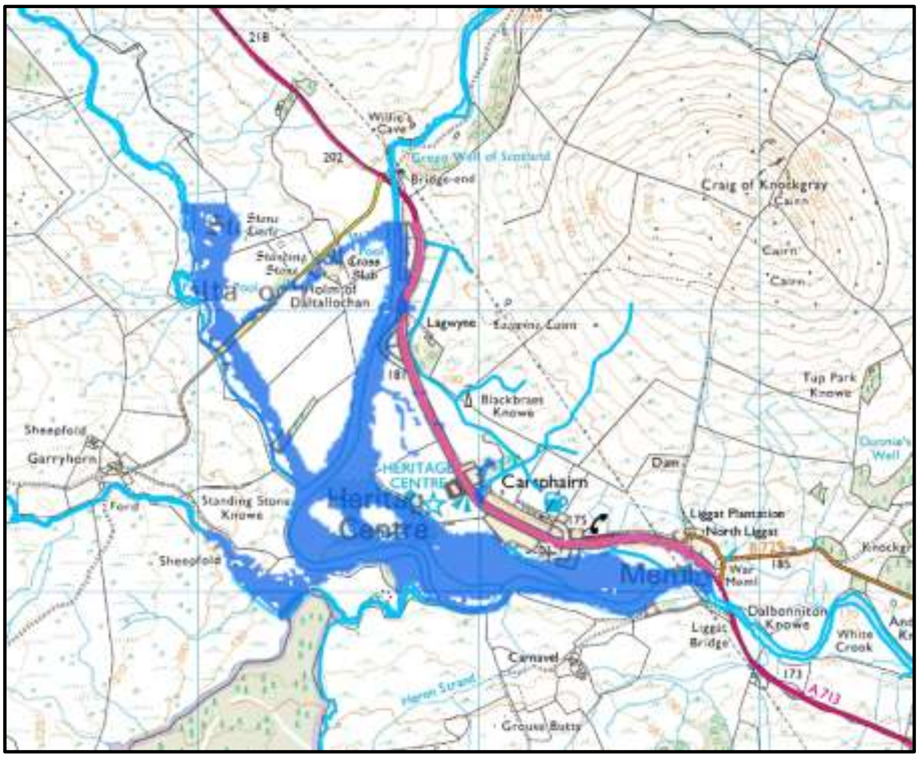
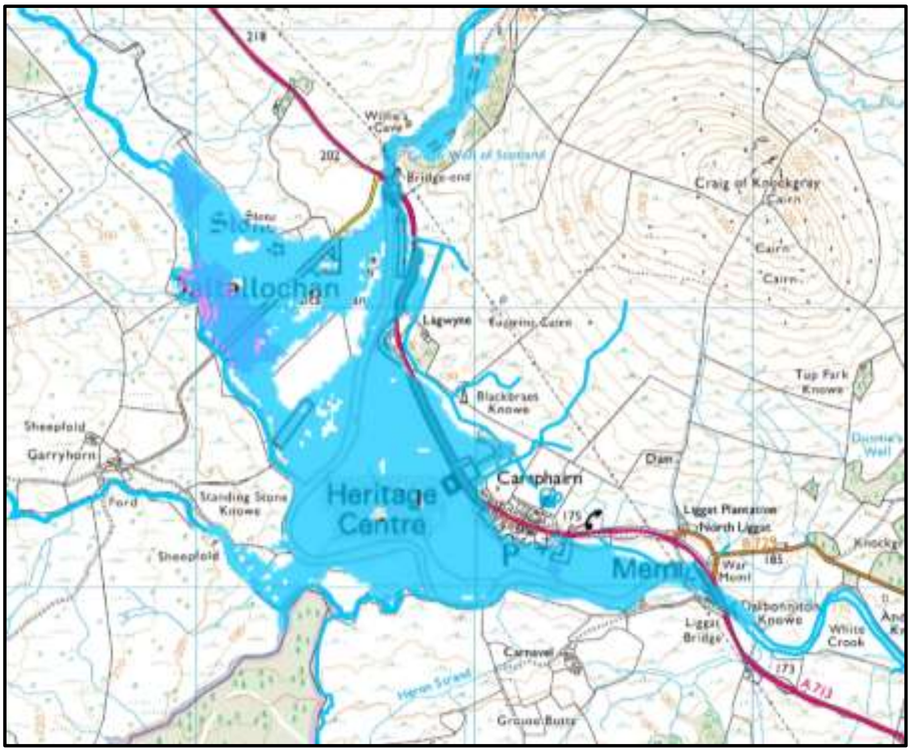


Figure 5: Approximate extent of SEPA 1 in 200 year fluvial flood maps of Carsphairn (reproduced manually by Kaya Consulting)



3.2.2 Hydrometric Data

SEPA do not operate any flow monitoring stations within the immediate location of the village of Carsphairn. However a number of flow monitoring stations are located within the surrounding south-west Scotland area, see Figure 6 . Kaya Consulting received the following data for each gauge;

- AMAX series data; and
- 15 minute stage recordings for the 2013 flood events.

A series of discussions were held with SEPA related to the AMAX series and rating curves at the site. Following these discussions the data, methods and design flows for the Water of Deugh were agreed with SEPA for use in the present study.

Figure 6: Map view of local SEPA river flow gauges

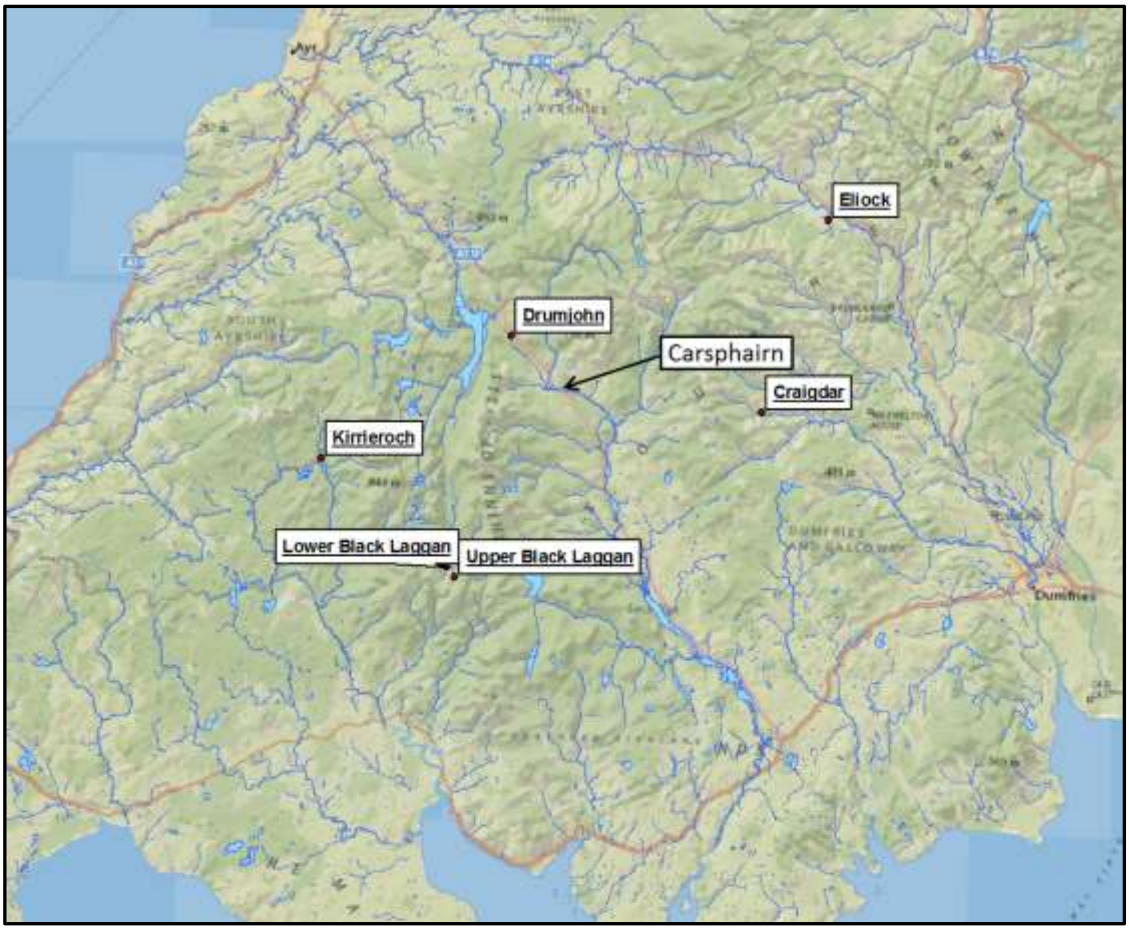
3.2.3 Rainfall Data

In addition to data from hydrometric gauges, data from various local rain gauges were also provided by SEPA. This included 15-minute rainfall totals for the full period of records, and are listed in Table 4 and shown graphically in Figure 7.

Table 4: List of SEPA rain gauges used for assessment

Rain Gauge	Gauge No.	Grid Reference
Upper Black Laggan	115657	247616 576885
Drumjohn	115612	252494 597541
Eliok	115562	279666 607398
Kirriereoch	115599	236207, 587069
Lower Black Laggan	115612	246949, 577748

Figure 7: Map view of local SEPA rain gauges



3.3 Data Received from Scottish Power

Scottish Power has provided detailed information on the Drumjohn Hydropower Station operating procedures as well as a site visit of the Power Station. A list of all received data is provided below:

- Carsphairn Flood Presentation – Uploaded via Public Contracts Scotland
  2. Galloway and Lanark Hydro Schemes Information:
  http://www.scottishpower.com/pages/galloway_and_lanark_hydro_schemes.asp
- Galloway Hydros Technical Factsheet:
  http://www.scottishpower.com/userfiles/file/GallowayTechnical2011.pdf
- Galloway Hydros Loch Doon Factsheet: http://www.scottishpower.com/userfiles/file/Loch-Doon-2014.pdf
- Galloway Hydros Flood Management:
  http://www.scottishpower.com/userfiles/file/GallowayFloodManagement2011.pdf
- 2014 Weir and Spillage Flow Calculations
- "Operating Instruction for the Management of Water Resources & Control of Natural Flooding Events at Galloway Hydros" Report Aug 2014 from Scottish Power

3.4 Ground Survey Data

The study area is not covered by LiDAR topographical data, therefore, in order to construct detailed mathematical models of Water of Deugh and tributaries, a channel cross-section topographical survey was undertaken including survey of the Liggat Road Bridge. In addition, spot levels were also taken of ground levels within the large floodplains between the channel and the village as well as ground levels within the A713 and surrounding houses.

MH Surveyors Ltd. were commissioned to undertake survey of 24 cross-sections of the Water of Deugh throughout the study area and 2 cross-sections of Green head Strand within the village (only 2 could be surveyed due to heavy vegetation). The location of survey sections is discussed in more detail in Chapter 5.

Topographical spot levels were also taken of ground levels within the large floodplains between the channel and the village. Ground levels were also recorded within the built up area of the village including the A713, adjacent gardens and surrounding ground features. The survey within the village was largely based on a site visit and historical flooding extents.

A survey of doorstep threshold levels was undertaken for all properties identified as lying within the floodplain area. These survey levels are key inputs to the cost benefit assessment component of the study.

The work was undertaken by MH Surveyors who carried out the survey in July 2014.

3.5 Kaya Site Visits and Consultation

A series of site visits were undertaken by members of the Kaya team and sub-contractors. Site visits are listed below:

- 18th June 2014: Michael Stewart undertook walkover survey visited Scottish Power to view the upstream infrastructure;

- 2nd July 2014: Callum Anderson undertook a walkover survey. The key purpose of the assessment was to finalise locations for model cross-sections, including requirements for channel topographical surveys;
- 23rd September 2014: Callum Anderson and Yusuf Kaya undertook walkover site visit to confirm modelling flow pathways and check initial model results.
- 17th November 2014: Callum Anderson and Yusuf Kaya undertook site survey to review proposed mitigation options and to present initial results to the local flood group.

During the site visits the entire modelled reach of the Water of Deugh, Carsphairn Lane and Green head Strand within the study area were visited and a photographic record of the watercourses was produced.

4 Hydrological Assessment

4.1 Objective and Location of Flow Estimates

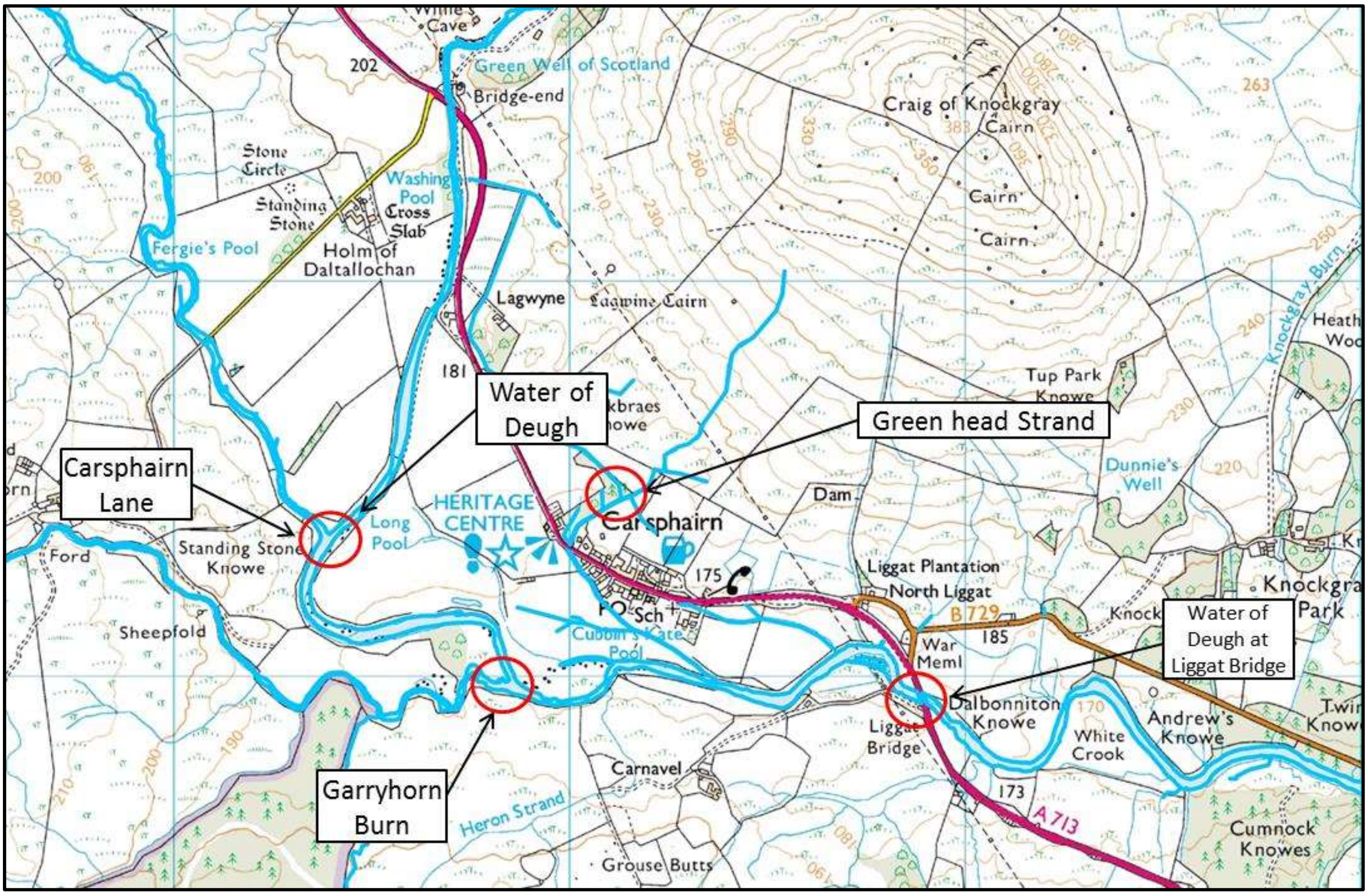
The objective of the hydrological analyses is to provide estimates of return period peak flood flows within the study area and to provide design flow hydrographs to be used as inputs into the mathematical modelling work described in Chapter 5. The assessment attempts to identify the return period of the 2013 flood event.

For consistency, the flood modelling was undertaken for flow conditions that produced design flows calculated at two locations;

- Water of Deugh downstream of the confluence with Carsphairn Lane; and
- Water of Deugh at Liggat Bridge.

Locations of flow estimation points are shown in Figure 8.

Figure 8: Location of flow estimation points



4.2 Catchment Description

The Water of Deugh is the main watercourse that flows to the west and south of the village of Carsphairn. The watercourse rises to the north of the village in an upland area that includes the Carsphairn Forest, with a catchment area highlighted in red in Figure 9.

Key tributaries affecting flooding at Carsphairn include Carsphairn Lane, which is a tributary of the Water of Deugh and joins the river to the west of the village; Garryhorn Burn, which is a tributary of the Water of Deugh and joins the river to the south-west of the village; and Green head Strand, which is a tributary of the Water of Deugh and runs through the northern part of the village and then along the western edge of the urban part of the village before discharging into the river at a point south-east of the village. Catchment areas for these watercourses are also shown in Figure 9.

The Deugh enters into Kendoon Loch around 4.5 km downstream of the village.

Catchments within the south-west of Scotland experience a relatively warm and wet climate compared to the rest of Scotland. The average annual rainfall for the Water of Deugh catchment is around 1800 mm based on the Flood Estimation Handbook (FEH). Annual mean temperatures are expected to range from 9.4 to 9.7 °C (Met Office: Regional Climate: Western Scotland.). In terms of physiography, most of the Water of Deugh catchment is upland forest in character with a large area of the Deugh catchment draining the Carsphairn Forest.

The catchment upstream of Carsphairn has been artificially modified to form part of SP's system for managing Loch Doon, which forms part of the wider Galloway Hydro Scheme. The modifications include abstractions from the catchment of Water of Deugh to support water volumes in Loch Doon, and return flows from Loch Doon to the Carsphairn Lane through the Drumjohn Power Station. Three watercourse offtakes are present within the upstream catchments:

1. Bow Burn, approximately 1.4 km east of the Deugh intake, see Figure 10. A weir diverts water into an aqueduct structure that transfers flows to a location immediately upstream of the intake to supplement flows into Loch Doon.
2. At a location close to (254727,598377), approximately 3.5 km to the east of Loch Doon, the Water of Deugh is impounded by a large weir which transfers flows from the Deugh to Loch Doon via the Loch Doon Tunnel. During periods of high flows excess water passing over the weir continues down the Deugh;
3. A third weir structure is located on the Muck Burn, which permanently diverts flows within the natural channel towards Loch Doon via an artificial canal, see Figure 10.

Water levels within Loch Doon can be controlled by a weir structure which releases a compensation flow down River Doon.

A schematic diagram of main watercourses and water abstraction and transfer features are shown in Figure 11.

Figure 9: General Catchment Map

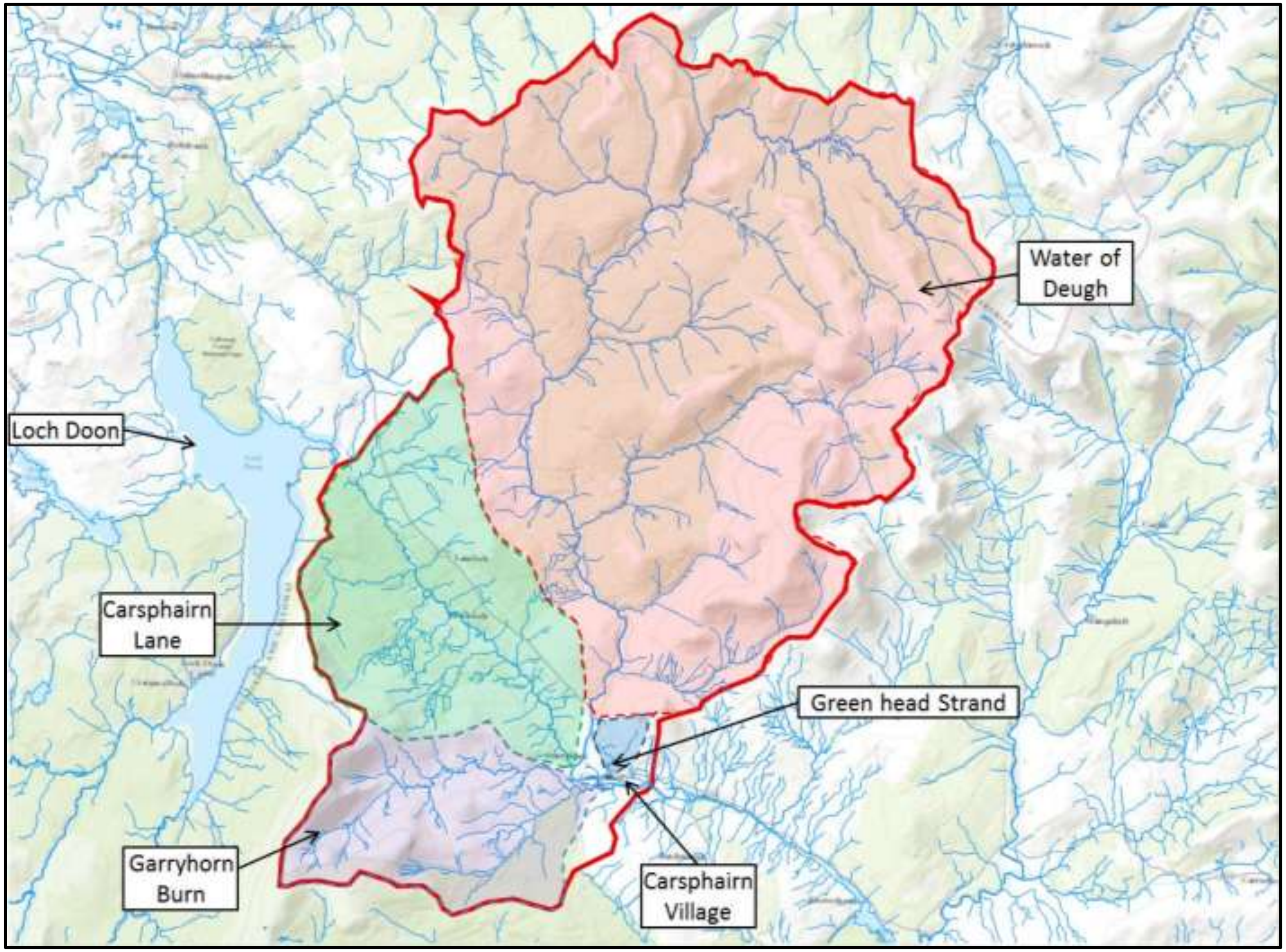


Figure 10: SP Infrastructure Schematic

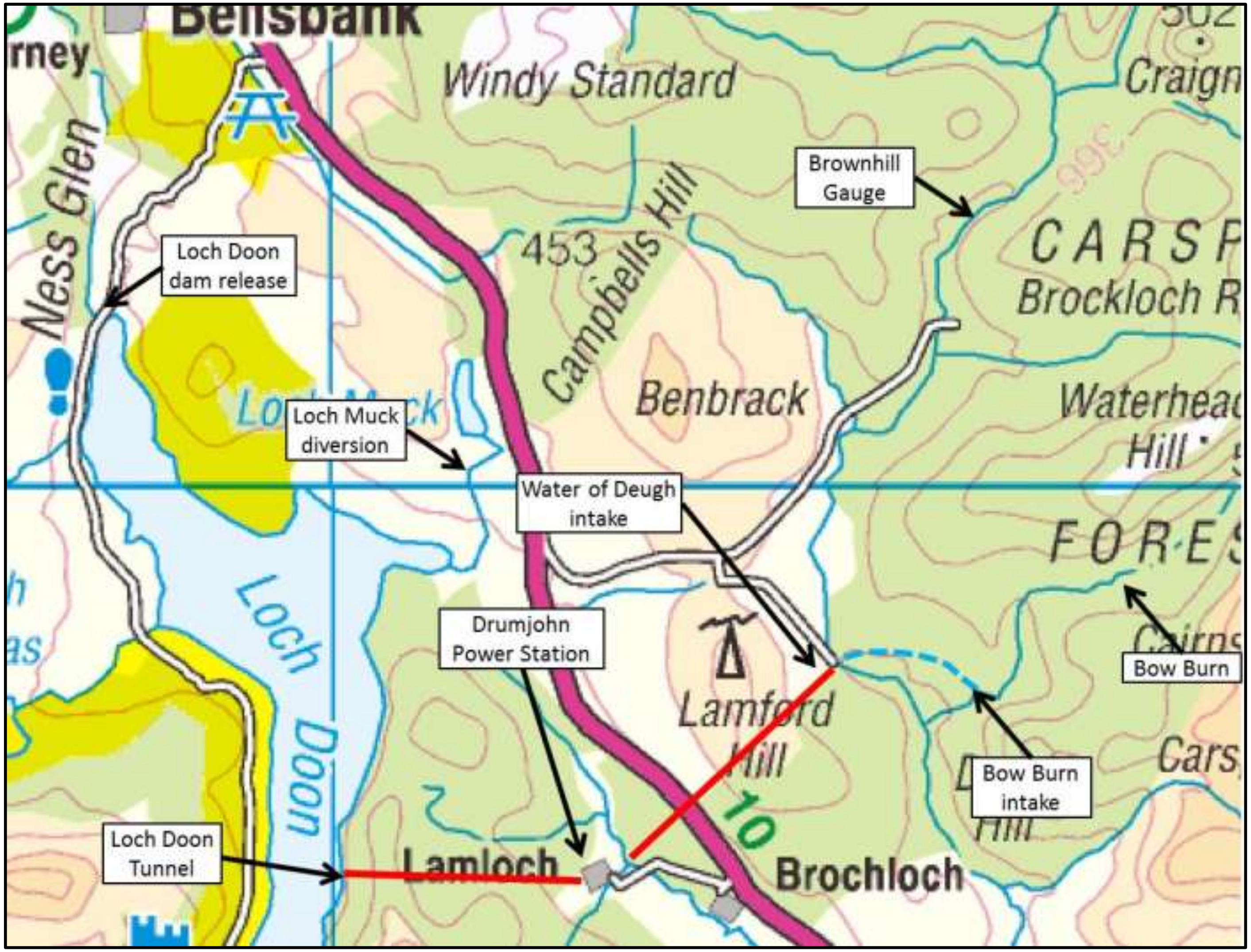
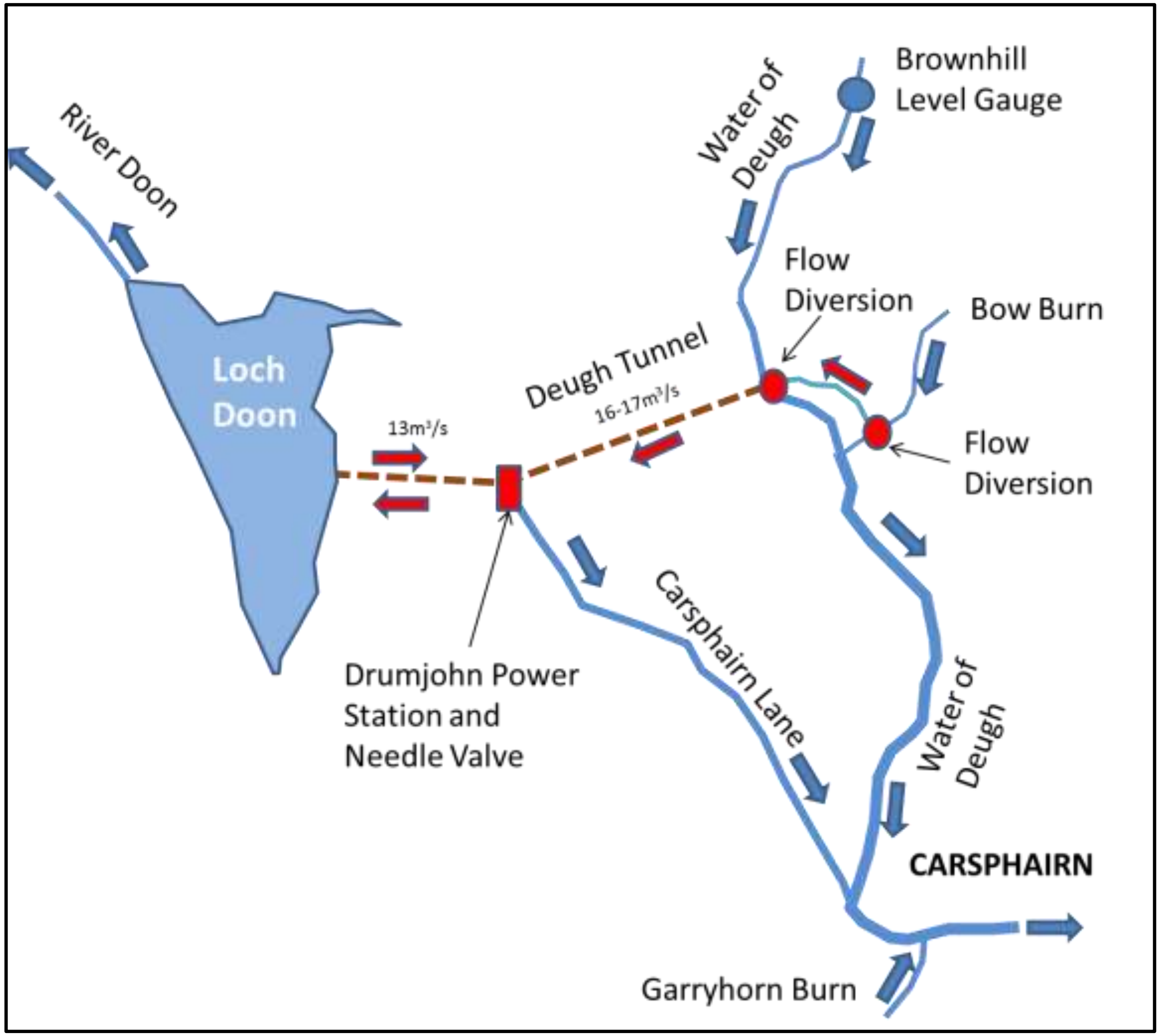


Figure 11: Schematic diagram of main watercourses and flow diversion features



The maximum capacity of Deugh Tunnel is believed to be approximately 16-17 m^3/s. Water is released either at Drumjohn Power Station or Drumjohn Needle Valve, which have a maximum discharge capacity of approximately 15 m^3/s. This flow enters Carsphairn Lane. Scottish Power indicated that on the day of the December 2013 flood and in accordance with Scottish Power operating rules that the Drumjohn Needle Valve was opened at 09.48 hours, and that flows discharged to Carsphairn Lane were approximately15 m^3/s.

4.3 Design Flows for Key Watercourses Based on Standard Methods

4.3.1 Design Flows for Water of Deugh and Main Tributaries

Design flows were calculated for Water of Deugh downstream of the confluence with Carsphairn Lane and Water of Deugh at Liggat Bridge, Figure 1. The Water of Deugh is ungauged and design flows were calculated using the Flood Estimation Handbook (FEH) Pooling Group method and FEH Rainfall-Runoff model.

Design flows for the two locations are shown in Table 4 and return period scaling factors are highlighted in Table 5. The results for the Pooling Group and FEH Rainfall-Runoff models are very similar.

Table 5: Catchment Characteristics for Water of Deugh

Parameter	Deugh downstream of Carsphairn Lane	Deugh at Liggat Bridge
Easting (m)	255400	256750
Northing (m)	593350	593050
AREA (km^2)	110.28	127.28
ALTBAR (m)	388	380
ASPBAR (^{o})	235	226
ASPVAR	0.12	0.06
BFIHOST	0.3	0.307
DPLBAR	11.8	12.69
DPSBAR	145.9	147.8
FARL	1	1
FPEXT	0.0404	0.0424
FPDBAR	0.58	0.619
FPLOC	0.741	0.741
LDP	25.59	27.7
PROPWET	0.63	0.64
SAAR (mm)	1807	1824
SAAR4170 (mm)	1760	1775
SPRHOST	54.04	53.53
URBCONC1990	0	0
URBEXT1990	0	0

URBLOC1990	0	0
URBCONC2000	0	0
URBEXT2000	0	0.0001
URBLOC2000	0	0

The 200 year scaling factor for Water of Deugh calculated using the FEH Pooling Group method is between 2.3 and 2.4 for the two locations on the river (i.e., factor by which annual median flood (Q_{med}) needs to be multiplied to give the 200 year flow). This value is low compared to the standard Flood Studies Report (FSR) values for southern Scotland of 3.18. The FSR methods have been superseded by the FEH methods, but the standard FSR scaling factors are often reasonable guides to likely scaling factors for catchments in the UK and if FEH methods produce different values it is worth further analysis to review reasons for the different values. Annual maximum series (AMAX) data for 14 SEPA gauged sites in Dumfries and Galloway were obtained and single site analysis undertaken for each of the gauges. The 200 year scaling factor for each site is presented in Table 6, illustrating that values <3 are common for many sites, suggesting values of 2.3 and 2.4 for the study area are not uncommon for catchments in Dumfries and Galloway.

Table 6: Return Period Flows for Water of Deugh

Return Period	Deugh downstream of Carsphairn Lane (m^3/s)		Deugh at Liggat Bridge (m^3/s)	
	FEH Pooling Group	FEH Rainfall-Runoff Model	FEH Pooling Group	FEH Rainfall-Runoff Model
2	[a]122	107	[a]138	120
5	153	137	174	156
10	174	164	199	186
25	203	203	234	231
50	226	236	263	268
100	252	268	294	304
200	280	307	329	348

a Values for Q_{med} were based on catchment characteristics. An assessment of appropriate donor catchments were made with values varying from 118 to 147 m^3/s for the first three donors for Deugh at Liggat Bridge. Taking the first 5 possible donors the average Q_{med} was 141 m^3/s. This was sufficiently close to the Q_{med} based on catchment characteristics for this value to be selected for the analysis.

Table 7: Return Period Scaling Factors for Water of Deugh

Return Period	Deugh downstream of Carsphairn Lane		Deugh at Liggat Bridge	
	FEH Pooling Group	FEH Rainfall-Runoff Model	FEH Pooling Group	FEH Rainfall-Runoff Model
2	1	1	1	1
5	1.254	1.280	1.263	1.300
10	1.427	1.532	1.445	1.550
25	1.663	1.897	1.696	1.925
50	1.855	2.206	1.905	2.333
100	2.064	2.505	2.133	2.533
200	2.291	2.869	2.385	2.900

Table 8: 200 Year Scaling Factors at Gauged Sites in Dumfries and Galloway

Watercourse	Gauge location	Scaling Factor
Water of Fleet	Rusko	1.498
Water of Deugh	Newton Stewart	2.126
Water of Deugh	Minnoch Bridge	1.708
Bladnoch	Low Malzie	1.445
River Dee	Glenlochar	1.526
River Nith	Friars Carse	2.562
Cluden Water	Fiddlers Ford	2.270
River Nith	Drumlanrig	2.171
Urr Water	Dalbeattie	2.556
Scar Water	Capenoch	1.637
River Stinchar	Balnowlart	1.333
River Doon	Auchendrane	1.461
Water of Luce	Airyhemming	2.319
Water of Girvan	Robstone	1.422
Water of Deugh		2.3 – 2.4

4.3.2 Design Flows for Green head Strand

The catchment area of Green head Strand was calculated to be around 1 km^2, extracted from the FEH CD-Rom Version 3. Other catchment characteristics are shown in Table 9.

Design flows for the small ungauged Green head Strand were calculated using FEH Rainfall-Runoff method and Institute of Hydrology (IH) small catchment method (Report IH124). The results are provided in Table 10.

Table 9: Catchment Characteristics for Green head Strand

Parameter	Value
Easting (m)	256000
Northing (m)	593300
AREA (km^2)	1.04
ALTBAR (m)	231
ASPBAR (^{o})	221
ASPVAR	0.7
BFIHOST	0.389
DPLBAR	0.99
DPSBAR	119.3
FARL	1
FPEXT	0.0718
FPDBAR	0.742
FPLOC	0.526
LDP	2.09
PROPWET	0.69
SAAR (mm)	1640
SAAR4170 (mm)	1535
SPRHOST	48.32
URBCONC1990	0
URBEXT1990	0
URBLOC1990	0
URBCONC2000	0
URBEXT2000	0.0024
URBLOC2000	0

Table 10: Return Period Flow Estimates for Green head Strand

Method	Q_{200} (m^3/s)	Q_{200} + climate change (m^3/s)	Comment
FEH Rainfall-Runoff[a]	5.8	7.0	Known to provide high estimates for some small catchments
IH124[b]	4.0	4.8	

a Catchment design rainfall= 78.3 mm and design storm duration= 3.0 h.

b SAAR= 1640 mm and soil type 4 (i.e. SOIL=0.45).

4.4 Return Period of 2013 Event

Neither the Water of Deugh nor any of its tributaries have standard SEPA gauges with long periods of record. As a result, an assessment of the return period of the 2013 event needs to be based on a combination of different data sources;

- Analysis of gauged data at SEPA flow data from nearby catchments;
- Analysis of gauged data at SEPA meteorological data (rainfall) from nearby sites;

- Flow calculation from SP;
- Modelling using FEH Rainfall-Runoff Model using observed rainfall data; and
- Modelling using ISIS1D/2D flood model compared to observed December 2013 flood extent.

4.4.1 Analysis of SEPA Flow and Rainfall Data

Data from 15 SEPA flow gauges and 7 SEPA rainfall gauges were obtained from SEPA. For the flow gauges the full AMAX series were obtained along with 15 minute water level and flow data during the 2013 event. For the rain gauges 15 minute data for the full period of record at each gauge were obtained.

At each flow gauge single site flood frequency analyses and Pooling Group analyses were undertaken and the peak flow during the 2013 event was compared to the results of the analysis to give an estimated return period for the event. The results are summarised in Table 11.

At each rainfall gauge a return period analysis was undertaken for a range of storm durations and the rainfall total during the 2013 was assigned a return period based on the analysis. Results for the 12-hour duration storm are provided in Table 12. The 12-hour storm is the critical storm duration for Water of Deugh catchment from FEH Rainfall-Runoff model and considered the most appropriate duration for the assessment. The rainfall depths are then compared to the return period rainfall depths extracted from the FEH CD-Rom Version 3, Rainfall Depth data.

A comparison of the rainfall intensities predicted from analysis of site data and from data from the FEH CD-Rom is presented in Figure 13. The results show that for all sites bar Lower Black Laggan and Eliok, the site data provides a reasonable fit to the FEH data up to return periods consistent with the length of record at each gauge (see Table 12). For higher return periods the quality of fit is poorer for most sites apart from Upper Black Laggan and Kirriereoch. The raw data for Eliok was of poorer quality that that for other stations, with more gaps in the data and anomalous rainfall depth returns. Hence, the poor fit for this site is not unexpected. It is unclear why there is a poor fit for Lower Black Laggan.

The return period for the 2013 event for each of the SEPA gauged sites is illustrated in Figure 12.

The results indicate that numerous gauges (flow and rainfall) experienced events of between 1 in 10 and 1 in 50 years in December 2013, with higher return period rainfall and flow events occurring towards the west of Dumfries and Galloway; in the east of the council area return periods were generally < 1 in 10 years. The highest return period event was observed at Hall Bridge flow gauge on the River Nith, which experienced a return period of around 1 in 100 years, although downstream of Hall Bridge in the Nith the observed return period fell to 1 in 50 year and 1 in 40 year at Drumlanrig and Capenoch. The rain gauge closest to Carsphairn at Drumjohn experienced a rainfall event with around 1 in 10 to 1 in 15 year return period, with gauges to the west at Eliok and Craigdar experience events at around 1 in 20 to 1 in 25 years.

As the headwaters of Water of Deugh lie in the upland areas to the west of Drumjohn and close to the headwaters of the River Nith (Figure 14), the regional pattern of return period rainfall and flow might suggest that rainfall in the Deugh headwaters might be in excess of the 1 in 15 year return period observed at Drumjohn. Hence, the return period for the event in Water of Deugh might be considered to have a return period of around 1 in 20 to 1 in 50 years, based on the available regional data.

4.4.2 SP Calculation

Based on information provided by SP the needle valve controlling flows from Loch Doon to Drumjohn was opened at 9.48 am on 20th December 2013. This resulted in a flow of approximately 15 m^3/s (less than 7% of natural flow) being discharged from Loch Doon into Carsphairn Lane. These flows will need to be added to the natural peak flow generated by rainfall on the Water of Deugh catchment.

Scottish Power calculated flows of;

- 95.3 m^3/s at the Water of Deugh offtake (56 km^2 catchment) giving an areal flow of 1.7 $m^3/s/km^2$
- 21.3 m^3/s at the Bow Burn offtake (17 km^2 catchment) giving an areal flow of 1.25 $m^3/s/km^2$

There is a high degree of uncertainty associated with these estimates as they are based on observed water levels and standard weir equations. However, taking the higher areal flow estimate (as Water of Deugh is the main contributing catchment), this would suggest natural flows of around 127 km^2 x 1.7 $m^3/s/km^2$ = 215 m^3/s at Liggat Bridge. Added to this is 15 m^3/s for the flow discharged through Drumjohn, giving a total flow of around 230 m^3/s at Liggat Bridge.

If an areal flow rate of 1.5 $m^3/s/km^2$ is used (average of two calculated values) this gives a flow estimate of 206 m^3/s.

4.4.3 Modelling Based on FEH Rainfall-Runoff

The observed rainfall at Drumjohn, with 0.92 areal reduction factor applied (based on FEH CD-Rom Version 3) was applied to the FEH Rainfall-Runoff method using catchment characteristics for the Water of Deugh at Liggat Bridge. The model predicts a flow of 125 m^3/s and with 15 m^3/s from Loch Doon this gives a total flow of 140 m^3/s. This value appears low as it would suggest a return period of around 1 in 2 years based on the flood frequency analysis outlined above. Analysis of observed flow and rainfall data, as well as observations made by residents, would suggest a higher return period.

The calculation described above is based on standard inputs to the FEH Rainfall-Runoff model. However, some edits to these standard inputs can be justified;

- Catchment characteristics for Water of Deugh suggests a Standard Percentage Runoff during the event of around 55%. There had been considerable rain in the weeks prior to the December 2013 event, so a higher Percentage Runoff value can be justified.

Table 11: Analysis of SEPA flow gauge data and assessment of return period of 2013 event

Watercourse / Gauge location	Water of Fleet / Rusko	Water of Deugh / Newton Stewart	Water of Deugh / Minnoch Bridge	Bladnoch / Low Malzie	River Dee / Glenlochar	River Nith / Friars Carse	Cluden Water / Fiddlers Ford
Gauge no	81007	81002	81006	81004	80002	79002	79005
Grid reference	259200 559000	241250 565250	236300 574600	238150 554400	273350 564100	292350 585150	292850 579550
WIN-FAP	No	Yes	No	No	No	Yes	Yes
Max flow 30.12.2013 flood	74	290	131	125	401	713	171
[a]Flow return period	2	10	2	5	25	15	25

Watercourse / Gauge location	River Nith / Drumlanrig	Urr Water / Dalbeattie	Scar Water / Capenoch	River Stinchar / Balnowlart	River Doon / Auchendrane	Water of Luce / Airyhemming	Water of Girvan / Robstone	River Nith / Hall Bridge
Gauge no	79006	80001	79004	82003	82002	81003	82001	79003
Grid reference	285850 599350	282100 560950	284550 594050	210700 583200	233700 615950	218050 559900	221700 599650	68410 12970
WIN-FAP	Yes	Yes	Yes	Yes		Yes	Yes	No
Max flow 30.12.2013 flood	573	151	190	202	85	91	141	
[a]Flow return period	50	25	40	2	10	1	50	100

[a] *Based on GL Distribution*

Table 12: Analysis of SEPA rain gauge data and assessment of return period of 2013 event – 12-hour duration storm

Rain Gauge	Upper Black Laggan	Craigdar	Drumjohn	Eliok	Kirriereoch	Lower Black Laggan
Gauge no	115657	115541	115612	115562	115599	115612
Grid reference	247616 576885	273942 590947	252494 597541	279666 607398	236207 587069	246949 577748
2013 12-hour rain depth	71.0	65.6	59	[a]50.6 (53.6)	[a]59.6 (62.6)	[a]78.2 (79.2)
Ranking of 2013 event in AMAX series	8/31	1/26	1/12	2/13	4/26	4/32
[b]Rainfall return period – observed data	5	15	15	25	10	10
Rainfall return period – FEH CD-Rom data	5	20	10	10	10	5

a 12-hour total based on day ending at 9 am. Value in brackets is the maximum 12-hour rainfall depth for any 12 hour period during the event. A rainfall day ending at 9 am was chosen as this appears to be the default reporting time for daily totals, in the case that the gauge did not provide 15-minute totals during the day, i.e., total for day is reported in data set at 9 am.

b Based on GEV distribution on annual maxima rainfall

Figure 12: Summary of return period estimates for 2013 event, based on observed rainfall and flow data

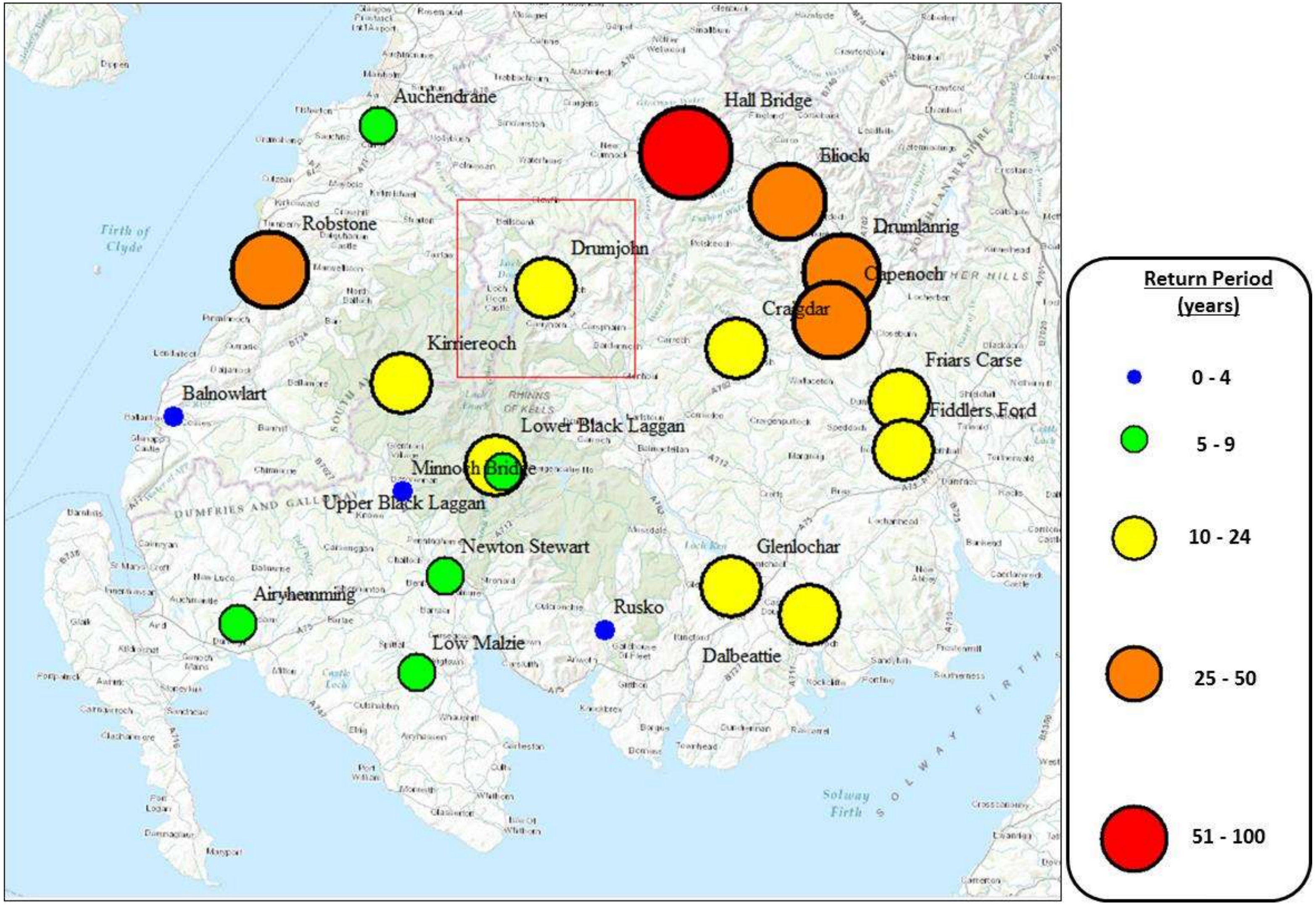
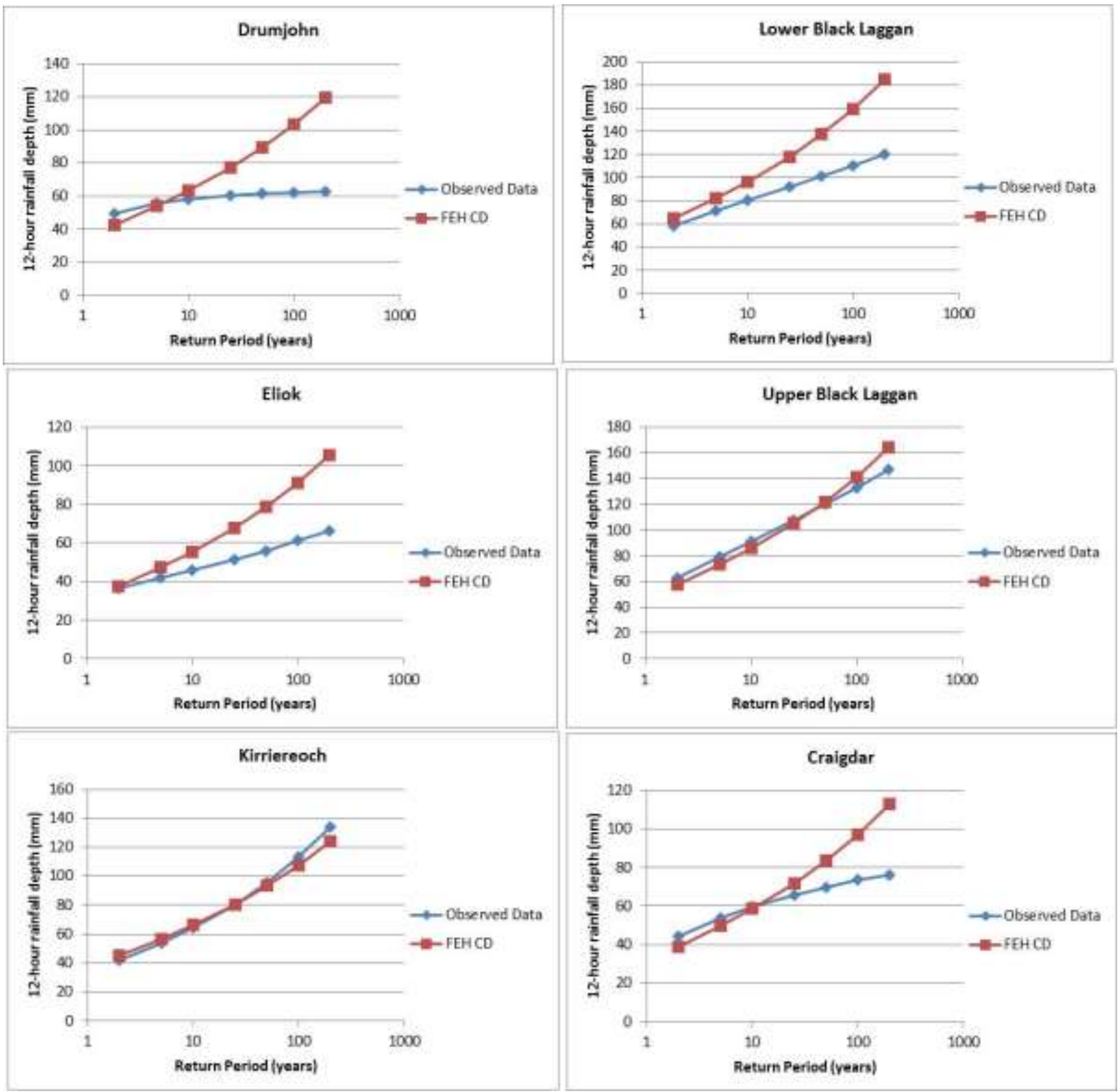


Figure 13: Comparison of return period rainfall assessments; based on observed data and data from FEH CD-Rom



Drumjohn rainfall station is at around 231 m AOD. However, much of the headwaters of Water of Deugh lies at a higher elevation than the rain gauge site, with topography shown in Figure 14. At Liggat Bridge the catchment has elevations ranging from 170 m AOD to 800 m AOD, with an average elevation of 384 m AOD. As rainfall is expected to increase with elevation, this information suggests that the recorded rainfall at Drumjohn may need to be increased to provide an appropriate total for the whole Water of Deugh catchment. The approach taken was to compare the 50 year, 12 hour storm durations from the FEH CD-Rom Version 3 at Drumjohn (point location) and the full catchment at Liggat Bridge. The value at Drumjohn is 89.2 mm, with the corresponding value 88.5 mm (with areal reduction factor) for the catchment at Liggat Bridge. This analysis does not suggest a basis for an increase in rainfall depths for the catchment at Liggat Bridge, but does suggest that rainfall at Drumjohn can be applied to the catchment without an areal reduction factor, i.e., one-to-one relationship between observed rainfall at the gauge and rainfall for the catchment.

An attempt was made to calibrate the FEH Rainfall-Runoff model for the Water of Deugh catchment at the Deugh offtake. As outlined above Scottish Power estimated peak flows at the offtake in December 2013 to be around 95 m^3/s. An FEH Rainfall-Runoff model was set up using observed rainfall at Drumjohn (no areal reduction factor) and adjusting the Percentage Runoff until a peak flow close to the observed flow was obtained. Simulation indicated that a Percentage Runoff of 95% would produce a flow of 91 m^3/s, based on observed rainfall at Drumjohn.

A value of 95% Percentage Runoff is a very high value for natural catchments; however, taking this value and running the full Water of Deugh catchment at Liggat Bridge for unadjusted Drumjohn rainfall and a Percentage Runoff of 95% gives a flow of 200 m^3/s for the observed rainfall. Flows for other Percentage Runoff values are; 90%, 190 m^3/s; 85% 180 m^3/s, 80%, 170 m^3/s.

Model output graphs are shown in Figure 15.

The flow from Loch Doon during the event was 15 m^3/s, which needs to be added to the flow estimates from the FEH Rainfall-Runoff model. This would suggest a flow at Liggat Bridge during the December 2013 event of between 185 – 215 m^3/s.

Figure 14: Topography of Water of Deugh catchment, showing location of Drumjohn gauge

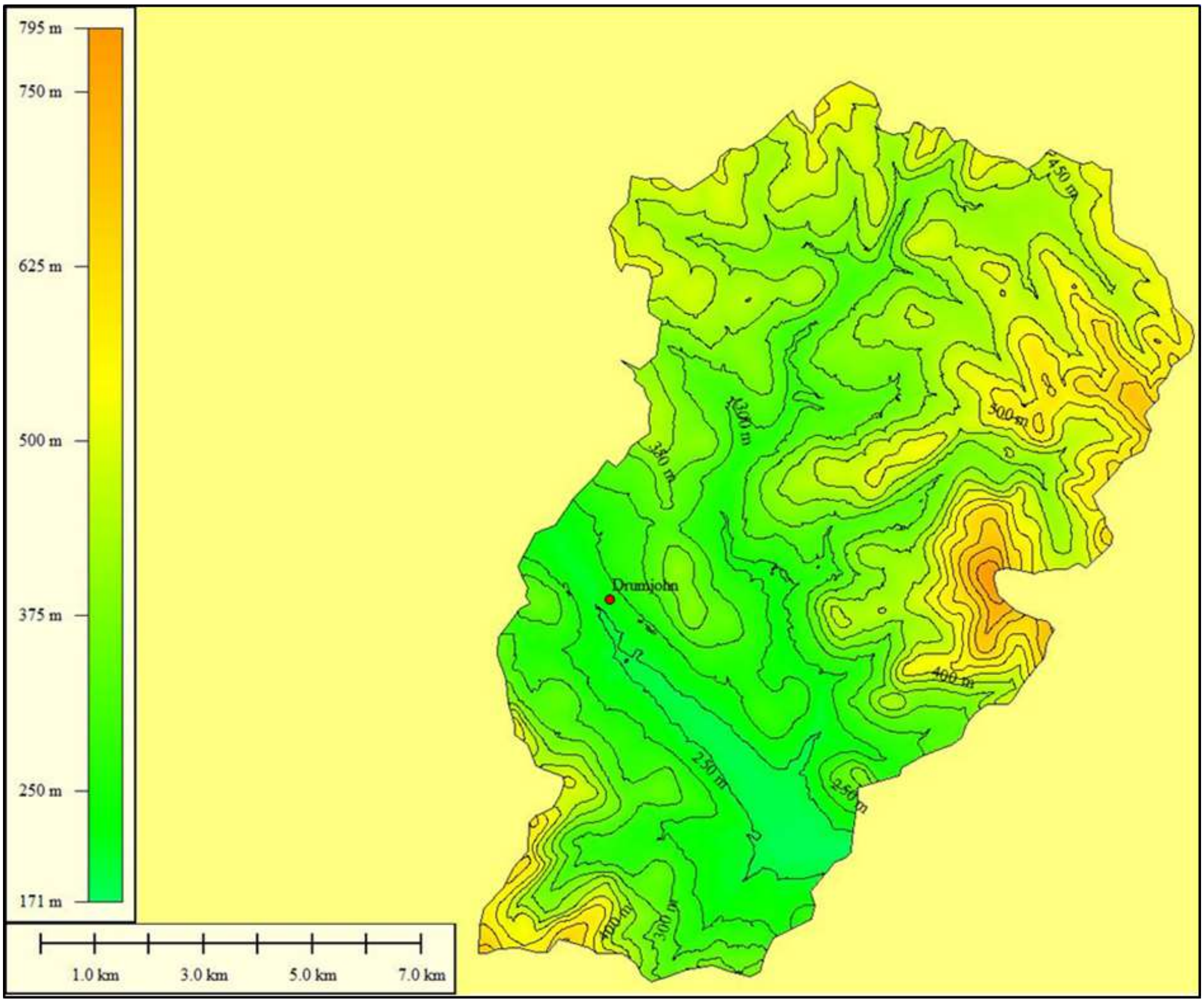
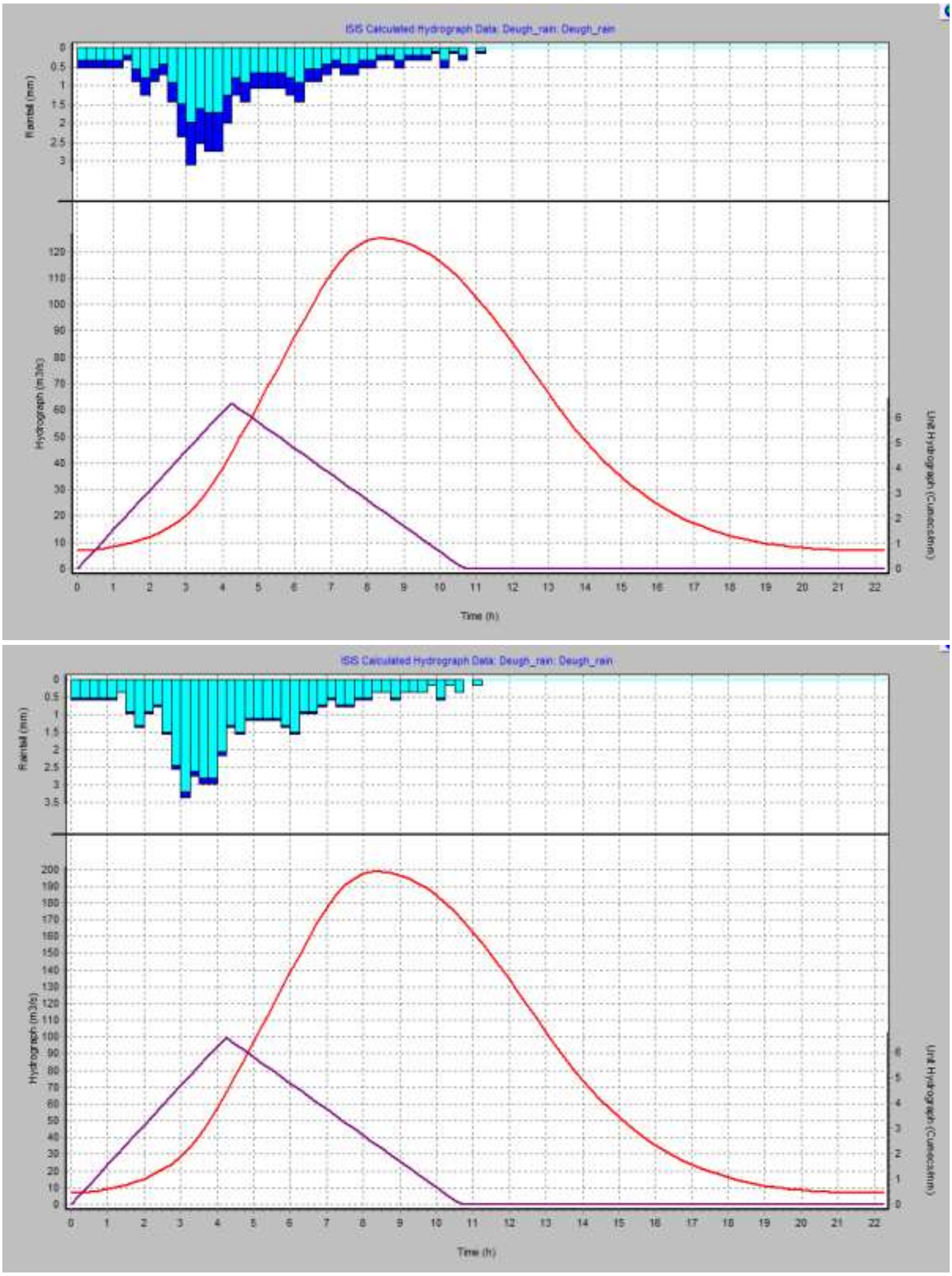


Figure 15: Modelled flows for December 2013 using FEH Rainfall-Runoff Model. Top; Un-calibrated model. Bottom; Model with Adjusted Parameters



4.4.4 Modelling Based on ISIS1D/2D Model

The ISIS1D/2D model of Carsphairn was calibrated for the December 2013 event. Full details of the model calibration are provided in Section 5.4. The results of this assessment were that the best fit to observed flood level and inundation extent data within Carsphairn were obtained for;

- A flow of around 190 m^3/s on Water of Deugh downstream of Carsphairn Lane
- A flow of around 205 m^3/s on Water of Deugh at Liggat Bridge. This flow is impacted by attenuation due to flooding within Carsphairn and surrounding floodplains. The attenuation predicted by the 2D model is likely more than would be considered by standard hydrological methods (e.g., FEH Pooling Group or FEH Rainfall-Runoff model). Hence, in order to compare flows with those generated by the Pooling Group or other methods, the total flow at Liggat Bridge (assuming no attenuation) would be around 230 m^3/s.

4.4.5 Summary and Conclusions for 2013 Event

Based on work to date, a range of flow estimates are obtained for the 2013 event;

- Analysis of observed rainfall and flow data during the December 2013 event from gauges across Dumfries and Galloway indicated that the event in the Carsphairn area might have a return period of between 1 in 25 and 1 in 50 years.
- Scottish Power flow calculations based on water levels at their offtake structures gives a flow of 206 - 230 m^3/s. This would be consistent with a return period of around 1 in 10 to 1 in 25 years at Liggat Bridge
- Running FEH Rainfall-Runoff models produces an estimate of 170 - 200 m^3/s at Liggat Bridge This would be consistent with a return period of around 1 in 5 to 1 in 10 years at Liggat Bridge
- Initial review of flood flow predictions suggests a flow of around 190 m^3/s in Water of Deugh downstream of Carsphairn Lane, equivalent to a return period of around 1 in 20 years from Table 6. Downstream of the village at Liggat Bridge the equivalent total flow was predicted to be around 230 m^3/s, which is equivalent to a 1 in 25 year event at this location, based on Table 6.

Based on the information presented above it would appear that the December 2013 event had a peak flow of around 210 to 230 m^3/s at Liggat Bridge downstream of Carsphairn. This event had a return period in excess of 1 in 10 years and which was unlikely to be more than 1 in 50 years. Our best estimate of the return period of the event is 1 in 25 years.

4.4.6 Summary of Final Design Flows and Model Flow Scenarios

In order to run mathematical models used to predict flood levels in Carsphairn, design flow hydrographs need to be defined for the inflow model boundaries, namely:

- Water of Deugh just upstream of Carsphairn;
- Carsphairn Lane at the confluence with Water of Deugh;
- Garryhorn Burn at the confluence with Water of Deugh; and
- Green head Strand upstream of Carsphairn.

Where possible inflow hydrographs are derived using recorded data; however, as there are no flow gauges close to the village, design flow hydrographs were derived using FEH Rainfall-Runoff model which were scaled to produce the required peak flow calculated in Section 4.3.1.

As described above there are three main inflows into the model. Each catchment has different characteristics in terms of area and flow pathways. It is unlikely that the maximum flow in all three catchments would occur at the same time. As a result, the FEH Rainfall-Runoff model was run to derive a hydrograph shape at the downstream of the town at Liggat Bridge. The flows have then been apportioned based on the ratio of the individual catchment versus the catchment at Liggat Bridge, see Table 13 for a tabulated list of peak inflows to the model. All flows within the model have been synchronised so that the peaks occur at the same time.

Table 13: Summary of peak model inflows

Return Period (years)	Total Flow (m^3/s)	Deugh U/S Carsphairn (m^3/s)	Carsphairn Lane, Confluence (m^3/s)	Garryhorn Burn, Confluence (m^3/s)	Green head Strand (m^3/s)
2	140	95	25	15	<5
5	175	120	30	20	<5
10	200	140	35	25	<5
25	235	165	40	25	<5
50	265	185	45	30	<5
100	295	205	50	35	<5
200	330	230	60	35	5
200+CC	395	275	70	45	5

5 Mathematical Modelling

5.1 Overview

A 1D/2D linked modelling approach using the ISIS 1D/2D mathematical modelling package has been used to predict the flood extent within the study area. This model predicts channel flow using a 1D river model based on ISIS 1D and floodplain flows based on two-dimensional representation of overland flows based on ISIS 2D. This is the standard way of modelling river systems with large floodplains, as is the case in Carsphairn.

5.2 1D Model Set-up

5.2.1 Survey

MH Surveyors Ltd. was commissioned to undertake a comprehensive river channel survey of watercourses within the study area. The survey included channel cross-sections and hydraulic structures (i.e. bridges, culverts) throughout the study area and selected floodplain areas within the village, as described below:

Water of Deugh:

- In total 24 river channel cross-sections were surveyed within the wider study area;
- Survey of Liggat Bridge structure; and
- Survey of sediment bar upstream of Liggat Bridge.

Garryhorn Burn:

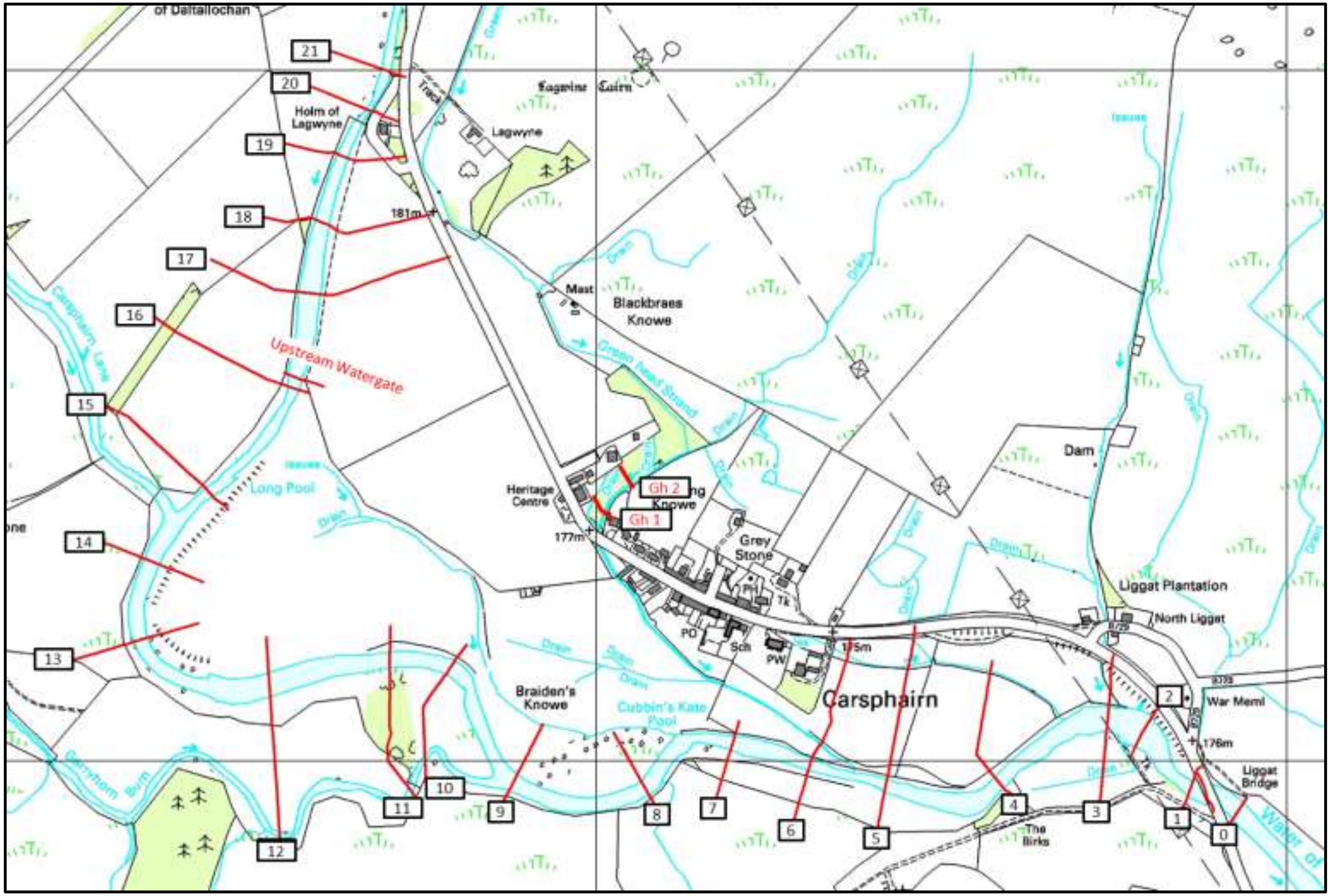
- 4 channel cross-sections of the Garryhorn Burn surveyed in the study area;

Green head Strand:

- 2 channel cross-sections of Green head Strand were surveyed in the study area (a number other sections were attempted but could not be surveyed due to dense vegetation);
- Culvert details under the A713; and
- Bypass culvert details under A713.

The locations of surveyed cross-sections are provided in Figure 16.

Figure 16: Location of surveyed cross-sections (Garryhorn sections included within Deugh sections 12 to 9)



5.2.2 Structures

Two structures have been included in the 1D model; Liggat Bridge and the Green head Strand culverts under the A713 (as well as Watergates):

- Liggat Bridge – is a concrete road bridge spanning the entire channel. The soffit of the bridge is elevated significantly above the bed of the channel and would not cause an impediment to flows within the channel. The bridge is supported by one large concrete pier measuring approximately 5.3 m wide and has also been included in the model.
- Culverts under A713 – Dimensions for two 1.2 m diameter culverts and two rectangular bypass culverts A713 have been surveyed. The locations of the four culverts are shown in Figure 17.
- Watergates: Within the ISIS mathematical modelling software there is no unit to represent a watergate, hence a ISIS blockage unit has been used to represent the obstruction which the gate would cause. It was estimated that a 5% blockage to the available flow area would provide a conservative representation of the gate within the model.

5.2.3 Friction

Following a number of site visits it was noted that the main channel was relatively flat and wide with no significant vegetation causing obstructions on the banks, as a result a Manning's n roughness value of 0.045 was used for the main channel which is likely to be on the conservative side. A roughness value 0.045 was used for floodplains and embankments.

5.2.4 Green head Strand

Due to significant vegetation within the Green head Strand during the channel survey, it was only possible to survey two cross-sections upstream of the A713. Initial 2D modelling results indicated that flood waters could enter the upper reaches of the channel and flow towards the A713. A number of additional cross-sections have been interpolated along the upstream line of the channel using available Nextmap2 topographical data (based on aerial topography). As a result, cross-sections in this area are not as detailed as they would have been following ground survey; however; it provides a vehicle for floodwaters entering the upper reaches of the Strand to flow to reach the village.

5.2.5 Tributaries

The Carsphairn Lane has been included into the model as inflow boundary only, as it is some distance away from the areas of interest. The lower part of the Garryhorn Burn is included in the 1D model using the surveyed 4 channel sections. Due to the distance these tributaries are away from the village, extensive survey of either channel upstream of their junctions has not been undertaken.

5.2.6 Downstream Boundary

The furthest downstream section surveyed as part of this study is at the upstream face of Liggat Bridge. For modelling purposes, this section has been copied approximately 200m downstream of the bridge and bed level lowered by 1 m. This allowed the bridge being represented in the model. A normal depth boundary was used at this new downstream section with water level gradient set to the average bed gradient in the area based on surveyed cross-sections.

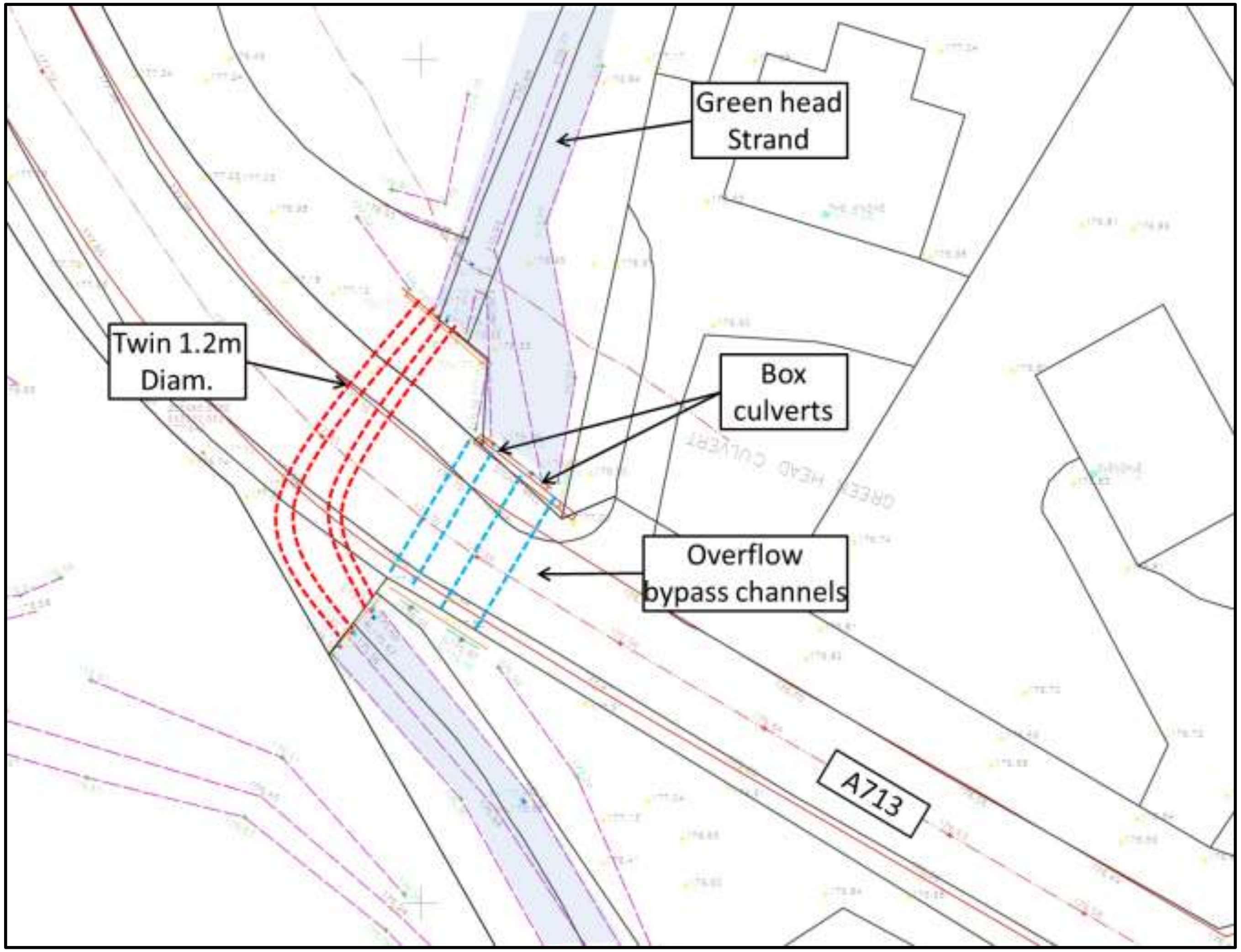
5.2.7 1D Model Parameters

A summary of model parameters are provided in Table 14 below.

Table 14: 1D model parameters

Model Parameter	Value used
Main channel roughness (Manning's n)	0.045
Bridge section roughness (Manning's n)	0.045
Culvert Roughness (Manning's)	0.012
Green head Strand overtopping discharge coefficient:	0.9
2D model linkages coefficient	1
Upstream flow	Hydrographs based on FEH Rainfall-Runoff method adjusted to match adopted design flows
Downstream boundary	Normal depth based on average channel gradient

Figure 17: Survey of Green head Strand culvert



5.3 2D Modelling

5.3.1 Survey

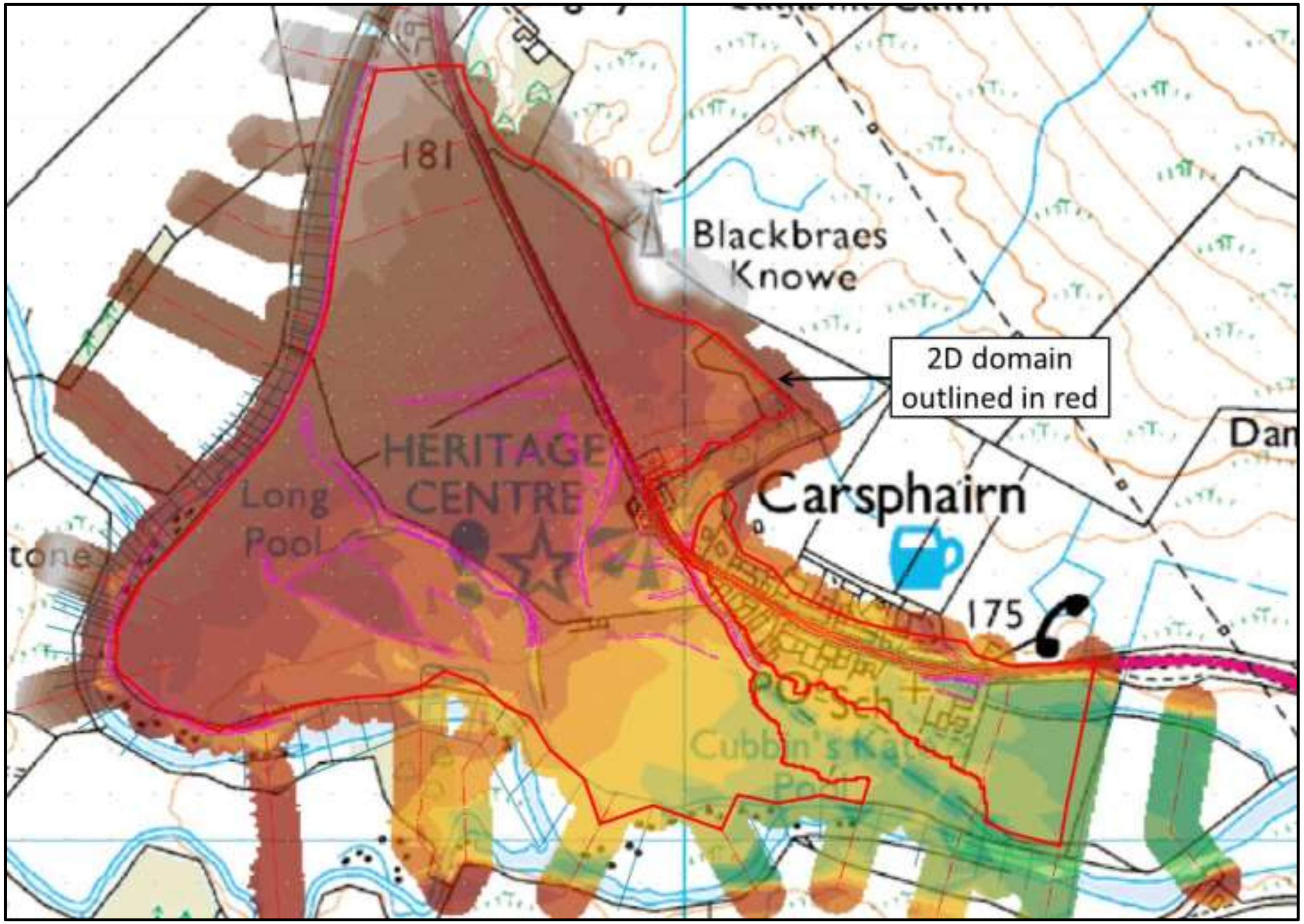
Following the 2013 flood event and discussions with local residents, an extensive topographical spot level survey was undertaken within the study area. The survey covered the river floodplains to the west of the town. The survey was more detailed in areas of known flood paths, where there are rapid changes in elevation and where there are flood embankments. There was less detail in areas of flatter ground. This approach is standard in areas where there are large floodplains with no detailed LiDAR coverage.

5.3.2 2D Model Domain

The cross-sections for the left bank of the Deugh are truncated at bank top locations which have been dynamically liked to the 2D domain through a designated boundary condition ('link line'). Water levels in the 1D domain, exceeding the bank top levels, are passed into the 2D domain which is constructed based on a DTM of the surrounding floodplain. Flood waters are able to exchange between domains (i.e. river channel and floodplain), with conservation of mass between the domains. However, cross-sections for the Deugh right bank and for the Garryhorn Burn have been extended so that flood waters remain within the 1D domain.

The extent of 2D domain is shown in Figure 18.

Figure 18: 2D model domain



5.3.3 2D Linkages

Flood waters leaving the 1D domain are able to enter the 2D domain via spills ("link lines") which have been positioned at bank top locations, or high points between the channel and floodplain areas. Where detailed overtopping levels have been surveyed the link lines were specified based on the surveyed levels. However, where there is no detailed survey information, the overtopping levels have been determined by the generated DTM grid. Details of the ground survey information along river embankments are shown in Figure 19.

5.3.4 Friction

Ordnance Survey Mastermap vector data of the floodplain areas were obtained for the study area. This shows land use type which allowed a friction map to be developed assigning friction values to different areas of the floodplain. Table 15 below shows the different friction values used for each different grid attribute.

Table 15: 2D model friction values

Surface	Roughness value (manning's n)
General Building	0.5
Road	0.025
Wooded Area	0.1
General Surface	0.033
Inland Water	0.03

Due to the number of terraced housing within Carsphairn and the effect the individual structures will have on floodplain flows, buildings have been rendered impermeable with flood waters unable to pass through the buildings. In addition, dry walls such as the boundary wall located at the boundary of "The Knowe" Bed and Breakfast has also been set as impermeable. However masonry field boundaries on the southern floodplain area have not been rendered impermeable.

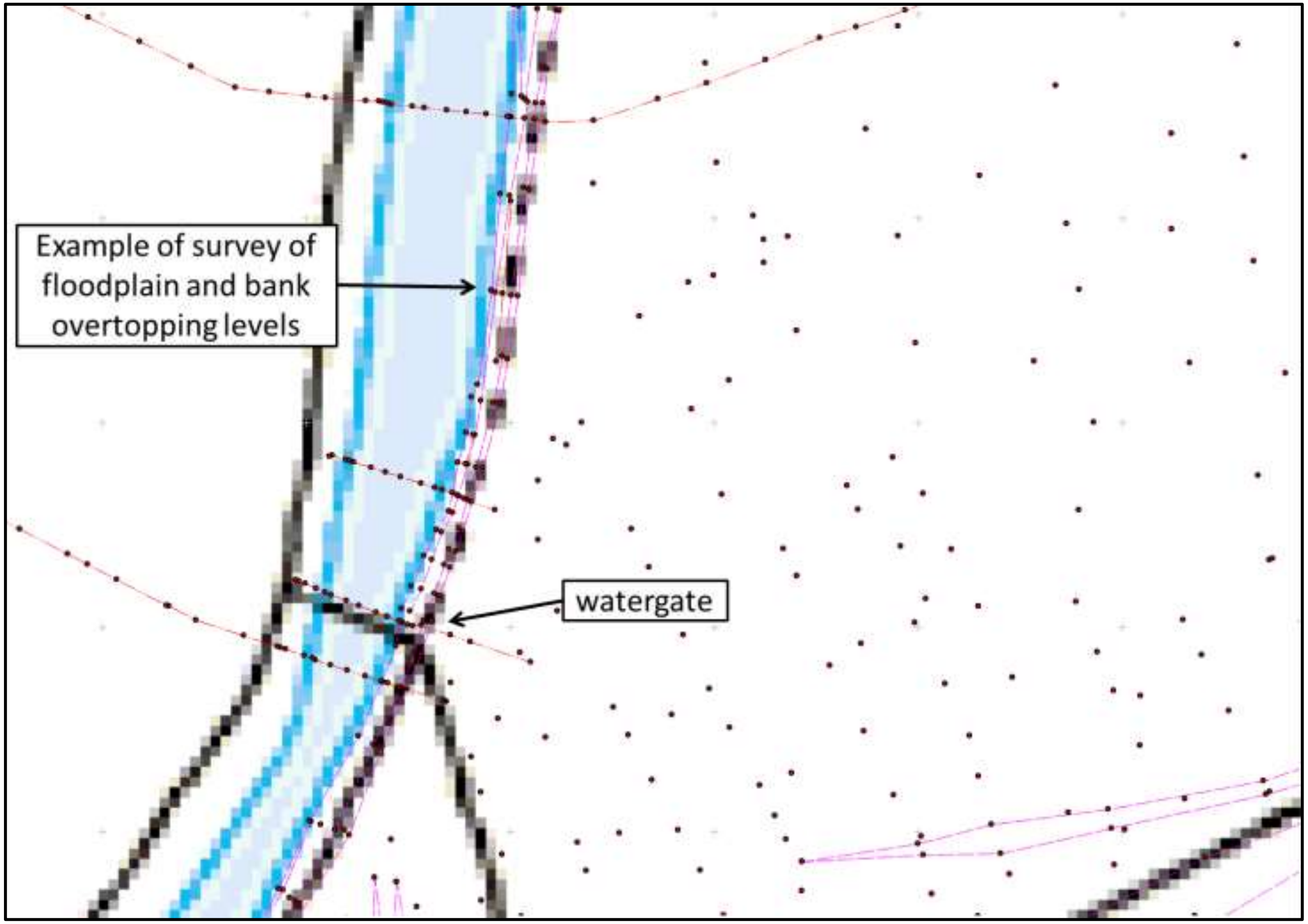
General surface areas assumed to be the areas with short grass or earth with little or no vegetation.

5.3.5 2D Boundaries

Flood waters leaving the 1D domain can enter the 2D domain through link lines (spills) located at overtopping locations throughout the village. Other than spills from the 1D model, there are no other additional inflows into the 2D domain.

The downstream boundary of the 2D domain was set to water level at section 5 (Figure 16). This allows backwatering effect to be taken into account in both 1D and 2D models.

Figure 19: Model survey at river banks and watergate



5.4 Model Calibration

Mathematical models of this nature are normally calibrated against historical flood data where there is sufficient and reliable historical flow and water level data available. This involves comparison of model predicted water levels/flows and observed water level and flood data. Calibration is carried out by adjusting physical parameters within the model which have been estimated based on standard methods, i.e., river channel friction values, spill coefficients, etc. The model is re-run with different parameters until a reasonable agreement is obtained with recorded/observed water levels and flood extents, making sure that model parameters stay within acceptable limits.

For most modelling studies calibration is not possible given a lack of historical information to compare against model predictions. However, for this study it was possible to compare model flood predictions against data obtained during the December 2013 event.

The key hydraulic calibration parameters used to calibrate the model included:

- Manning's "n" values for river channel and floodplain (2D domain);
- Coefficients for spill units;
- Discharge co-efficient including weirs;
- Changes to building representation; and
- Changes to downstream boundaries.

5.4.1 2013 Calibration Event

The largest flood event in Carsphairn in recent years occurred on 30th December 2013, which caused flooding of some properties including the main street. The event is documented in Section 2.3. Anecdotal and photographic information were used in conjunction with the topographic survey information of the study area to identify the approximate maximum flood extent, peak flood level and key flood flow pathways.

As described in Section 4.4 above, the December 2013 event was considered to be comparable to a 1 in 25 year return period event and provided a reasonable size event for calibration purposes. The peak flow rate used in model calibration for this event was 190 m^3/s on Water of Deugh, downstream of Carsphairn Lane.

Table 16 provides a comparison of observed and predicted water levels during the December 2013 event. The results show that the model predicts water levels well within the uncertainty of observations and the model grid. The uncertainty associated with observations is expected to be around ±0.05 m. As the model grid is made up of 5 m square cells, the ground level in each cell will be an average of surrounding levels. Hence, the error in ground levels might be around ±0.05 m to ±0.1 m. As a result, model results within ±0.1 m are considered reasonable.

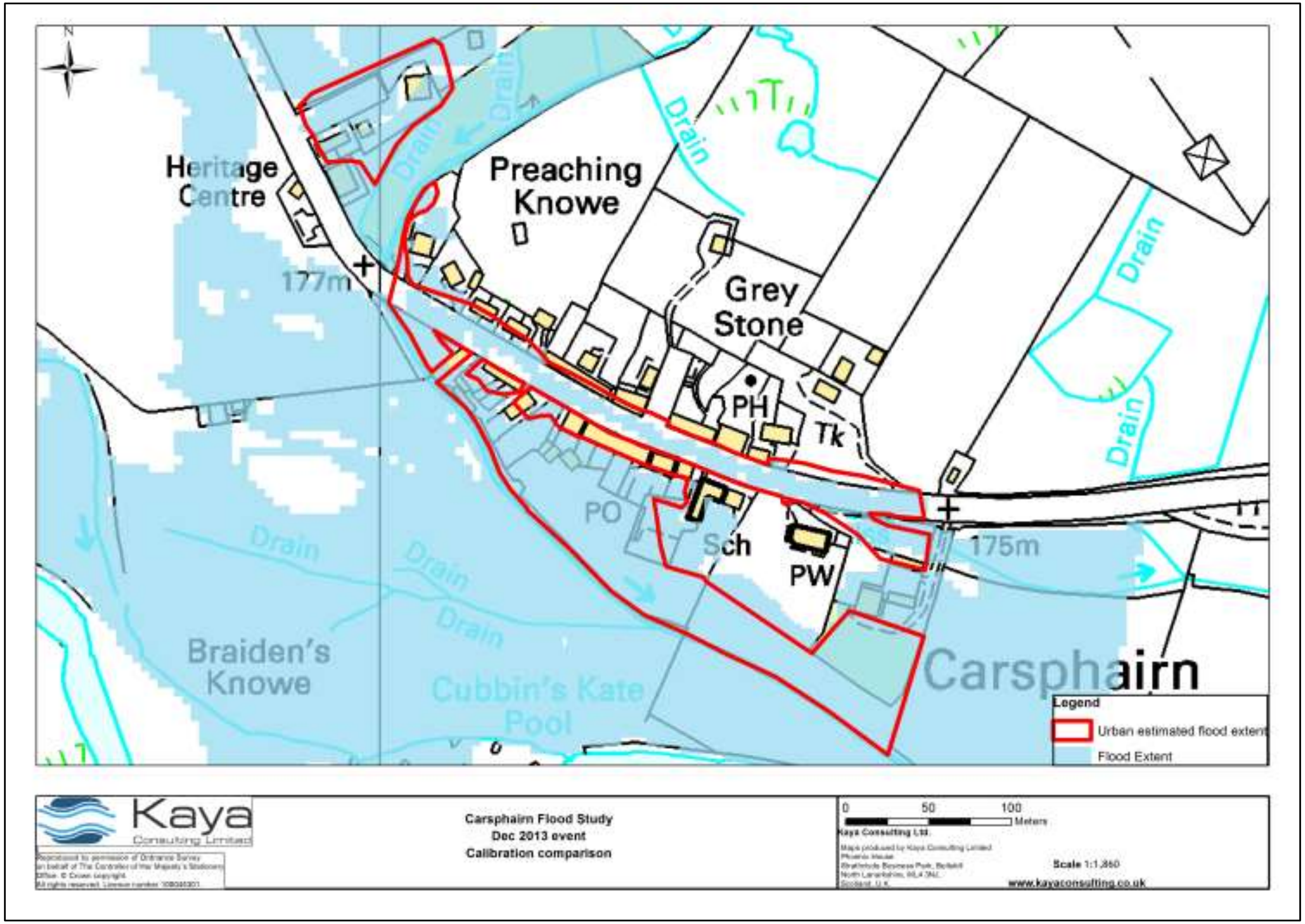
The modelled maximum flood extent for the December 2013 event was compared with the observed flood extent in Figure 20. The model predictions are very similar to the observed extent within the village. The model shows flooding of the main road and buildings to the north and south of the road, as well as land to the east of the village. The model appears to over-predict flooding of gardens of properties to the south of the main road, but there are uncertainties with the observed flood extent in this area, and there may have been flooding in other areas not shown in Figure 20, particularly those areas difficult to see from the properties and main road. Overall, the results are considered reasonable, at least within the urban area.

Based on comparisons of observed and modelled flood levels and flood extents for the December 2013 event, the model is considered to give a reasonable comparison with observed flood depths, inundation extent and flooding mechanisms. However, model calibration is limited by the extent and quality of data and by the lack of independent measurements of the flood flow in the river adjacent to Carsphairn, but compared to many other modelling studies these results are considered good and gives confidence in the ability of the model to predict flooding within the village. Model predictions could possibly be improved if LiDAR data covering all floodplain areas was available.

Table 16: Model results compared against photographic evidence and anecdotal evidence

Location	Ground Level (m AOD)	Approximate 2013 Flood depth (m)	Modelled flood depth (m)	Difference Modelled and Observed (m)
Greenhead Cottage	176.54	~0.3	0.3	<0.05
Greenhead Mains	176.57	~0.3	0.3	<0.05
Ellenslea	175.58	~0.4	0.4	<0.05
Greystones/Kirklee	175.08	~0.5	0.4	-0.1

Figure 20: Predicted flood extent vs estimated 2013 flood extent (2D domain only)



5.5 Model Runs for Return Period Flood Events

The calibrated 1D-2D linked model of the Water of Deugh and its tributaries was run for a range of return period flows, including a run with the effect of climate change and the December 2013 event. Model runs undertaken and peak flows assumed for each run are summarised in Table 17.

Table 17: Modelled Scenarios (flows rounded to nearest 5m^3/s)

Run No.	Scenario	Peak flow in Water of Deugh (m^3/s)	Peak Flow in Carsphairn Lane (m^3/s)	Peak Flow in Garryhorn Burn (m^3/s)	Peak Flow in Green head Strand (m^3/s)
1	Q2	95	25	15	<5
2	Q5	120	30	20	<5
3	Q10	140	35	25	<5
4	Q25	165	40	25	<5
5	Q50	185	45	30	<5
6	Q100	205	50	35	<5
7	Q200	230	60	35	5
8	Q200+CC	275	70	45	5
9	Q1000	300	75	50	5
10	Q Dec 2013 event	150	40	35	5

(Q200: 200 year flow; CC: climate change)

5.6 Model Results – Base Case Condition

The model results at selected cross-sections and for all return periods are provided in Table 18, whilst detailed flood maps are provided in Appendix B. A detailed description of flood mechanisms for the 1 in 200 year event is described below.

Model results summarised in Table 18 and Figures 36 to 44 presented in Appendix B indicate that if during the December 2013 event there was no discharge from Drumjohn station, the return period of the event would be reduced to of the order of 1 in 10 years and there would still be flooding in Carsphairn as shown in Figure 38.

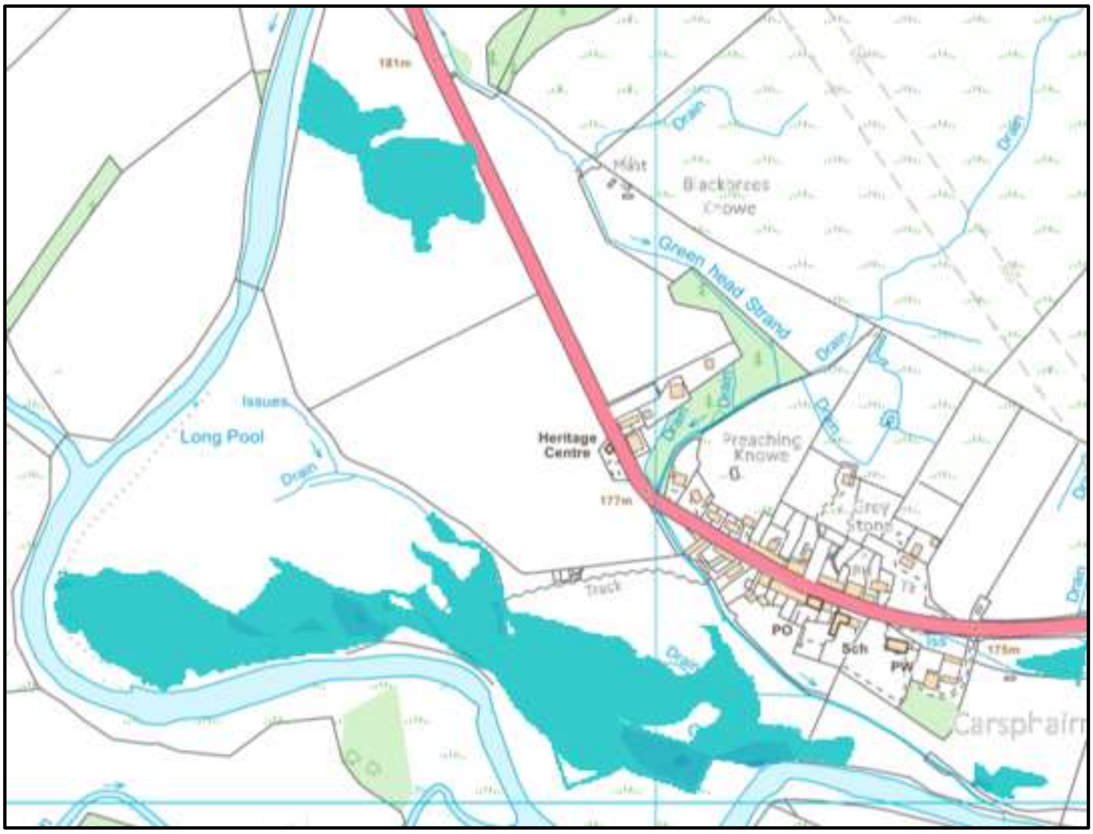
Table 18: Model Results for Water of Deugh; Base Case

Cross-section	Run 1: Q2	Run 2:Q5	Run 3: Q10	Run 4: Q25	Run 5: Q50	Run 6: Q100	Run 7: Q200	Run 8: Q200+ CC	Run 9: Q1000
SEC_21	183.6	184.0	184.2	184.5	184.7	184.8	185.1	185.2	185.2
SEC_20	183.2	183.5	183.7	183.9	184.1	184.2	184.4	184.7	184.8
SEC_19	182.9	183.1	183.2	183.3	183.4	183.4	183.5	183.6	183.6
SEC_18	182.4	182.6	182.6	182.7	182.7	182.7	182.8	182.9	182.9
SEC_17	181.9	182.1	182.2	182.3	182.3	182.3	182.4	182.5	182.5
US_GATE	181.2	181.4	181.5	181.5	181.6	181.6	181.6	181.7	181.7
GATE	181.0	181.1	181.1	181.2	181.2	181.2	181.3	181.3	181.3
US_LANE	179.8	180.0	180.1	180.3	180.3	180.4	180.5	180.5	180.6
SEC_16	181.0	181.1	181.2	181.2	181.2	181.3	181.3	181.3	181.3
SEC_15	179.9	180.1	180.2	180.3	180.4	180.4	180.5	180.6	180.6
SEC_14	179.6	179.8	179.8	180.0	180.0	180.1	180.1	180.2	180.2
SEC_13	178.8	178.9	179.0	179.1	179.1	179.1	179.1	179.2	179.2
SEC_12	178.2	178.3	178.4	178.4	178.4	178.5	178.5	178.5	178.5
SEC_11	177.5	177.6	177.6	177.7	177.7	177.7	177.8	177.8	177.8
SEC_10	177.0	177.1	177.1	177.2	177.2	177.2	177.3	177.3	177.3
SEC_9	176.1	176.3	176.4	176.4	176.5	176.6	176.6	176.7	176.8
GARRY_9	176.1	176.3	176.4	176.4	176.5	176.6	176.6	176.7	176.8
SEC_8	175.9	176.0	176.2	176.2	176.2	176.3	176.4	176.5	176.6
SEC_7	175.3	175.4	175.6	175.6	175.7	175.8	175.8	175.9	176.0
SEC_6	174.9	175.0	175.2	175.2	175.2	175.3	175.4	175.5	175.5
SEC_5	174.0	174.2	174.5	174.5	174.6	174.7	174.8	175.0	175.1
SEC_4	173.8	174.1	174.3	174.3	174.4	174.5	174.6	174.8	174.9
SEC_3	172.8	173.0	173.3	173.3	173.5	173.7	173.8	174.1	174.3
SAND_BAR	172.4	172.6	173.0	173.0	173.1	173.3	173.5	173.9	174.0
SEC_2	171.2	171.5	171.9	171.9	172.1	172.3	172.5	172.9	173.1
US_BRIDGE	171.3	171.7	172.2	172.2	172.4	172.7	172.9	173.3	173.5
SEC_1	170.0	170.3	170.7	170.7	170.9	171.1	171.2	171.5	171.6
SEC_0	169.0	169.3	169.7	169.7	169.9	170.1	170.2	170.5	170.6
G10	176.4	176.9	178.1	177.5	177.6	177.9	178.0	178.1	178.2
G9	176.3	176.9	178.1	177.4	177.6	177.8	177.9	178.1	178.1

5.6.1 Flooding Mechanisms in Carsphairn

As flood levels rise, the model predicts that the earliest overtopping of the Water of Deugh channel will occur in the fields to the south-west of the village. The fields are low lying and do not benefit from any significant flood defences on the left bank of the river (looking downstream), see Figure 21.

Figure 21: Flooding mechanism, early in flood event



As the flood event develops (around 7 hours after the beginning of flooding) flood waters begin to overtop the left hand bank of the channel, a short distance downstream of Holm of Lagwyne Farm, Figure 21. Observations suggested that flooding from the Deugh initially occurs immediately upstream of the existing watergate located between Carsphairn Lane confluence and Holm of Lagwyne Farm. Modelling suggests that although the watergate has some influence on flood levels (the model considered a 5% blockage of the channel at the watergate), the key driver of flooding is the low banks to the north of the watergate. A detailed bank overtopping survey was undertaken of the left bank of the river between the Green head Strand confluence and the Holm of Lagwyne Farm. As a result, confidence of overtopping levels within the model in this location is high.

The model does not represent the floodplain on the right bank of the river as accurately as the left bank, as the right bank was not surveyed in detail. It is likely that this results in more conservative (higher) predictions of flooding in Carsphairn, with more water passing to the east within the model.

Flood waters overtopping the left bank of the Deugh flow towards low lying areas on the floodplain before reaching and overtopping the A713. From this location flood waters are predicted to enter the Green head Strand close to Blackbraes Knowe, Figure 22.

At this stage in the flood event, flood waters are predicted to have overtopped small embankments close to the confluence with the Green head Strand and a small drain which drains surface water from the A713 to the east of the church. Flood waters overtopping the A713 and entering the Green head Strand are predicted to cause surcharging upstream of the A713 culvert. Flood waters overtopping the culvert pass on to the A713 close to Knowe B&B, before flowing south-east through the village, Figure

23. Additional flow paths were also noted with flood waters entering the Green head Strand downstream of the A713 causing overtopping with flood waters entering back gardens of properties.

The predicted 200 year flood extent is shown in Figure 24.

Figure 22: Flooding mechanism – flood event developing

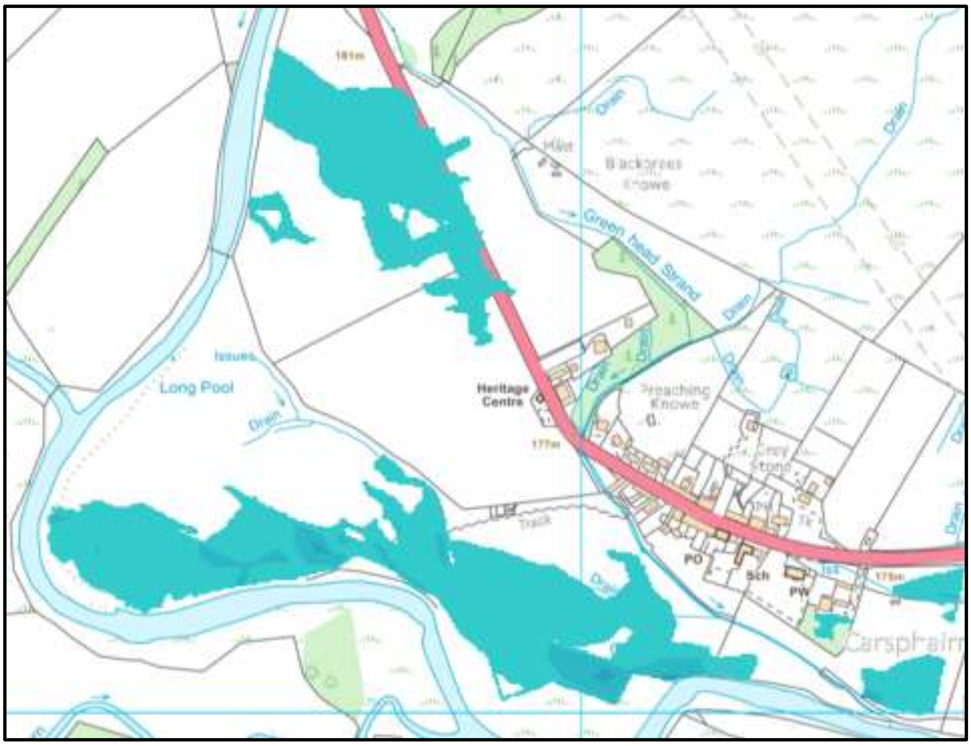


Figure 23: Flooding mechanism – flooding of village

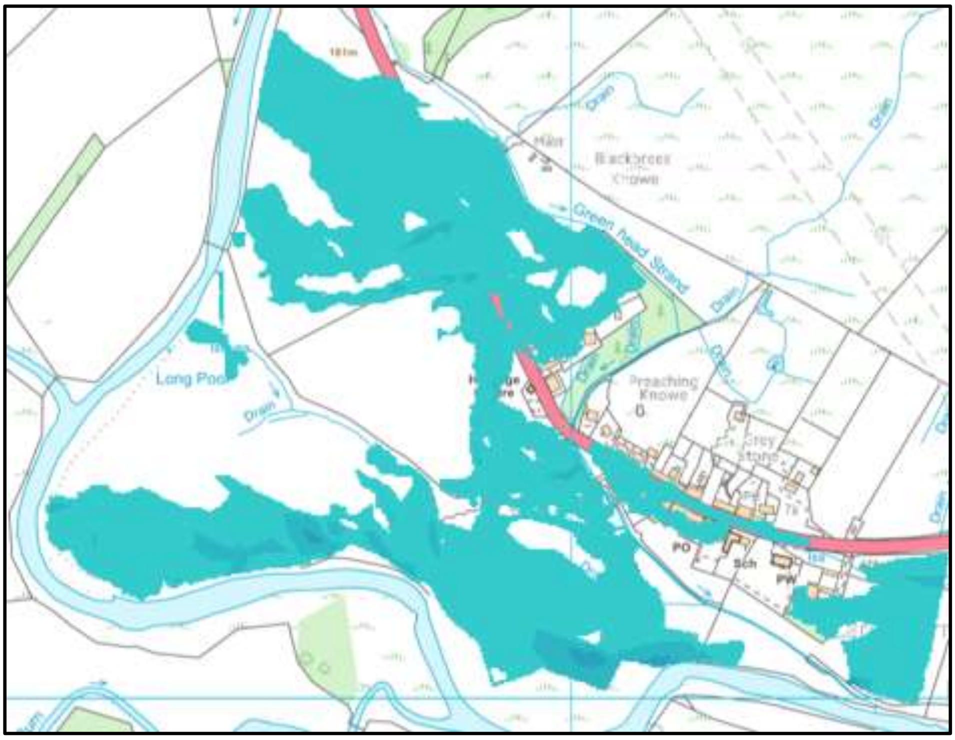
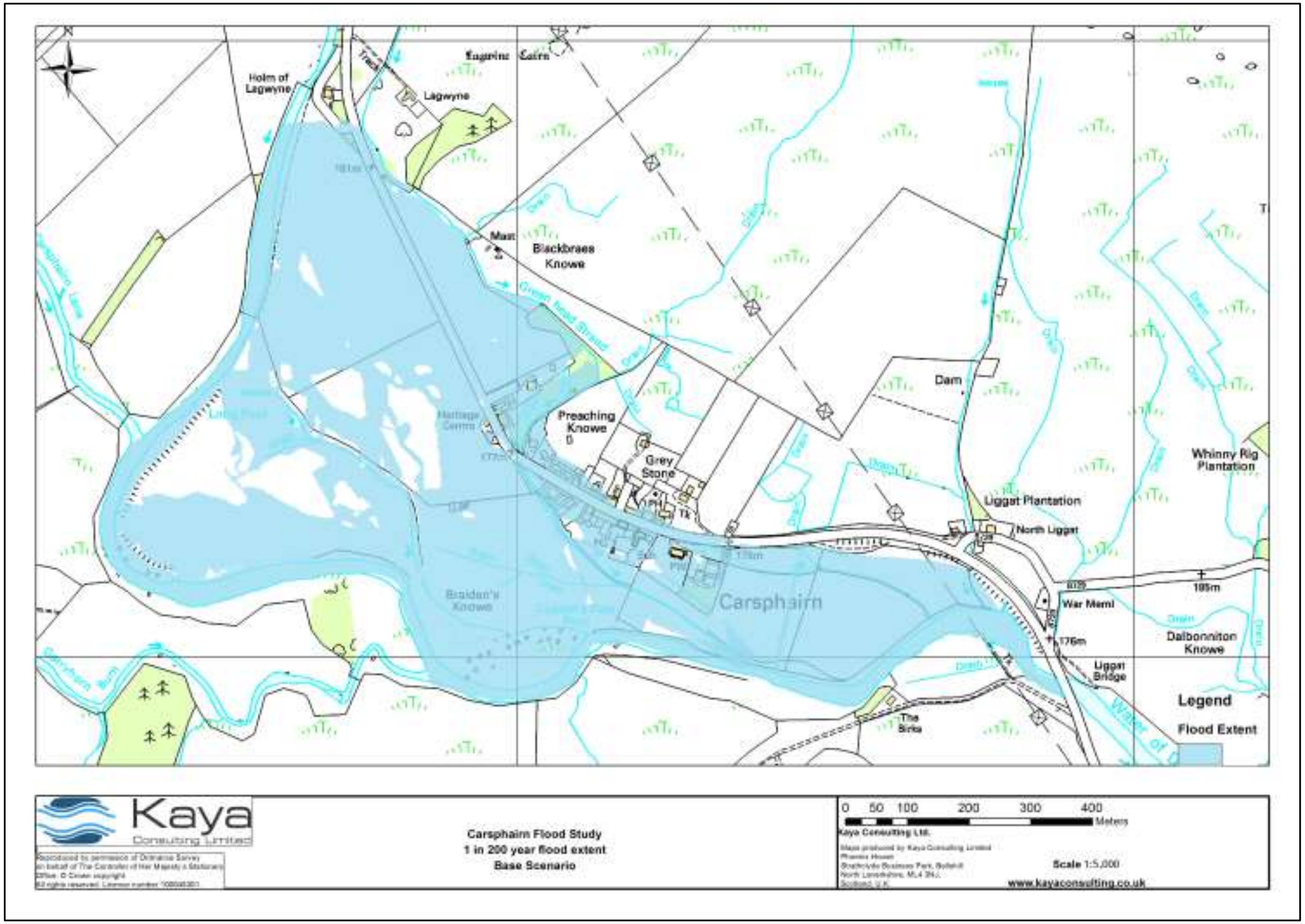


Figure 24: 1 in 200 year event flood map (Base Scenario)



5.7 Sensitivity Analysis

A model sensitivity analysis provides an illustration of the effects of changing key model parameters on the important model outputs (in our case flood levels). By re-running the model, changing one input parameter at a time, the effect of that input on the model results can be isolated. Repeating this process to account for several model parameters of interest within the range of their possible input values, gives a sensitivity analysis that, when compared with the model assumptions and knowledge of realistic inputs, can provide an indication of the uncertainty associated with the model predictions.

The sensitivity analysis considers changes in Manning's n roughness coefficient, 25% and 50% blockage to Liggat Bridge, 25% blockage to the watergate and change to downstream normal depth boundary. The sensitivity runs undertaken are summarised in Table 19. Results from these runs were compared to the 'base case' 200 year flow model run (Run 7 in Table 18) and are presented below.

Table 19: Sensitivity Analysis Scenarios

Scenario no.	Change to model
S1	Manning's n increased by 20%
S2	Manning's n decreased by 20%
S3	Liggat Bridge blocked 25%
S4	Liggat Bridge blocked 50%
S5	Watergate blocked 25%
S6	Downstream boundary decreased by factor of 10

Roughness: Model roughness values were adjusted by (+/-)20% from design values summarised above. This produced a change in peak water levels in the floodplain areas on average by approximately 0.1-0.3 m. This does not have a significant effect on the predicted extent of inundation shown in Figure 24.

Liggat Bridge blockage by 25% and 50% Liggat Bridge was blocked using a standard ISIS blockage unit. Both model runs indicated an increase in waters levels immediately upstream of the bridge with little effect noted within flood levels at the village. The model runs indicated that water levels upstream of the A713 bridge increased by approximately 0.7 m and 1.0 m for the 25% and 50% blockage respectively.

Watergate blocked: Providing a blockage of 25% to the watergate increased water levels by up to 0.8 immediately upstream of the gate. This is an extreme case where 25% of the total flow area within the channel has been blocked for modelling purposes. This is approximately equal to having a 0.8m diameter pipe across the full width of the channel. If a watergate is completely blocked across the full width of the channel, it is likely that it would be washed down by the impact of hydrodynamic forces exerted on it by such extreme flows. However, assuming 25% blockage of the flow area provides an absolute upper bound to water level increase which a watergate could cause. The model results indicated that such an increase in water level would be local to the watergate and it would rapidly diminish upstream over a short length.

The biggest impact of a watergate on extreme flows is likely to be turbulence it generates on the water surface. This causes water level to increase locally at the gate. Removal of watergates would reduce such risk locally but would not make a noticeable change to the risk of flooding to Carsphairn.

Downstream boundary: Decreasing the downstream normal depth boundary by a factor of 10 results in a local increase in water levels of up to 2.5 m at the last cross-section of the model. The difference in water level between village and downstream end of the model is over 6 m. As a result, changes in water level at the downstream model boundary by 2.5m have no effect on water levels at the village.

The sensitivity runs indicate that the modelled flood extent is not sensitive to reasonable changes in roughness and downstream boundary conditions. Blockage of Liggat Bridge would result in increases in flood levels; however, this is local to the bridge and peak water levels are around 1.5 m below ground levels at Kirklee opposite the church.

6 Possible Flood Mitigation Measures

Flooding of properties in Carsphairn occurs due to flood waters overtopping the banks of Water of Deugh. It was also shown that flood waters entering the Green head Strand largely originating from Water of Deugh cause additional flooding from the small stream which runs south through the northern part of the village.

An initial assessment has been carried out to identify possible flood mitigation options. In developing these options consideration has been given to discussions with local residents and Dumfries and Galloway Council officials. Based on these, a number of flood mitigation options have been identified and assessed.

The potential flood mitigation options identified are:

1) Direct Defences;
    - Blocking main overland flow paths from Water of Deugh to A713
    - Defences around village
2) Natural Flood Management;
    - Upstream storage
    - Afforestation
3) Flow Diversion; and
4) Sediment Management

An assessment of each of the above options has been undertaken and, where possible, their effect on flows and water levels through Carsphairn has been quantified using the calibrated mathematical model of the river and its floodplains. Assessment of each option is briefly discussed in the following sections, followed by a results matrix outlining feasible options which may be considered for further assessment.

6.1 Level of Protection

In Scotland, the standard level of protection against flooding is 1 in 200 year (i.e. a flood which has an annual probability of exceedance of 0.5%). This is the level of protection for most type of development including residential and commercial/industrial, except for sensitive infrastructure like schools, nursing homes, hospitals for which a higher level of protection is required (i.e. 1 in 1000 year).

Although 1 in 200 year would be the ideal level of protection for residential and commercial areas, sometimes this may not be cost effective or indeed acceptable to local residence. For example, if the most effective option of flood mitigation is direct defences and the required defence heights are such that it would cut-off the river from the surrounding areas, a lower level of defence providing a lower level of protection may be more acceptable. Hence, in this assessment, both the 200 year level of protection and lower level of protection have been considered.

Model runs carried out for this assessment indicate that threshold level of flooding (i.e. return period of a flood at which flooding of properties commence) is approximately 1 in 2 to 5 years. It was predicted that during a 5 year flood approximately 7 properties was predicted to be affected by flooding. This does not mean that these properties would flood every 5 years. Taken over a long period of time, say 50 years, these properties would be expected to flood of the order of 10 times. Statistically, most of flooding could occur in a shorter flood rich period followed or preceded by a longer calm period.

Carsphairn benefits from a limited historical flood defence scheme which comprised two overflow culverts which serve the Green head Strand under the A713.

There are no formal flood defences which protect the village from the Water of Deugh; however, between the village and Water of Deugh there are a number of informal grass embankments which provide a level of protection from flood waters from entering the urban area via the fields to the south and west.

6.2 Freeboard Allowance

It is standard practice to assume the following freeboard allowances for flood walls and earth embankments:

Flood walls: 0.3 m
Earth embankments: 0.6m.

The greater freeboard allowance for earth embankments is due to their inherited higher risk of subsidence and erosion. However, in some cases these effects are included in the design of the embankment and a standard 0.3m freeboard may be applied to both types of defences.

6.3 Option 1 – Direct Defences

6.3.1 Reinstatement of channel embankments

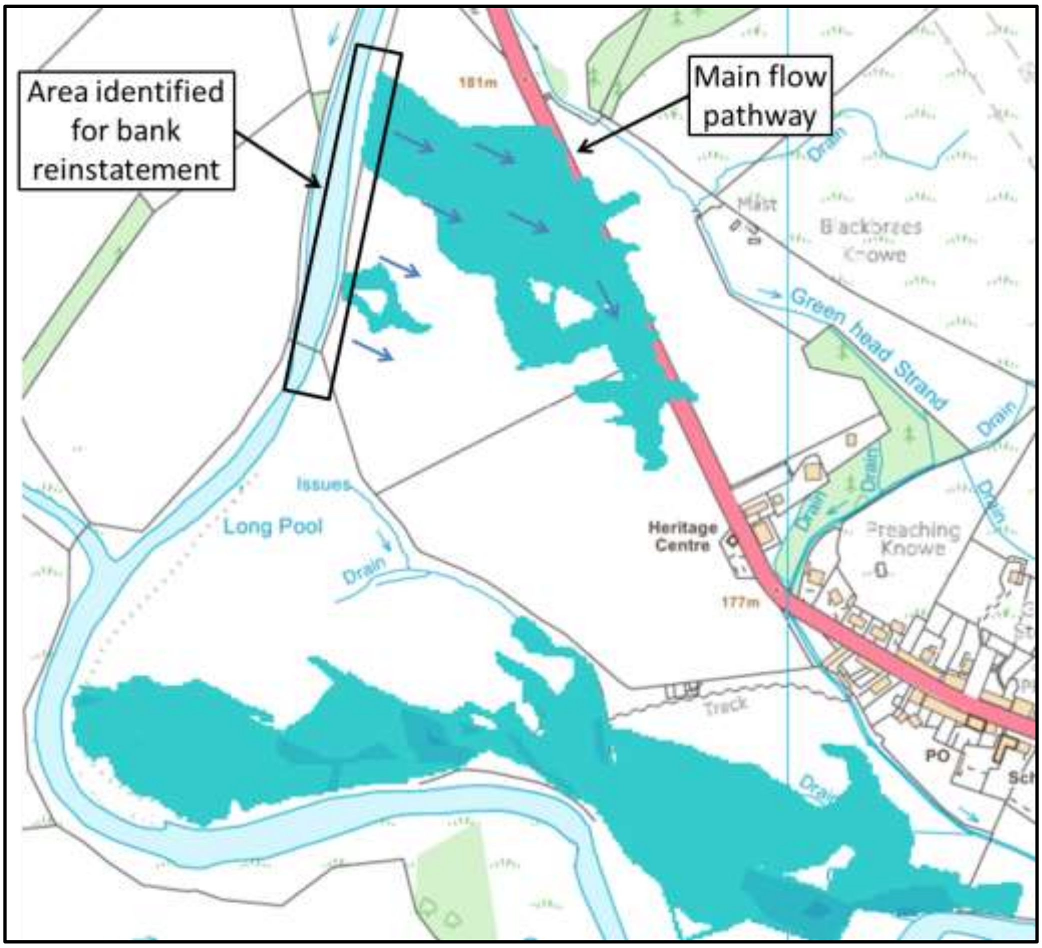
The modelling work outlined above and anecdotal information from local residents indicate that some flood waters arriving at Carsphairn originate from water overtopping the left bank of the Deugh, a short distance upstream of the confluence with Carsphairn Lane. There is a watergate a short distance upstream of the confluence and overtopping of the bank commences immediately upstream of this. Water overtopping the river bank in this area flow east and spill on the A713.

This option involves raising the bank level in this area to prevent flood waters overtopping the river bank and flowing towards the A713. The area potentially where the existing river bank could be raised is shown in Figure 25.

Raising of the bank along the line indicated in Figure 25 would be able to prevent flooding north of the Heritage Centre showing in Figure 24. However, flooding of properties would still occur from the floodplains to the south and south-west of the village. As flows are prevented from spilling on the floodplain, more water passes downstream, although this would only translate into a small increase in water level due to large floodplains.

An alternative to this option is to place the flood defence near to the A713. This would allow storage capacity of the floodplain to be utilised, but would require a longer length of flood defence, see Figure 25. This is considered below in Section 6.3.2.

Figure 25: Location of potential bank reinstatement



6.3.2 Flood wall and embankments

The construction of local flood defences to directly protect areas of risk of flooding may sometimes be the most cost effective solution to mitigate flooding risk. In this option the construction of a mix of flood walls and earth embankments has been considered. The potential lines of defences are shown in Figure 26.

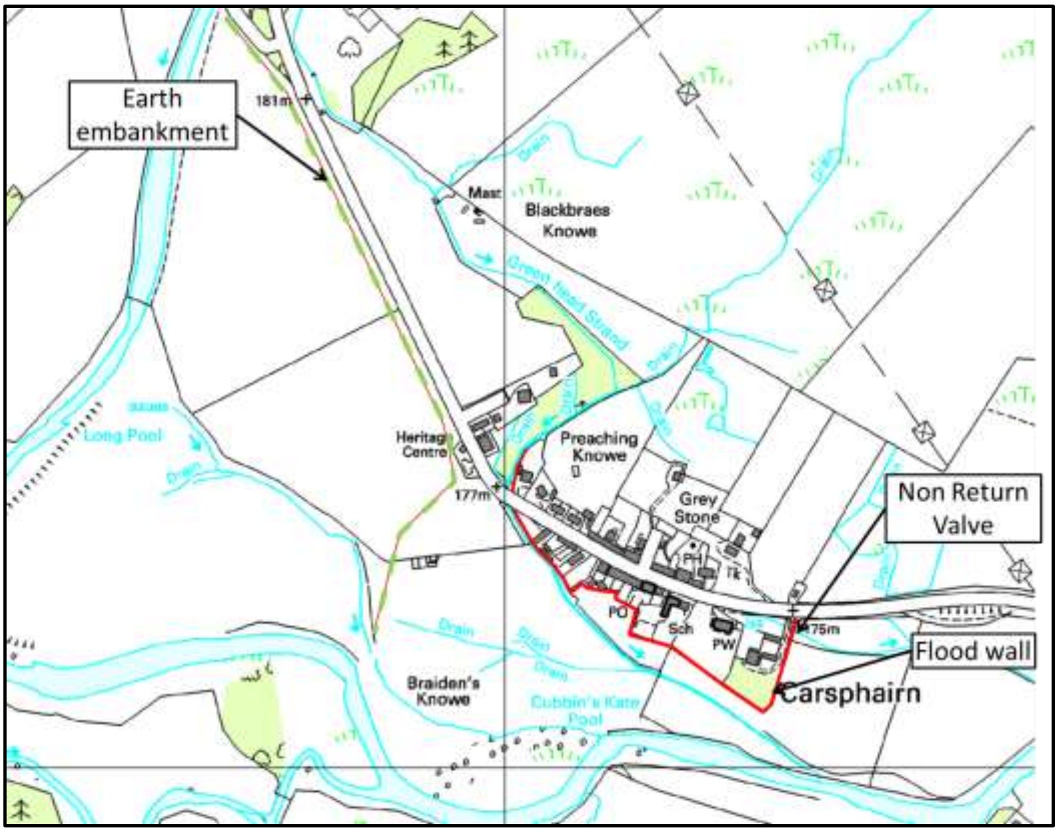
A flood embankment (or wall) can be constructed along the west side of the A713 to prevent flood waters reaching the road. This may have to be extended south (as shown in Figure 26) to direct flood flows away from the properties.

In addition to the above flood embankment, a flood wall would be required along the east bank of Green head Strand to protect properties from flood waters approaching the village from the west and south, as shown in Figure 26.

6.3.2.1 Moving of Green head Strand channel away from properties

There is very little space available between Green head Strand and properties downstream of the A713 where flood defences could be constructed. It is possible to move the channel of the Strand away from the properties in this area by forming a new channel along the field and parallel to the existing channel. This would create a wider space between the new channel and back gardens of the properties and defences along this length could be replaced by an earth embankment along this space. The new channel should be at least similar or larger size than the existing channel. If this option were considered further, the line and shape of the diversion channel will need to be considered in more detail during the detail design stage.

Figure 26: Location of potential direct flood defences



6.4 Option 2 – Natural Flood Management

6.4.1 Potential Areas for Upstream Flood Storage

A well-recognised method of sustainable flood management is to attenuate flood flows in the upper catchment to reduce peak flows arriving in urban areas. A desktop investigation was undertaken to identify areas which could be suitable for use for additional flood storage during extreme events. The review considered local features such as roads and location of properties as well as topographical information from NextMap data and OS maps.

No significant natural floodplains, where additional flood attenuation could be provided, were identified within the headwaters upstream of the Loch Doon offtake. The catchment in this area is relatively steep and in such catchments it is not practical to provide significant flow attenuation without constructing large man-made structures (such as dams). Hence, due to the steepness of the channel in this upper reach any flood attenuation scheme constructed would be limited to retaining a small volume of water before the structure is overtopped.

The assessment indicated that significant headwater storage solutions on the tributaries of the Deugh could not be achieved without the construction of significant water retaining dams. Therefore, there does not appear to be an effective upstream natural flood storage option which would be worth further consideration.

6.4.2 Afforestation

There has been considerable research in assessing the effect of afforestation on flooding risk in the downstream catchment. Depending on the type of trees planted and local soil structure, it may be possible to plant trees in the upper catchment and reduce peak flows downstream. However, research has shown that in order to have a noticeable effect on peak flows downstream, a large proportion of the catchment would need to be planted and it normally takes 10 to 15 years before trees have some degree of maturity for their beneficial effect to materialise.

It is understood that some deforestation has taken place in the upper catchment of the Water of Deugh. Although this would increase surface water runoff, the effect of this on peak flows at Carsphairn would likely to be small.

Afforestation is most effective if existing catchment has a poor vegetation cover and a large proportion of the rainfall immediately turn into surface water runoff. With a good initial vegetation cover, the incremental benefit afforestation would provide would be limited. As large parts of the upper catchment are already in woodland, afforestation of small areas would not have a significant effect on flooding risk at Carsphairn. However, planting trees in the upper catchment would contribute to reducing peak flows downstream.

6.4.3 Flood storage within adjacent floodplains

There are large floodplains to the west and south of Carsphairn, between the village and Water of Deugh channel. As shown in Figure 24, there are large areas within these floodplains which are higher than the predicted water level and do not flood. It is possible to lower these areas to create additional flood storage.

Model results indicated that lowering these areas to provide additional flood storage reduces peak water levels locally by 100-200 mm, but flooding of the properties at Carsphairn would still occur. This is due to large volumes of flows in the river compared to the additional storage volume created in these areas. However, it does provide limited benefit.

6.5 Option 3 – Diversion of flows within upstream catchment

As described in Section 4.2, the catchment upstream of Carsphairn has been artificially modified to form part of SP's wider Galloway Hydro Scheme. The modifications include abstractions from the catchment of Water of Deugh to support water volumes in Loch Doon, and return flows from Loch Doon to the Carsphairn Lane through the Drumjohn Power Station in case of high flows in Loch Doon. Three watercourse offtakes are present within the upstream catchment:

1. Bow Burn, approximately 1.4 km east of the Deugh intake, see Figure 10. A weir diverts water into an aqueduct structure that transfers flows to a location immediately upstream of the intake of Deugh Tunnel which transfers flows into Loch Doon.

2. At a location close to (254727,598377), approximately 3.5 km to the east of Loch Doon, the Water of Deugh is impounded by a large weir which transfers flows from the Deugh to Loch Doon via the Deugh Tunnel. During periods of high flows excess water passing over the weir continues down the Deugh;

3. A third weir structure is located on the Muck Burn, which permanently diverts flows within the natural channel towards Loch Doon via an artificial canal, see Figure 10.

As indicated above, water transfer already take place between watercourses within the upper catchment as part of the hydro scheme, and limited scope would exist to alter these without having a significant impact on the hydro scheme.

However, one option queried during consultation was to increase the volume of water which could be diverted from Water of Deugh to Loch Doon. Currently flood waters are diverted by a weir to Loch Doon via the Loch Doon tunnel. The Loch Doon tunnel is approximately 3.5 wide and has a reported capacity of approximately 15 m^3/s based on information provided by Scottish Power.

Transferring more water from the Deugh to Loch Doon reservoir would require the construction of at least a similar size tunnel. This could reduce peak flows passing downstream by of the order of 15 m^3/s. This equates to approximately 15% of the estimated 2 year flow, 8% of 50 year flow and 6% of 200 year flow summarised in Table 13. The impact on this on peak water levels at Carsphairn would be small (i.e. it would reduce 200 year flow to 150-160 year flow with less than 0.1m reduction in peak water level in Carsphairn).

This option would increase flooding risk along River Doon (downstream of Doon Reservoir) and would not be acceptable. Alternatively, it would require a change to the operating procedures of Loch Doon to ensure that additional capacity was retained within the loch to facilitate emergency flows from the Deugh.

In summary, an effective option involving transfer of flood flows to neighbouring catchments to reduce peak flows in the Water of Deugh to make a noticeable difference in water levels at Carsphairn appears unlikely.

6.6 Option 4 – Sediment Management

One of the issues raised during consultation was the effect of sediment deposition in the river channel leading to increased flooding risk of the village. It was observed that sediment deposition occurred along the reach of the river upstream of the confluence with Carsphairn Lane around Sections 17 and 19 (Figure 16), downstream of the confluence around Section 12 and upstream of Liggat Bridge around Section 3 and 4. This is clear in longitudinal plot of river bed shown in Figure 27. Although it is an exaggerated scale, the bed level clearly rises in these three places.

Model runs were carried out to assess the effect of peak water levels by lowering the river bed in the identified three areas as shown in Figure 27.

Model results for 200 year flow indicated that water levels could be reduced by up to 300 - 400 mm within the channel locally close to Cross-section18, although no significant reduction in water levels downstream of this location were predicted, see Figure 28. It should be noted that the model results did show a change in the mechanism of flooding within the floodplain. Initial overtopping of the channel occurs at the watergate, with more flooding entering the floodplain to the south of the A713, see Figure 29. This has a knock on effect on flooding depths within the floodplains with shallower flooding predicted to the west of the village, see Figure 30; however, flood depths within the village reduce by only around 100 mm.

Figure 28 indicates that the biggest reduction in peak water levels is caused by the removal of sediment around Sections 18 and 12. Removal of sediment around Sections 3-4 does not appear to make a noticeable difference in peak water levels in the river.

A review of historical maps show long-term changes of the river in this area, which suggests that the sediment load in the river is relatively high. Therefore, it is reasonable to assume that after removal, sediment deposition will continue to take place in this areas and regular removal of sediment will likely be required. Regulatory bodies do not allow removal of sediment from natural rivers unless absolutely necessary. As the beneficial effect of such activities to reduce flooding risk to Carsphairn appears to be small, it may be difficult to provide sufficient justification for getting approval from SEPA.

In summary, removal of sediment deposition around Sections 17 to 19 and Section 12 provides up to 100 mm reduction in peak water levels, but sediment deposition in these places will likely to continue and regular removal of sediment from these areas will likely be required.

Figure 27: Channel maintenance locations

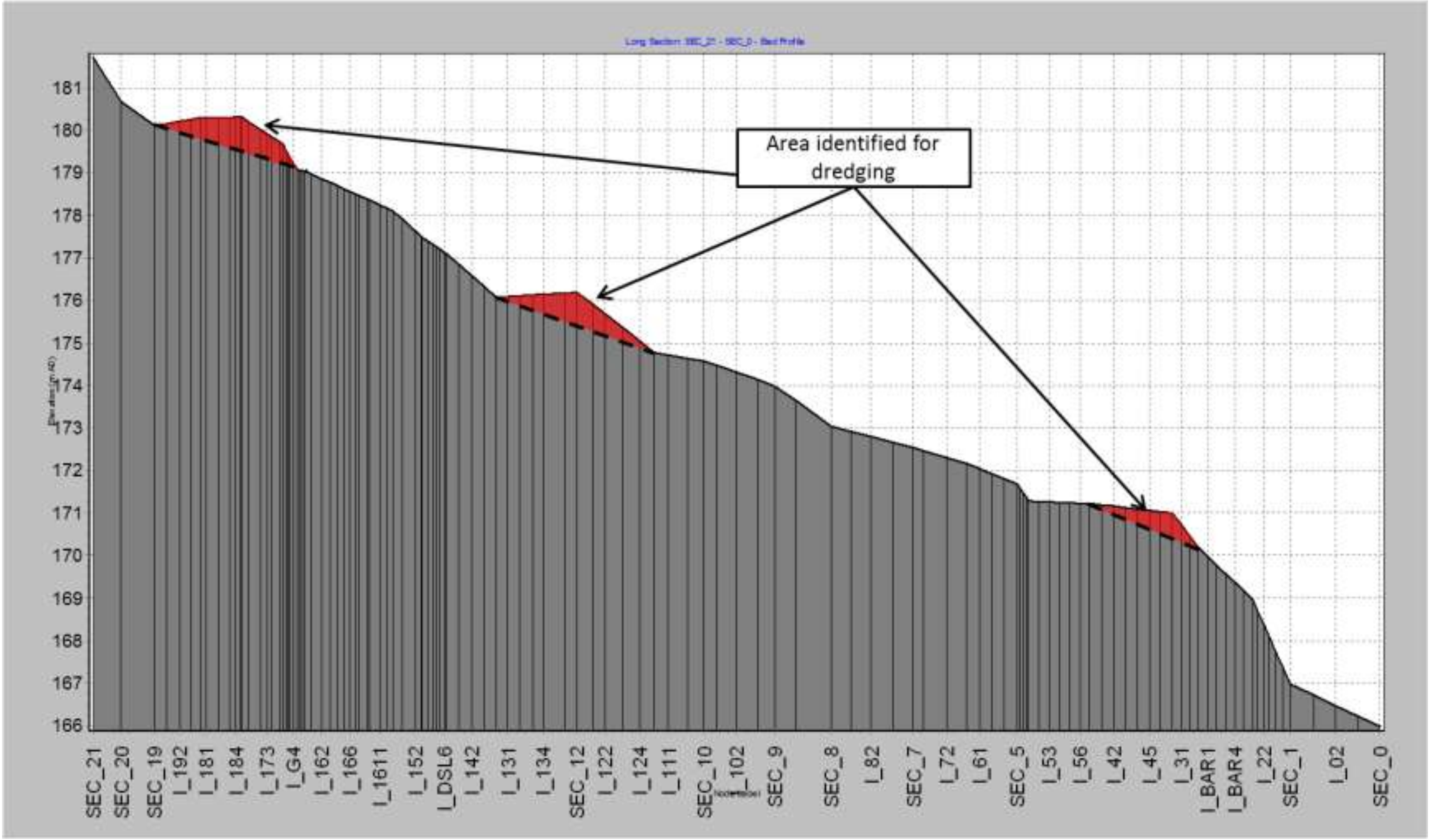


Figure 28: 200 year base vs 200 year Dredge Scenario - Long profile

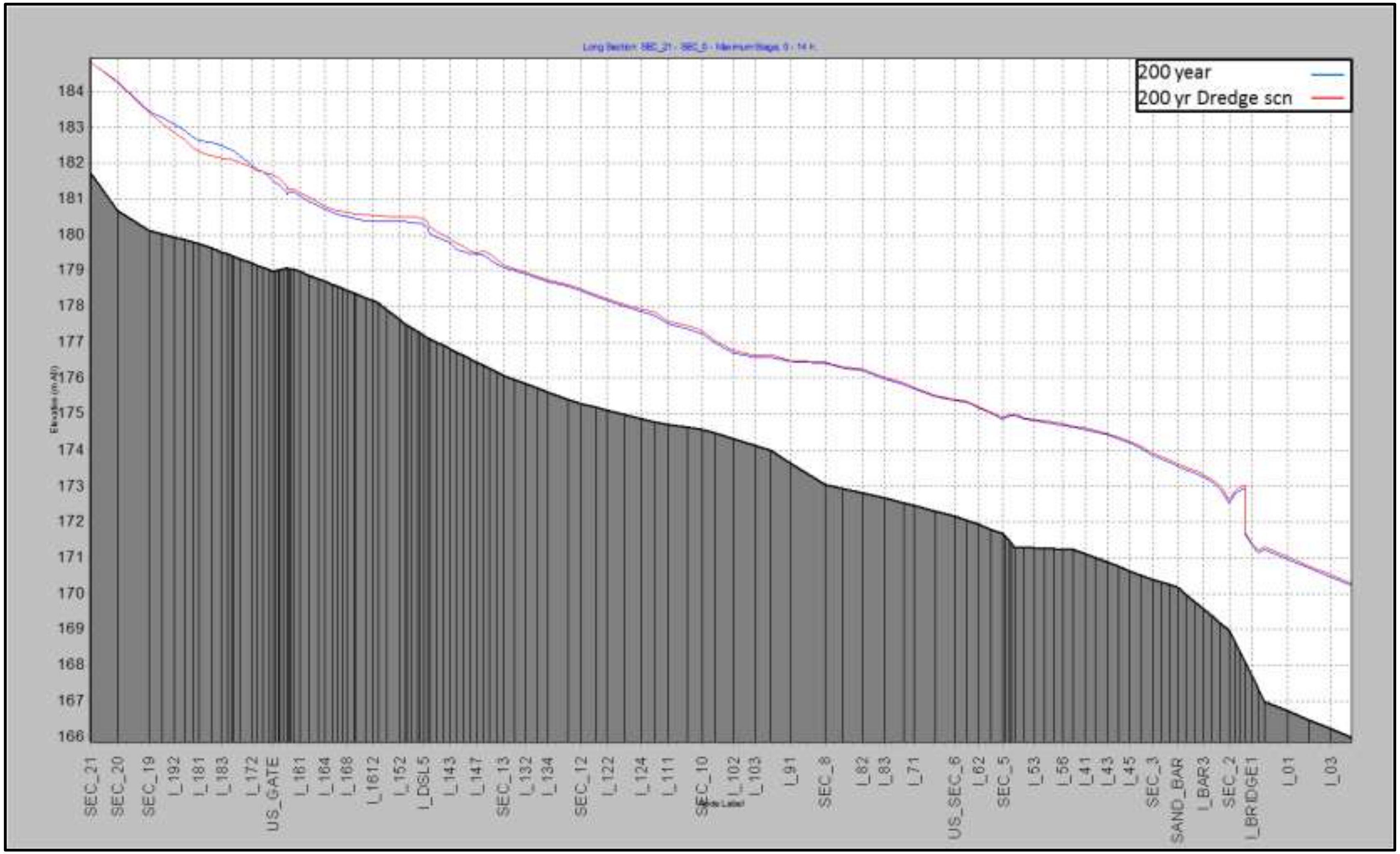


Figure 29: Initial site flooding based on dredged scenario

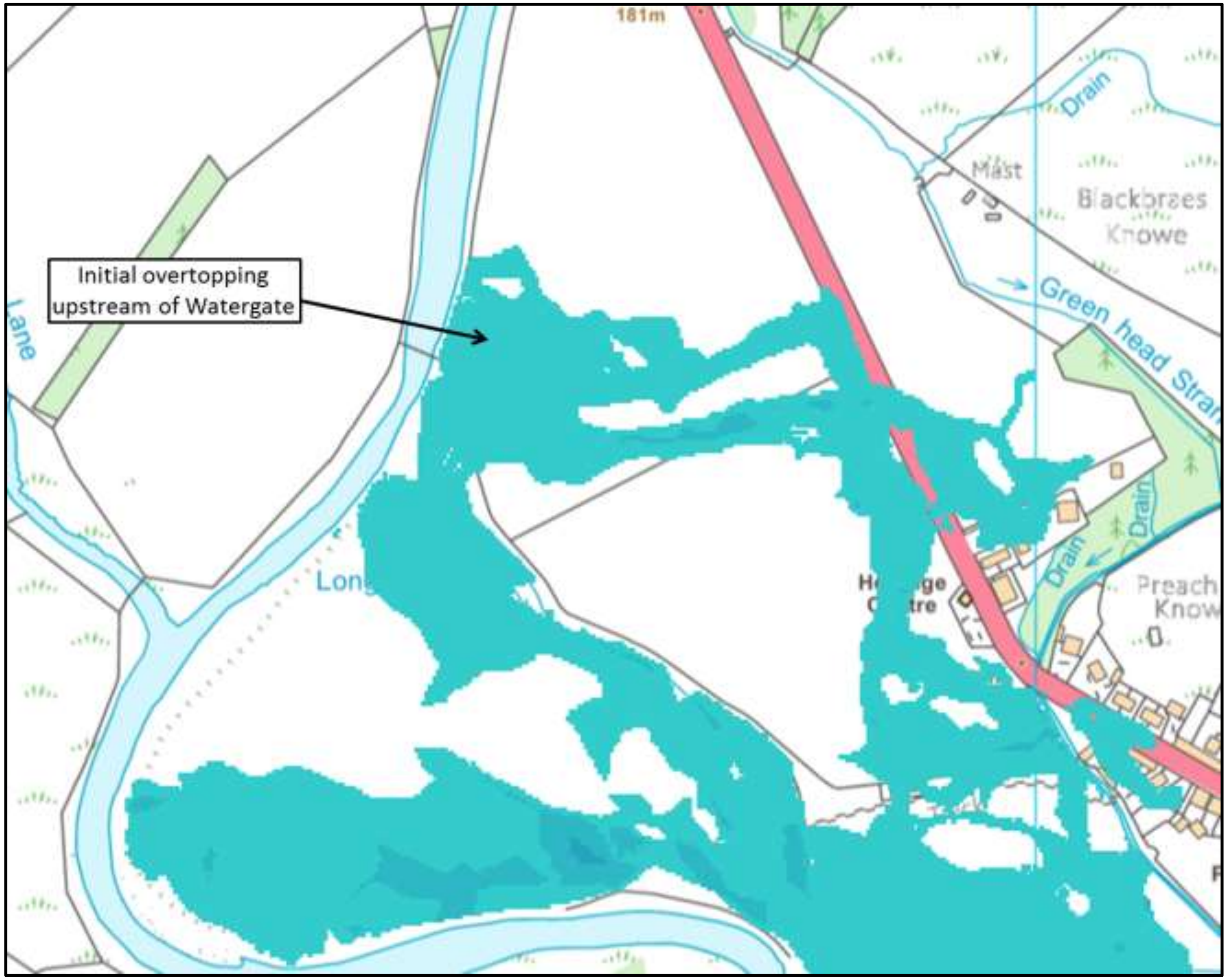
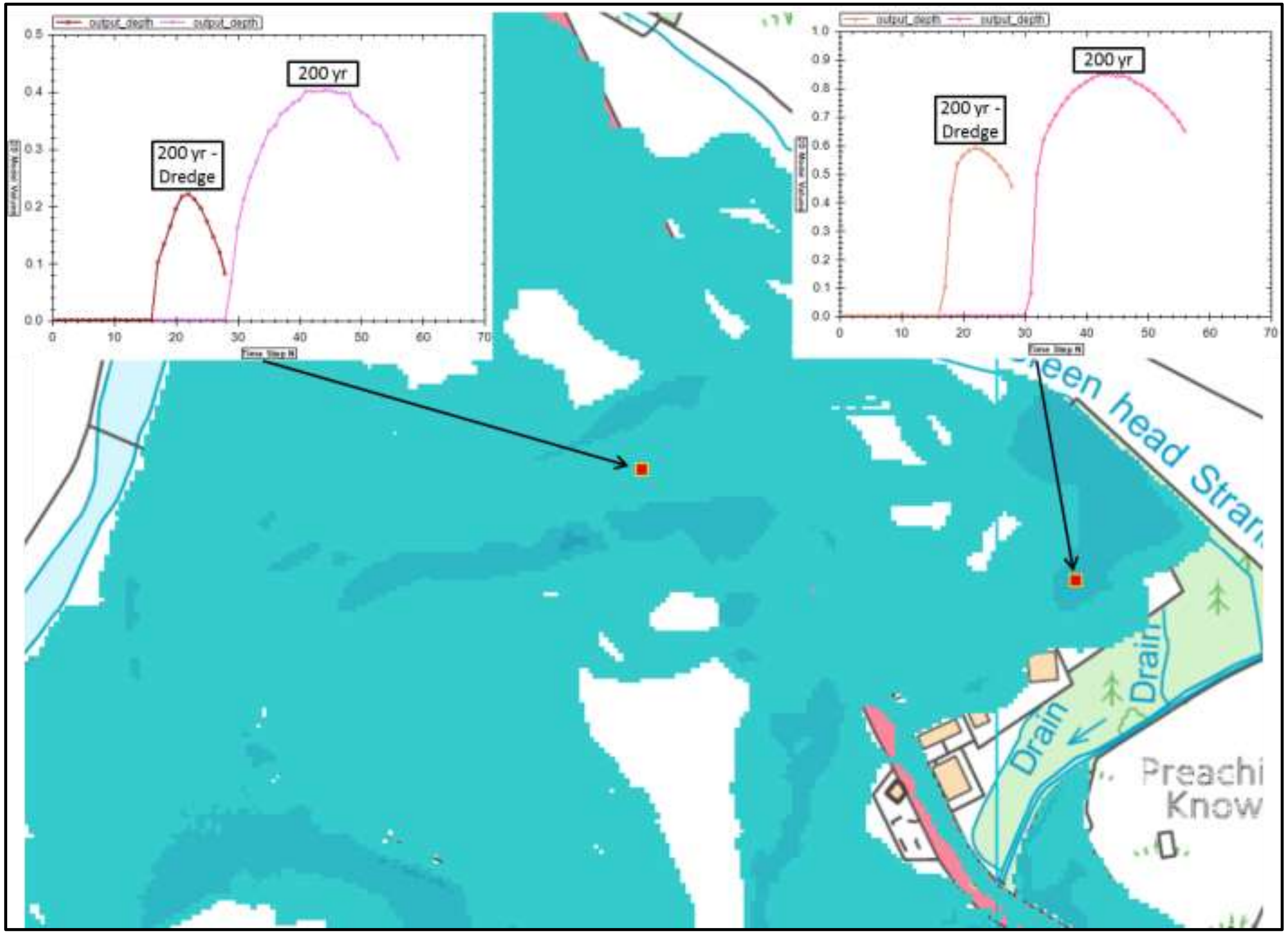


Figure 30: 200 year base vs 200 year Dredge Scenario – Floodplain depths



6.7 Option Assessment

A total of four possible flood mitigation options were assessed using the calibrated mathematical model. Of these, only the direct defence option appears to provide the desired level of protection (i.e. protection against the 200 year flood), with others providing partial benefits only. However, these options, including some variations of the main options, are ranked in terms of:

- standard of defence;
- sustainability; and
- delivery potential.

The ranking has been based on the following weightings:

- Low = 1 (least benefit)
- Medium = 3 (moderate benefit)
- High = 5 (most benefit)

The results are presented in Table 20.

Table 20: Option assessment matrix

Option	Technique	Standard of defence	Sustainability	Scheme delivery potential	Total score
Direct Defence	Blocking main overland flow path	2	3	4	9
Direct Defence	Earth embankment north of village	2	3	4	9
Direct Defence	Earth embankment and flood wall	5	3	4	12
Natural Flood Management	Upstream storage	1	4	1	6
Natural Flood Management	Afforestation	1	5	2	8
Natural Flood Management	Lower ground levels in adjacent floodplain	1	5	4	10
Flow Diversion	Increase diversion to Loch Doon	1	2	1	4
Sediment Management	Channel maintenance between sections 11 and 14	1	1	1	3
Sediment Management	Channel maintenance between sections 2 and 4	1	1	1	3

It appears from the above table that direct defence option has the overall best score.

Other flood management options include Property Level Protection measures. These measures provide cost-effective and easy-to-implement tools for home owners to take more effective action to protect their homes. These may include flood barriers for doors and airbricks, dry proofing (re-pointing, water proofing), dewatering and non-return valves etc. Such measures are only effective for shallow depth of flooding (less than 1 m) and may not be suitable for all house types (for example houses with wooden floors). However, they can reduce flood damage. During the December 2013 event, some of the properties flooded by flood waters coming through the wooden floorboards, for which Property Level Protection would not be effective.

The effectiveness of property Level protection depends on effective and timely actions of the property owner and effective flood warning (see Chapter 10).

6.8 Flood Mitigation Summary

Based on the results of mitigation options outlined above, direct defences in the form of flood walls and earth embankments appear the most effective way of providing the desired level of protection (i.e. 200 year) to Carsphairn. However, this assessment does not take into account other factors such as land ownership and local ground conditions, which will need to be considered at the next stage.

If the desired mitigation option is not acceptable, either due to the impact of construction works or local soil conditions, etc. consideration has also been given to a lower level of protection and this has been discussed in Section 7.

7 Modelling of Preferred Mitigation Option

The outline assessment summarised in Section 6 indicated that of the four main flood mitigation options considered only the direct defence option provides the desired level of protection. This option has been assessed in more detail and the methodology used and results of the assessment are summarised below.

7.1 Methodology

The baseline model representing the existing river channel and floodplains was modified to include a flood defence running parallel to the A713 to the west of the village, as shown in Figure 26.

The defences include the following:

1) An earth embankment, approximately 850 m long, running on the west side of the A713 and parallel to the road, then turning south-west to divert flood waters away from the properties.
2) A flood wall, approximately 500 m long, running along the east bank of Green head Strand and along the south boundaries of properties and around Canmore Farm to prevent flooding from the Strand and Duegh. It is expected that a non-return valve will be required on the small drain at the south-east of the village to prevent flood waters backing up the drain. It is possible that part of this 500 m long defence wall could be replaced with earth embankment where appropriate. This would not affect the assessment outlined below.

Initial model runs were carried out assuming a wall along the east bank of Green head Strand downstream (south) of the A713. Due to the lack of available space between the channel and properties in this area, the construction of any flood defences in this area would significantly affect back gardens of properties. In order to avoid this, it is possible to move the channel of the Strand away from the properties and create sufficient space between the new channel and properties where flood defences (likely in the form of earth embankment) could be constructed.

This option assumes that the left hand wall along the Strand, upstream of the A713 is maintained and flood waters are not able to pass through the wall. However, this will need to be assessed during detailed design stage.

7.1.1 Hydraulic Modelling

The baseline model was modified to prevent flood waters spilling outside the defence lines shown in Figure 31. The model was then rerun for the estimated 200 year flow and water levels along the river at model cross-sections were compared with those obtained from the model run for the base case (i.e. no defences). The results are summarised in Table 21. Model output locations where water level comparison is made between base case (no defences) and with defence cases are shown in Figure 32.

The differences in peak water levels along the line of the defences are provided in Table 21. This indicates that peak water levels at location 9 (south-west of Heritage Centre) increases the most (up to 1.1.m). This is due to flood defences blocking the existing overland flow path in this area. In other places the predicted increase in water levels is generally of the order of 0.3 m. Water level within the Strand on the south side of the A713 decreases by 0.5 m due to flood defences preventing flood waters spilling into the Strand upstream.

Table 21: Model results for defended and undefended cases

Output location	200yr Existing Water Level (m AOD)		Change in flood levels (m)	Required Defence Height above ground (m)[a]
	Existing	Defended		
1	182.8	182.8	0	0.4 (0.1)[b]
2	181.3	181.6	0.3	1.2 (0.8)
3	180.9	181.2	0.3	1.0 (0.7)
4	180.3	180.6	0.3	1.0 (0.7)
5	179.8	181.1	1.3	1.4 (1.1)
6	179.2	179.6	0.4	1.4 (1.1)
7	178.5	178.9	0.4	1.1 (0.8)
8	178.2	178.8	0.6	1.3 (1.0)
9	177.7	178.8	1.1	1.5 (1.2)
10	177.6	178.6	1	2.0 (1.7)
11	177.4	178.1	0.7	1.1 (0.8)
12	177.2	177.7	0.5	0.9 (0.6)
13	177.3	177.5	0.2	1.2 (0.9)
14	177.2	176.7	-0.5	0.8 (0.50)
15	175.3	175.3	0	0.6 (0.3)
16	175	175	0	1.0 (0.7)

a-includes 300mm freeboard
b-existing depth of flooding

Table 21 also shows the required defence heights above exiting ground level along the assumed line of the defences. Defence heights presented in the table include 0.3 m freeboard for both earth embankments and flood walls and are given as guidance only. These are average defence heights and will be refined during detailed design stage.

Defence heights are generally up to 1.5 m, except at point 10 where existing ground level is low and the required defence height rises to 2 m. This is in the middle of the floodplain and away from the properties.

The above model results do not change significantly if the channel of the Strand were moved away from the properties downstream of the A713. As the depth of flooding in this area is shallow, the effect of this on peak water levels is small.

Figure 31: Indicative line of modelled flood defence and 200 year inundation (with defences in place)

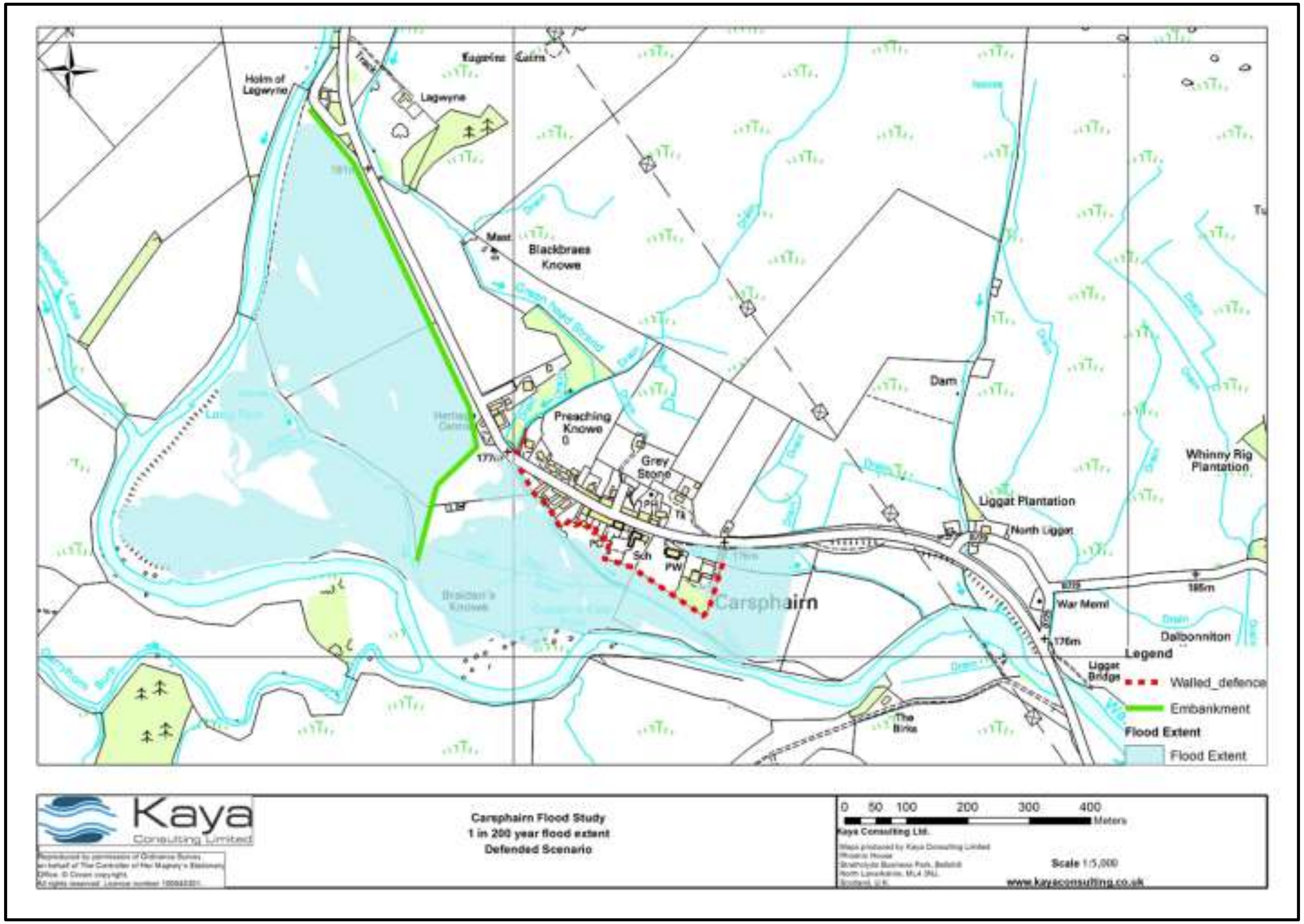
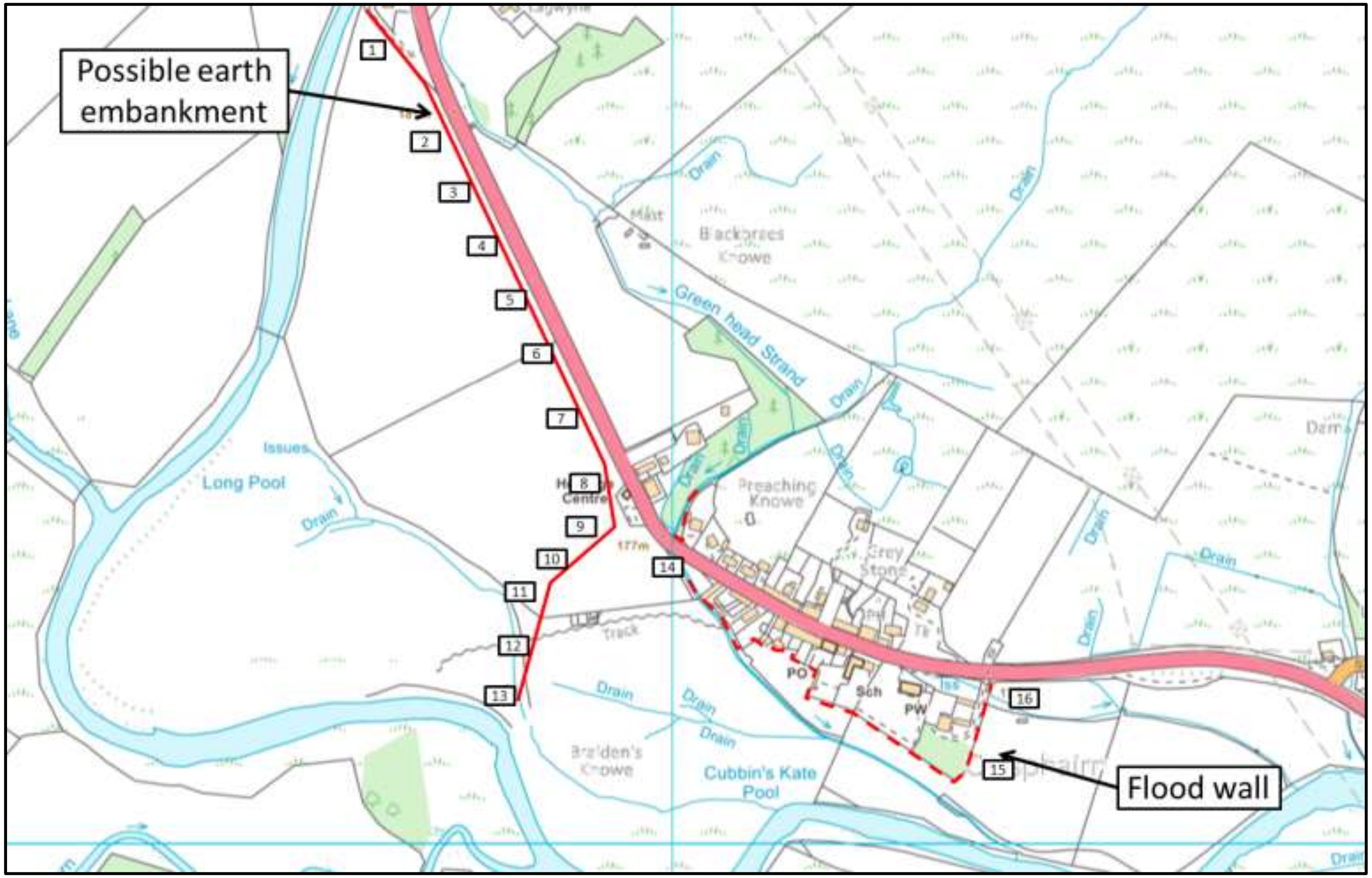


Figure 32: Model result locations (refer to Table 21)



7.2 Lower Level of Protection

The assessment summarised above has focused on the provision of 200 year level of protection for all properties in Carsphairn. In this section consideration has been given to providing a lower level of protection and comparing this to the 200 year level of protection.

The options considered for comparison include 50 year and 10 year level of protection.

It was shown in Chapter 6 that only the direct defence option provides protection to all properties at risk of flooding in Crasphairn. This involves the construction of earth embankments and flood walls.

Model results presented in Table 18 show that the difference in peak water levels between the 10 and 50 and 50 and 200 year floods are approximately 0.1 m and 0.1 m respectively. This indicates that defences to provide 50 year protection would only be approximately 0.1 m lower than defences required for the 200 year protection. Similarly, defences to provide 10 year protection would be approximately 0.2 m lower than defences required for the 200 year level of protection.

Although, lower flood defences would cost less, the differences of the order of 0.1-0.2 m in defence heights would not result in a significant reduction in the cost of the scheme. Hence, the corresponding increase in the benefit-cost ratio (see Chapter 9) would be relatively small. This indicates that the provision of a lower than 200 year level of defence would unlikely provide a significant cost saving.

8 Flooding Risk from Sewer System

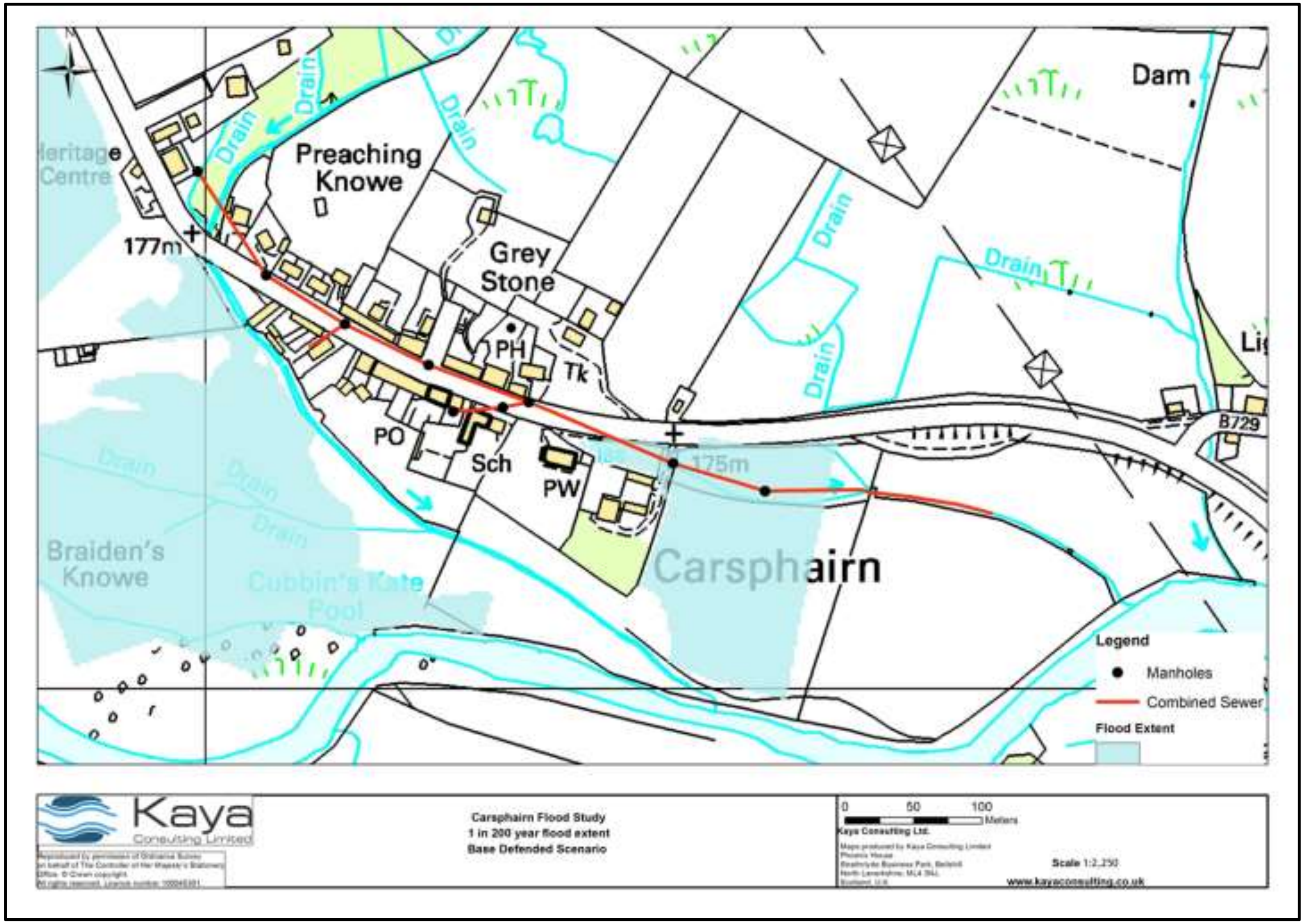
If the flood mitigation option involving direct defences were implemented, the peak water level in the river during extreme events would be higher than the existing ground levels on the land side of the defences. In such cases, flows from the river could back up into the local drainage system if there was a connection between the drainage system and the river (i.e., through outfalls). Flood waters backing up the drainage system would be able to come out of manholes within the urban area of Carsphairn and cause flooding.

In addition to flows backing up from the river during high flows, surface water from any rainfall during such times would not be able to flow into the river and would need to be managed within the defended area. This could cause or exacerbate flooding behind the defences. There is also a risk of seepage of river water under the defences and this will need to be taken into account in the detailed design stage.

When developing flood mitigation measures these sources of flooding will need to be considered and managed.

The locations of existing manholes on both the Scottish Water combined and surface water sewer system located within the predicted 200 year defended flood extent are shown in Figure 33. This information was extracted from Scottish Water service drawings. Flood waters would be able to enter the sewer through the manholes within the floodplain and come out of the manholes within the area protected by flood defences. Although sealing manhole covers to prevent water entering and discharging from the manholes could be considered, some sewers may not be suitable for this as it would pressurise the sewer and could cause water to escape from joints and other structurally weak points. This and other potential mitigation options will need to be considered during the detailed design stage.

Figure 33: Location of existing manholes and outfalls within 1 in 200 year defended flood map



9 Economic Appraisal

An outline cost-benefit analysis has been undertaken using the UK standard methodology based on;

- 'Flood and Coastal Erosion Risk Management Appraisal Guidance', 2010 published by Environment Agency; and
- 'The Benefits of Flood and Coastal Risk Management: A Handbook of Assessment Techniques – 2010', published by Flood Hazard Research Centre for DEFRA (Department of Environment, Food and Rural Affairs) and Environment Agency (EA). This report is also known as the Multi-Coloured Manual 2010.

The cost-benefit analysis undertaken in this chapter has been carried out based on conceptual designs of possible flood defence options. As a result, there is a high degree of uncertainty associated with the estimated costs. In order to account for such uncertainties, a standard 60% bias adjustment is made to the estimated scheme costs as part of cost-benefit analysis. Flood damage calculations are based on detailed mathematical modelling and surveyed finished floor levels for each property, and are more accurate. A number of assumptions have been made in this outline cost-benefit analysis and these are listed in Section 9.2.4.

9.1 Comments on Outline Design

The potential flood mitigation options are based on a high level conceptual design with costing being based on similar projects undertaken elsewhere in the UK. No design drawings have been prepared or no account has been taken of factors such as condition of existing defences, ground conditions, utility services, environmental aspects including contaminated land, site investigations, planning requirements, etc. Although the standard adjustment factor of 60% may cover such factors, the present outline analysis is the first stage in the development of the scheme and if the scheme were to be taken forward a more detailed assessment will need to be carried out as and when more detailed information becomes available.

9.2 Outline Cost Benefit Analysis

9.2.1 Properties at Risk of Flooding

The mathematical model as run for a range of flows (10, 25, 50, 100, and 200 year) and for each run the extent of inundation maps were prepared. Properties within the extent of predicted inundation were identified for each return period and counted. Because the number of properties affected is relatively small, this process was carried out manually. The results are shown in Table 22.

A list of properties within the flood inundation areas was made and national grid coordinates of each property were extracted. This information was then used to extract from the model results depth of flooding for each property.

Table 22: Predicted number of properties at risk in Carsphairn

Property Type	Existing Case				
	200+ cc	200	100	50	10
Residential	27	27	27	26	14
Non-Residential	5	4	3	3	2

9.2.2 Depth of Flooding

Depth of flooding of each property was extracted from the ISIS 2D model for each model run. This information was used to estimate flood damage.

9.2.3 Flood Damage Data

Flood damage data for each property was extracted from the Multi-Coloured Manual 2010 excel spreadsheets. An Excel Macro programme was developed to extract flood damage data from the appropriate section of the Multi-Coloured Manual based on property type, property age and depth of flooding.

Similar calculations were also carried out using Flood Damage module in ISIS software package. This produced similar results to manual calculations.

9.2.4 Assumptions

A number of assumptions have been made in this outline cost benefit analysis and these are summarised below:

a) Plan areas of each property calculated from 1: 1250 Ordnance Survey maps were considered sufficiently accurate for this assessment.
b) Age of each property was estimated based on visual appearance of the property. As the property bands within the Multi-Coloured Manual 2010 are quite broad it is likely that reasonably robust estimates of property age have been made.
c) Property values were estimated based on type and size of property and published property values. There is likely to be a high degree of error in these values as they have not been reviewed by experienced surveyors or estate agents. However, this would only have a significant effect on the analysis if estimated damage cost exceeds its value. In such cases the maximum flood damage cost is set to the value of the property. It is suggested that more reliable estimates of property values are made for future detailed cost-benefit analysis, particularly those properties with large estimated flood damage.

9.2.5 Outline Costing of Flood Management Measures

Flood management measures considered for this study have been developed to a conceptual stage only.

For the type of defences considered, average construction cost figures were used based on similar work elsewhere and national guidelines. No design drawings were prepared or quantities of materials assessed for costing of the defences. A standard unit cost appropriate for the type of defence and particular location was used. This approach was considered appropriate for the purposes of this study. Should the scheme be taken forward, the cost-benefit analysis will need to be refined as and when more accurate information on the design becomes available.

A number of items have not been included in the outline costing and these include the following:

- Civil/geotechnical investigations, asbestos and contamination surveys;
- Ground remediation or the removal of contaminated or deleterious materials, if applicable;
- Road and public footpath remedial works or upgrades;
- Remedial or upgrade works to existing public realm or private property;
- Land acquisition, legal and financing charges;
- Statutory charges; and
- Cost of environmental surveys.

Allowances have been made for:

- Professional fees (including design, tendering, supervision, etc.);
- Utility diversion costs; and
- Emergency service costs.

Outline costings have been prepared for the following flood mitigation options:

Table 23: Estimated scheme cost

Defence Option	Construction Cost (£M)	Preliminaries (£M) (10%)	Contingencies (£M) (15%)	Design & Supervision (£M) (15%)	Total (£M)
Direct Defences	0.96	0.096	0.15	0.15	[a]1.36[b]

a *Does not include the standard optimism bias of 60%. With 60% optimism bias, total cost of Direct Defence option becomes **£2M**. This is automatically added in the cost-benefit analysis.*

b Does not include land acquisition costs.

9.2.6 Outline Cost-Benefit Analysis

The national standard approach for cost-benefit analysis of flood schemes was applied to five options;

- Option 1: Do Nothing.
- Option 2: Maintenance only.
- Option 3: 200 year protection.

Direct flood damage costs only have been included in the analysis at this stage and intangibles, environmental and social impacts have not been included.

A standard 100 year analysis period was assumed in the calculations.

Option 1 - Do Nothing

The “Do Nothing” scenario sets a baseline for comparison. The scenario is based on a number of standard assumptions:

- Once a flood event occurs, no repairs are made to the damaged properties.
- Although each property suffers damage each time it floods, the total damage value of each property is limited to the present value of the property.
- It is assumed that only one breach (of defences) occurs in the analysis period (100 years).
- The probabality of a flood event occurring is increased over time due to lack of maintainance of exisiting defences.

This scenario is unrealistic as the Council has duties to carry out clearance and repair works (as per the Flood Risk Management (Scotland) Act 2009), but this ‘Do Nothing’ option is a standard used in all such cost-benefit analyses and it is used as a baseline for comparison purposes.

Option 2 - Maintaining Existing Defences and Properties

Option 2 has the following general assumptions:

- Over the analysis period each property will be subject to a number of floods of different magnitudes. The total flood damage is the summation of damage each time the property floods.
- Damages to defences and properties are assumed to be repaired. The total damage cost can therefore be higher than the present value of the properties over the analysis period of 100 years.
- It is assumed that a flood event can occur in any year and in each year there is the same probability of a flood occurring.
- Investment is made annually to maintain the flood defences in their current state. The risk of flooding remains constant throughout the analysis period.
- This option can also be described as the cost of maintaining all defences and properties at their present state.
- This is similar to present day scenario where Council maintains watercourses and existing defences. Also riparian owners have a duty to maintain the defences in their ownership.

Table 24: Estimated annual maintenance cost

Maintenance Item	Approximate Length (m)	[a]Estimated Indicative Cost (£)
Channel Clearance		400
General Maintenance		500
Contingencies and Emergencies		1,100
Total		2,000

a Estimated annual maintenance cost incurred by all responsible for maintaining existing defences to provide the same level of defence as at present, i.e. by Council and private owners

<u>Option 3 - Full Flood Mitigation Scheme (200 Year Level of Protection)</u>

Option 3 has the following general assumptions:

- Properties are protected for flows up to and including 200 year return period.
- A capital investment for the construction of the flood management scheme is made in the first analysis year followed by an annual maintenance each year.
- The risk of flooding is greatly reduced by the flood management scheme and as a result the damage to property is greatly reduced. Although the properties will be protected against flows up to the design flow (i.e., 200 year), there is still a residual risk, albeit very small, that a flood greater than the design flood occurring during the analysis period of 100 years.

It is assumed that the full flood mitigation scheme, which includes 500 m of flood walls and 850 m of earth embankments, is implemented.

A time varying annual maintenance cost is considered. It is assumed that for the first 20 years maintenance of the new flood alleviation scheme should be small (£2,000 per year), with maintenance increasing over time to £3,000 per year. Over the 100 year analysis period this is equivalent to £0.26M at present day value.

A Bias Adjustment Factor is applied to the costs. As outlined above the DEFRA/EA method recommends a value for Bias Adjustment of 60% for feasibility level studies. This means that an additional 60% is added to the costs of constructing the scheme and to maintenance. This factor can be reduced at detailed design stage as confidence in cost estimates is increased. As uncertainties associated with the scheme are eliminated during the design stages (through undertaking site investigations, environmental assessment, consultation with stakeholders, and changing market conditions), the estimated cost of the scheme will be improved and bias adjustment factor will be reduced.

Results of the analysis are summarised in Table 25. The values in the table refer to the costs for a scheme with direct defences only.

9.2.6.1 Summary Cost-Benefit Analysis

Summary results for the cost-benefit analysis are shown in Table 25.

The cost of the flood defence schemes assessed in this study is of the order of £1.36M. This includes 10% for contingencies, 15% for preliminaries and 15% for design and supervision services.

Table 25: Summary results of cost-benefit analysis

Cost-Benefit Summary	Option 1 Do Nothing	Option 2 Maintenance	Option 3 200 Year Protection
Cost	£M	£M	£M
Total Capital Cost	0	0	1.36
Total Maintenance Cost	0	[a]0.08	[b]0.07
Bias Adjustment (60%)	0	[c]0.05	[c]0.86
Total Cost	**0**	**0.13**	**2.29**
Benefit			
Average Annual Damages	0.13	0.13	0.01
Total Flood Damages	3.0	2.7	0.1
[d]Total Flood Damages Avoided	**-**	**[g]0.3**	**[g]2.9**
[e]Net Present Value of Benefits(NPV)	-	-	[g]-1.0
[f]Average Benefit/Cost Ratio (BCR)	-	**-**	**[g]1.27**

[a] *Annual maintenance - the value in the table is sum of money invested at present day value that would provide funding for future maintenance*

[b] *Time varying annual maintenance, with low maintenance soon after construction of new scheme rising to £0.1M per year after around 50 years. The value in the table is sum of money invested at present day value that would provide funding for future maintenance*

[c] *Capital and maintenance costs are increased by 60% to account for optimism bias in initial estimates of costs. The 60% factor is recommended by DEFRA/EA as appropriate for feasibility level studies.*

[d] *Total Flood Damages of Option 1 (Do Nothing) - Total Flood Damages of Option*

[e] *Total Flood Damages avoided - Total Cost*

[f] *Total Flood Damaged Avoided / Total NPV (including bias adjustment)*

IBCR= (NPV benefits 3 – NPV benefits 2)/(NPV costs 3 – NPV cost2)

Based on the analysis summarised above, it appears that 200 year level of protection is likely to be economically feasible as it would produce a benefit-cost ratio above unity. It should be noted that the current analysis is based on direct damages and no account has been taken of other factors such as environmental and social impacts, intangibles, etc. With such factors included, the final benefit-cost ratio will likely to be higher.

The analysis presented above has to be regarded as outline at this stage and will need to be refined as and when more detailed and reliable information becomes available.

Benefit-cost ratios for schemes providing lower level of protection would be marginally higher. This indicates that a flood prevention scheme providing up to 200 year level of protection would likely be economically viable.

10 Flood Warning

10.1 Background

The Flood Risk Management (Scotland) Act 2009 gives SEPA the responsibility to provide flood warning services in Scotland. SEPA currently provide warning through Floodline. Warnings are issued to all those registered and to local authorities and emergency services within flood warning areas. Flood Warning Areas are those areas where SEPA have the river and coastal monitoring in place to provide Flood Warnings for a targeted geographic area. Currently no such services are provided for the River Deugh catchment. However, a general warning is normally issued for the Dumfries and Galloway area.

Scottish Power, as part of their water management procedures, provides first stage or second stage flood warnings to relevant parties depending on the severity of the event.

- First stage flood warning: Issued to local residents and farms;
- Second stage flood warning: Issued to SEPA and Dumfries and Galloway Council for more serious events such as:
    - Higher river levels in the rivers Deugh at Brownhill and or Ken at Strahannah gauging stations;
    - Higher inflows to Kendoon reservoir;
    - Clatteringshaws Dam level approaching the spillway 585 feet OD; and
    - Loch Ken approaching 152 feet OD.

10.2 Flood Warning for Carsphairn

An effective flood warning system requires a number of key issues to be addressed including;

- Forecast/Warning lead time, i.e., the time period between issuing the warning and flooding occurring.
- Forecast/Warning accuracy.
- Warning dissemination
- Public/Community acceptance of the scheme

This assessment focusses on lead time. Without a lead time that will allow residents, businesses and emergency services to respond to flooding, a flood warning system will not be effective. Flood forecasts and warnings are driven by observed rainfall and flow data (rain gauges or flow gauges upstream of the area at risk) or rainfall or flow forecasts (often resulting from rainfall radar data).

It should be noted that before implementing a flood warning system, SEPA undertakes a cost-benefit analysis to check economic viability of the scheme. The benefit-cost ratio for a flood warning scheme is directly proportional to the number of people likely benefiting from the scheme. Therefore, implementing a comprehensive flood warning scheme to serve a small population is unlikely to be economically viable. However, there are lower cost flood warning schemes that could be considered for Carsphairn as an alternative, or part of, the implementation of a flood protection scheme.

A meeting was held with Michael Cranston, Flood Warning Manager at SEPA in August 2015 to discuss the steps required to develop a flood warning system for Carsphairn.

It was noted that Carsphairn was not within one of the Flood Warning Target Areas and Potentially Vulnerable Areas in SEPA's 'Flood Warning Strategy 2012 to 2016'. However, within the strategy there is a provision to consider service delivery options for areas not served by specific flood warning areas. SEPA have developed a 'grid to grid' rainfall-runoff model for the whole of Scotland based on a 1 km grid resolution. It would be possible to provide either grid based rainfall predictions for use in a local hydrological model, or provide grid based flow outputs from the grid based model. Methods of data transfer would need to be discussed and agreed with the council, e.g., whether the models are run within SEPA or by the council, but the discussions were encouraging in that SEPA were looking to develop ways of developing flood forecasting services in response to community needs.

The steps required for the development of a formal flood warning system for Carsphairn would be;

- Installation of river flow monitoring station upstream or close to Carsphairn. The station would need to be developed according to national standards. In consultation with SEPA, Dumfries and Galloway Council are in the process of installing a gauge just upstream of Carsphairn.
- Calibration of local scale hydrological model based on observed rainfall (existing stations, e.g., Drumjohn) and new gauged flow data
- Comparison of calibrated model with predictions based on SEPA grid to grid model
- Assessment of key flow thresholds for flood initiation. This can be done using the flood model already developed for this study, linked to the calibrated gauge data.
- Testing of flood warning system by using grid to grid model output to provide flood warnings for period of time on offline mode.
- Discussions with SEPA regarding operation of flood warning system.

The timescale for the development of a formal SEPA-led scheme could be of the order of years rather than months. There would be a need to install, calibrate and collect data from the new flow gauge and to use the data to calibrate a hydrological model. A reasonable flow record would be required to allow model calibration. As the formal scheme is developed there is scope to work with the local community to develop a community level flood warning system linked to the proposed flow monitoring station.

The installed gauge will transmit water level data in real-time to council offices with the potential for a series of trigger levels (based on water level) that can initiate local scale warnings to emergency services and to selected members of the local community (e.g., local flood forum and/or people known to have flooded in the past).

Criteria for initiating these warnings would be discussed and agreed with the local community. Such a system would not be linked to SEPA's forecasting systems (e.g., predictions of future rainfall or river flows). However, based on weather forecasts and local knowledge on historical floods a degree of flood warning could be provided to the community. For example, if river levels are observed to pass a given threshold level and general weather forecasts predict further rainfall, local mitigation measures could be put in place such as alerting emergency services to stay vigilant, to installation of property level protection (sand bags) and/or individuals moving valuable items to upstairs rooms or locations outside of areas of known flooding.

11 Summary and Conclusions

This report presents the results of a detailed flood study for Carsphairn, which was commissioned by Dumfries and Galloway Council and Scottish Power following the flooding on 30 December 2013.

The flood study undertook a detailed hydrological assessment for the Water of Deugh, developed a linked 1D/2D flood model of the river through the village, produced flood inundation maps for a range of return period flood events, assessed a range of possible flood alleviation measures and presented an initial cost-benefit analysis for the preferred flood mitigation option.

The 1D/2D mathematical model of Water of Deugh was calibrated against limited recorded flood level and flood extent information from the December 2013 event. The modelled flood extent matched reasonably well with the observed data. The modelling work indicated that flooding in Carsphairn would have occurred even without $15m^3/s$ flow released from Drumjohn Needle Valve.

The calibrated model was used to simulate inundation during floods with a range of return periods (2, 5, 10, 25, 50, 100, 200, 200 plus climate change, and 1000 year return periods). Flood maps were prepared for each event.

The model results predicted that 31 properties would be affected during a 200 year flood, of which 27 are residential. The threshold return period at which flooding would start to affect properties is 2 to 5 years.

A number of flood mitigation options were considered, including; flood storage upstream; direct defences where flood risk areas could be protected by flood walls and embankments; natural flood management measures, and removal of sediment from the river. Modelling work indicated that only the direct defence option would be able to provide the desired level of protection to all affected properties in Carsphairn.

It was calculated that a total of 500 m of flood walls and 850 m of flood embankments would be required to protect all the flood risk areas in Carsphairn from a 200 year flood. Wall heights would generally be up to 1 m high (above existing ground level), and embankments up to 1.5 m high. Options were also considered for defence schemes that provided lower levels of protection. In comparison, a scheme which would provide 10 year level of protection would require defence heights on average 0.2 m lower than that required for the 200 year.

An initial cost-benefit analysis was undertaken, based on the model results and conceptual level flood alleviation options. Hence, the cost-benefit analysis should be considered as initial only, with a high degree of uncertainty. A bias factor of 60% was added to cost estimates for the flood defence schemes as per standard practise for initial cost-benefit analyses.

The conclusions of the cost-benefit analysis were that the benefit-cost ratio for direct defence scheme is positive (1.27). This only includes direct flood damages and inclusion of environmental and social factors and intangibles would likely result in a higher ratio. This indicates that such a scheme would be economically feasible. However, Carsphairn village has not been designated a PVA (Potentially

Vulnerable Area) by SEPA and it may not, at least in the foreseeable future, attract grant aid from the Scottish Government.

Based on the outline cost-benefit analysis undertaken, a scheme consisting of direct defences and providing up to 200 year level of protection would appear technically and economically feasible and worth further consideration.

The study has shown that although the 1D/2D ISIS mathematical model which was specifically set up for this project produced good correlation with the December 2013 flood data, it can be refined to increase its accuracy in some areas by collecting additional topographical survey to cover, in particular, the large floodplains on the west bank of the river in the vicinity and upstream of the confluence with Carsphairn Lane, large fields between the A713 and Green head Strand and additional cross sections along the Strand. Such data would increase the confidence in model predictions, particularly in those areas where survey data is limited at present.

Appendix A – Photographs from December 2013 and January 2015 Events

Photo1: Flood waters travelling south-east on A713 (Dec 13)

Photo 2: Flooding opposite church (Dec 13)

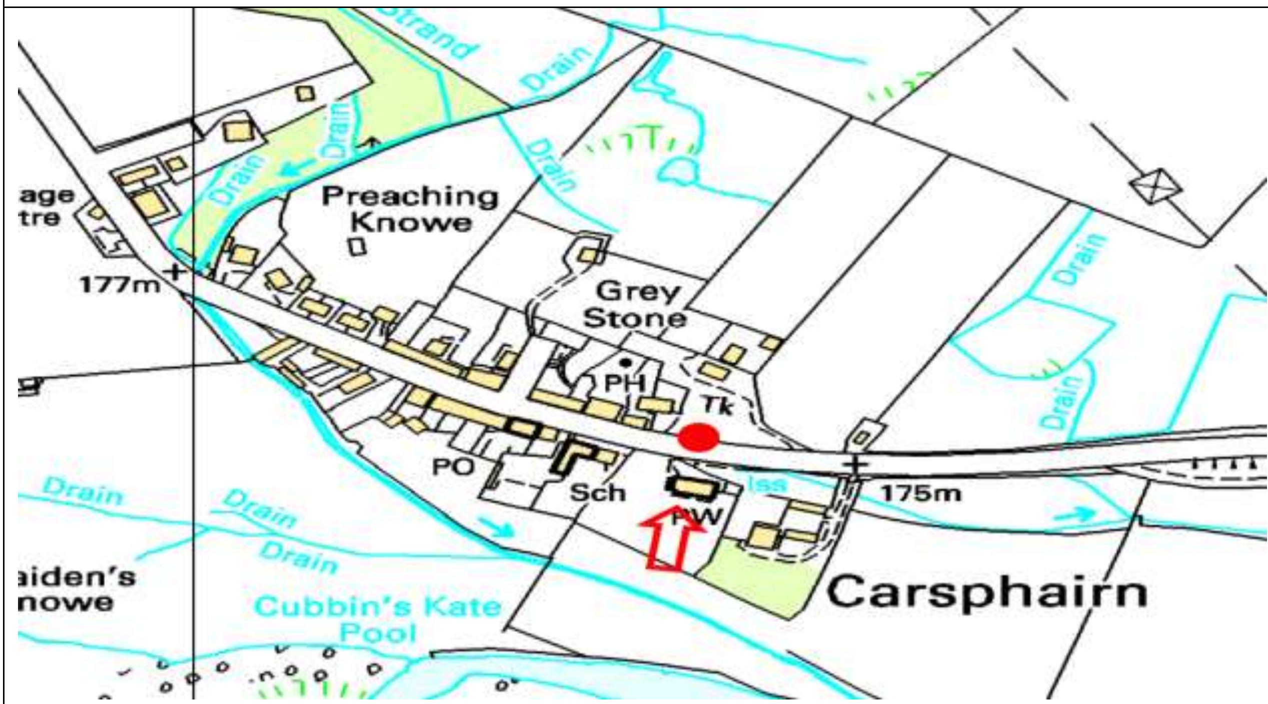


Photo 3: Flooding opposite church at Kirklee (Dec 13)

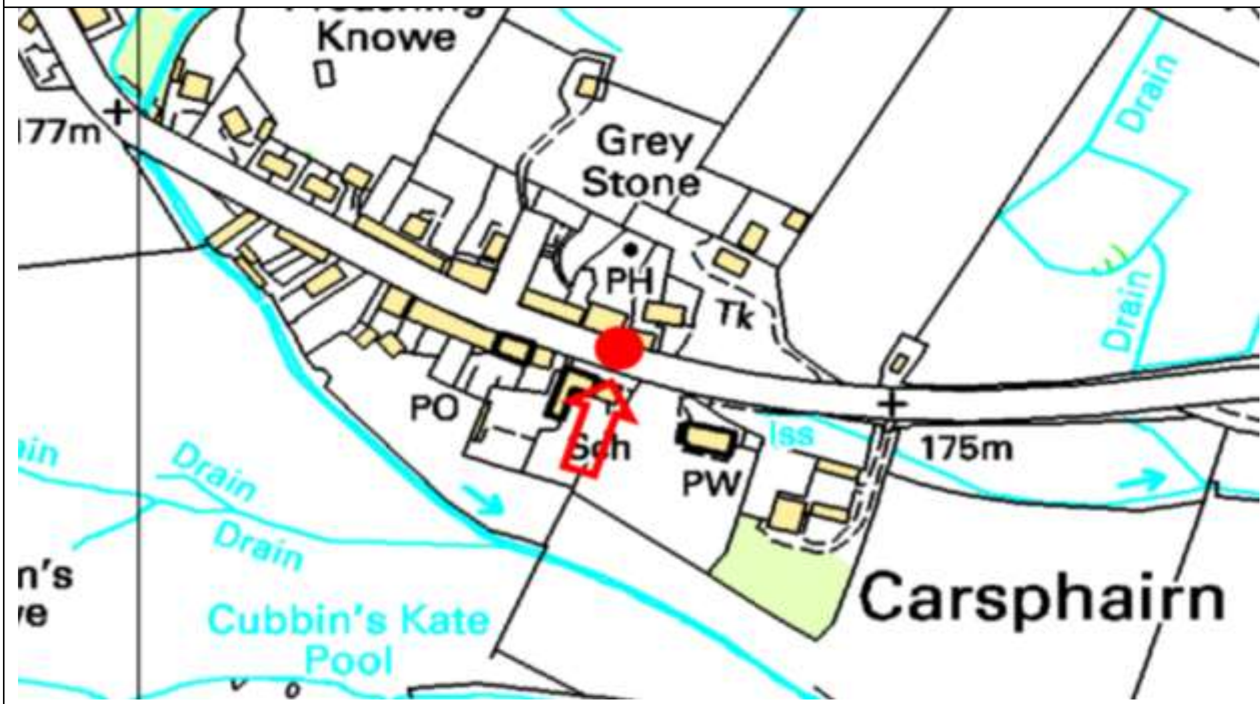


Photo 4: Flood waters overtopping from Green head Strand to the south of the village. (Dec 13)

Photo 5:Flow paths from Green head Strand (Jan 15)

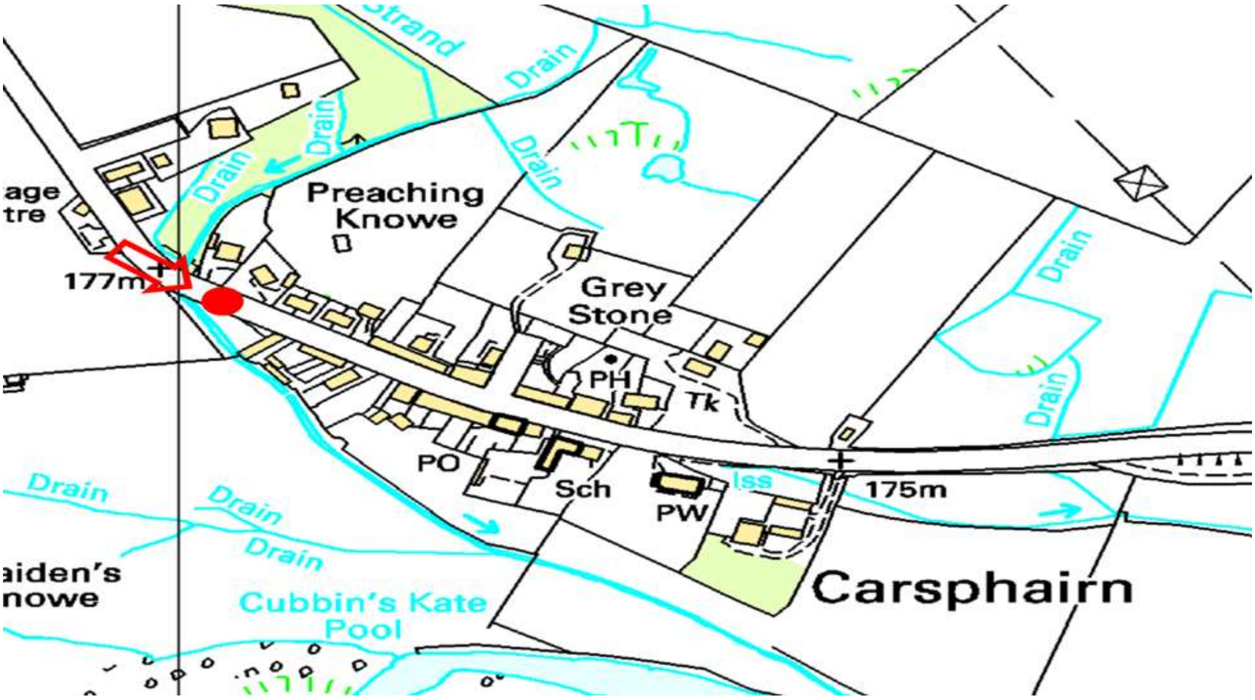


Photo 6: Flow paths from Green head Strand (Jan 15)

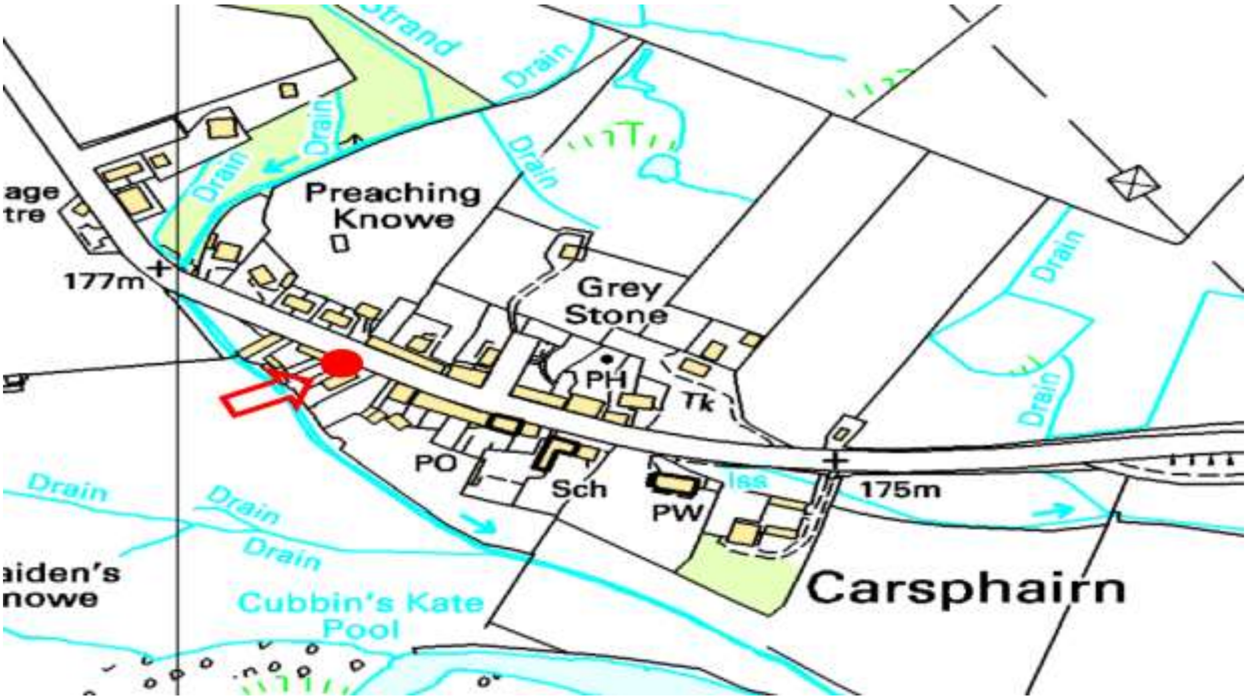


Photo 7: Flooding from Water of Deugh (Jan 15)

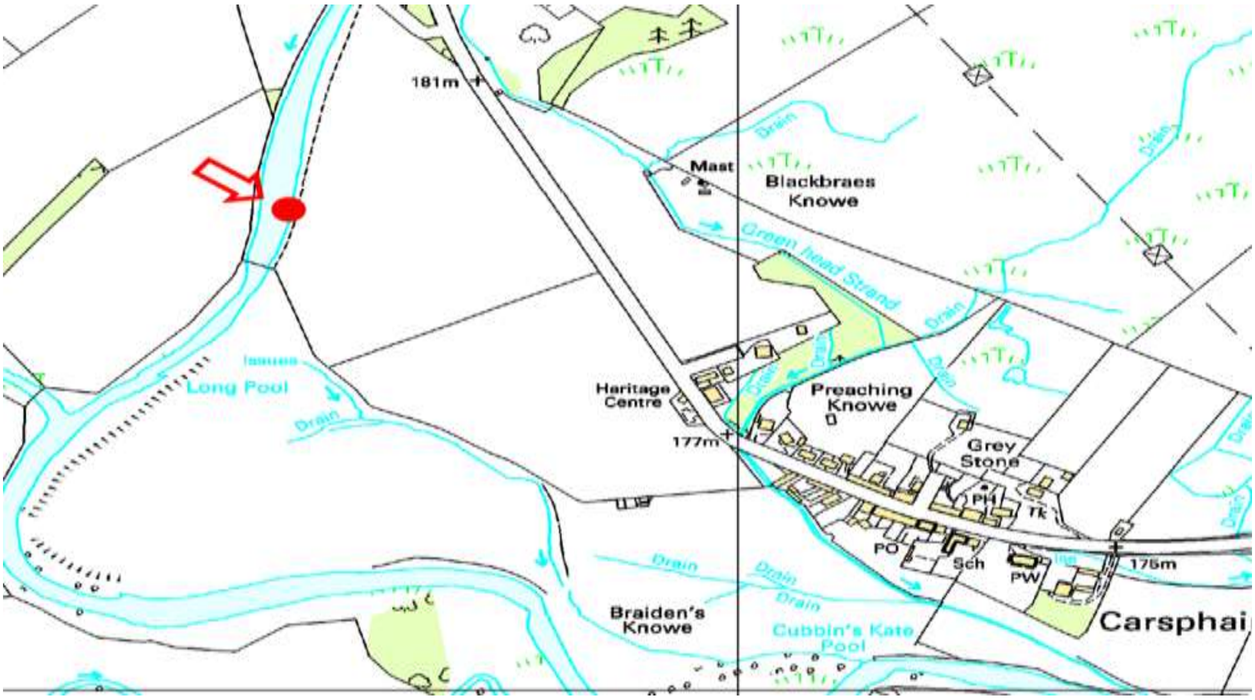


Photo 8: Flood plain flow towards A713 (Jan 15)

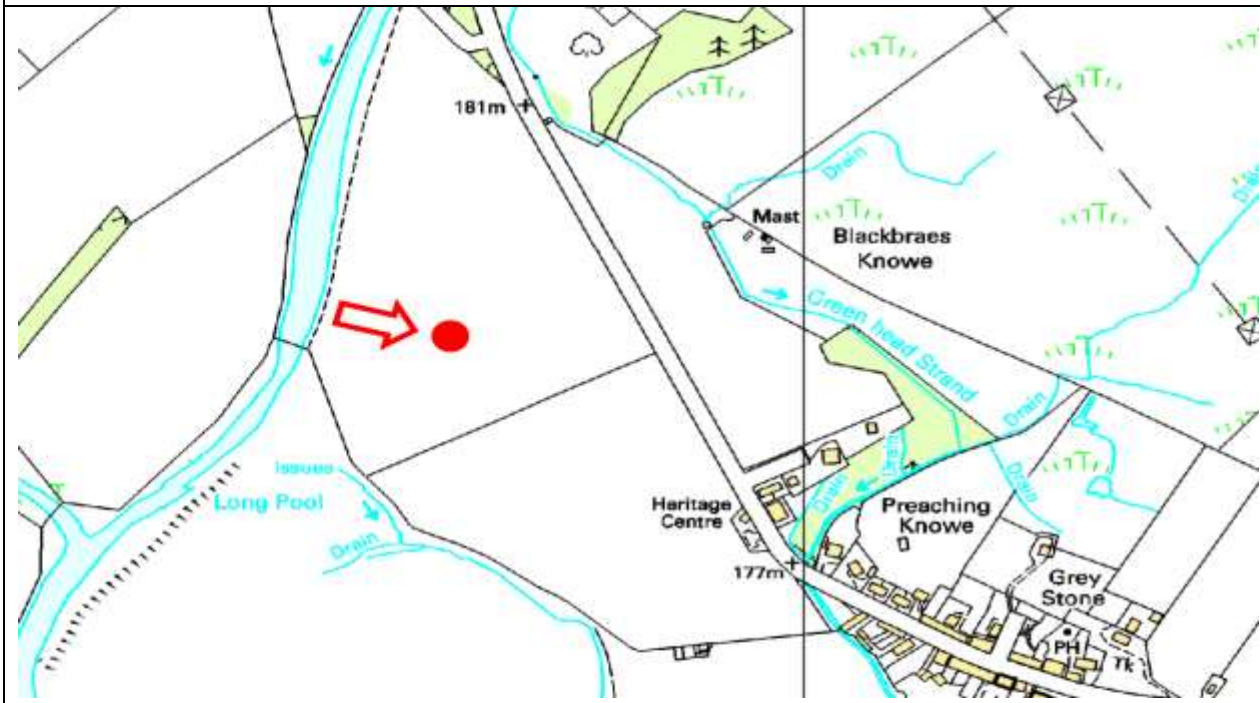
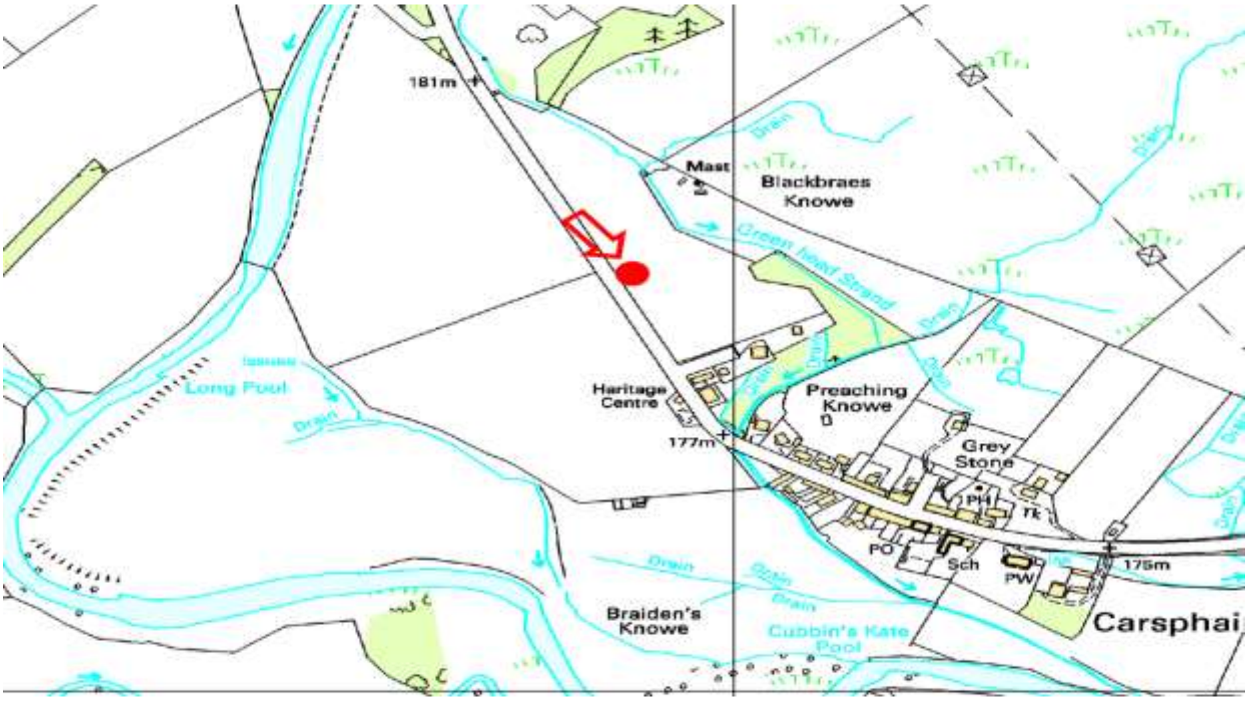


Photo 9: Flow path of water overtopping A713 (Jan 15)



Appendix B: Flood Mapping (2-1000 year Return Period)

Figure 34: Predicted 2 year inundation

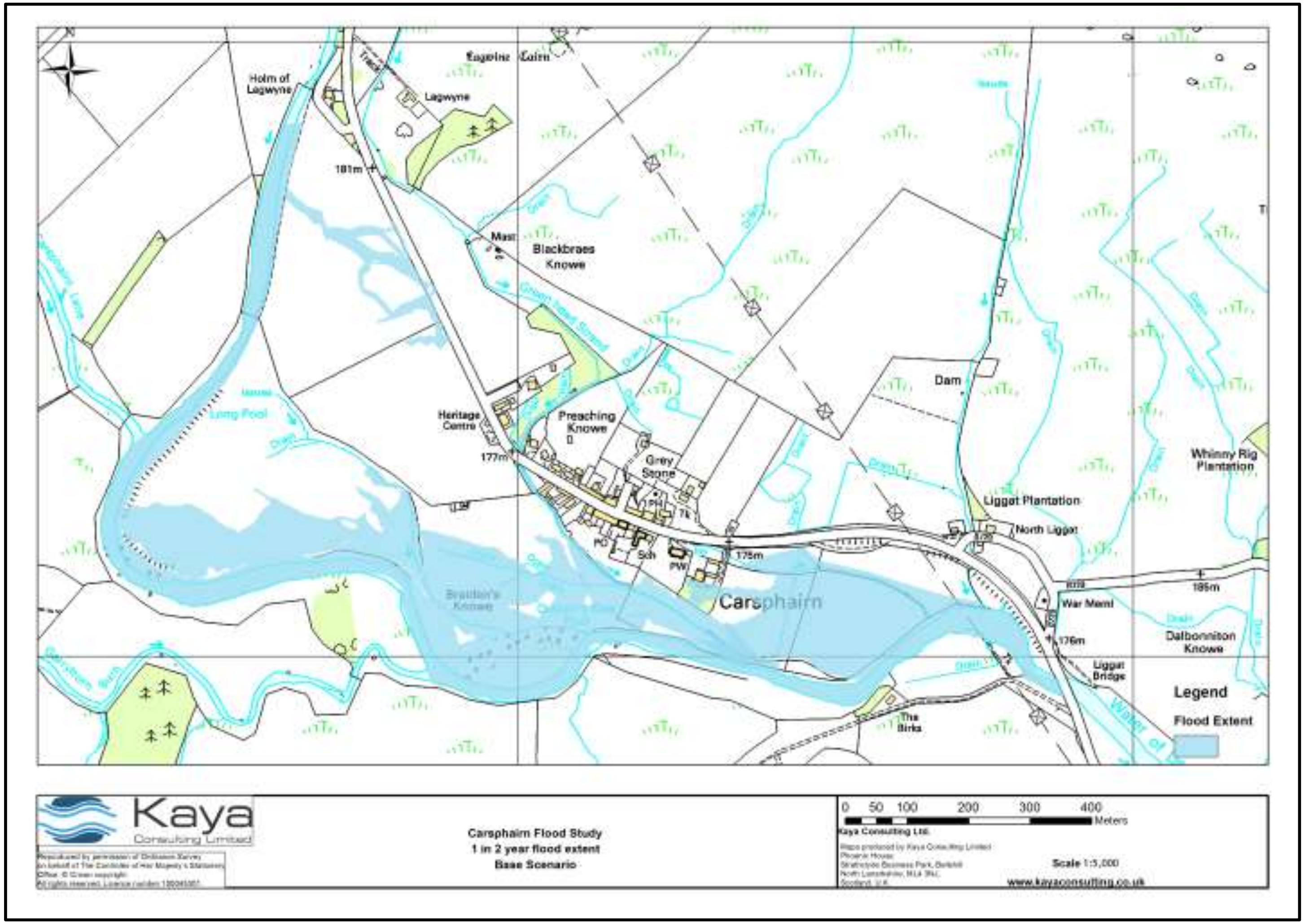


Figure 35: Predicted 5 year inundation

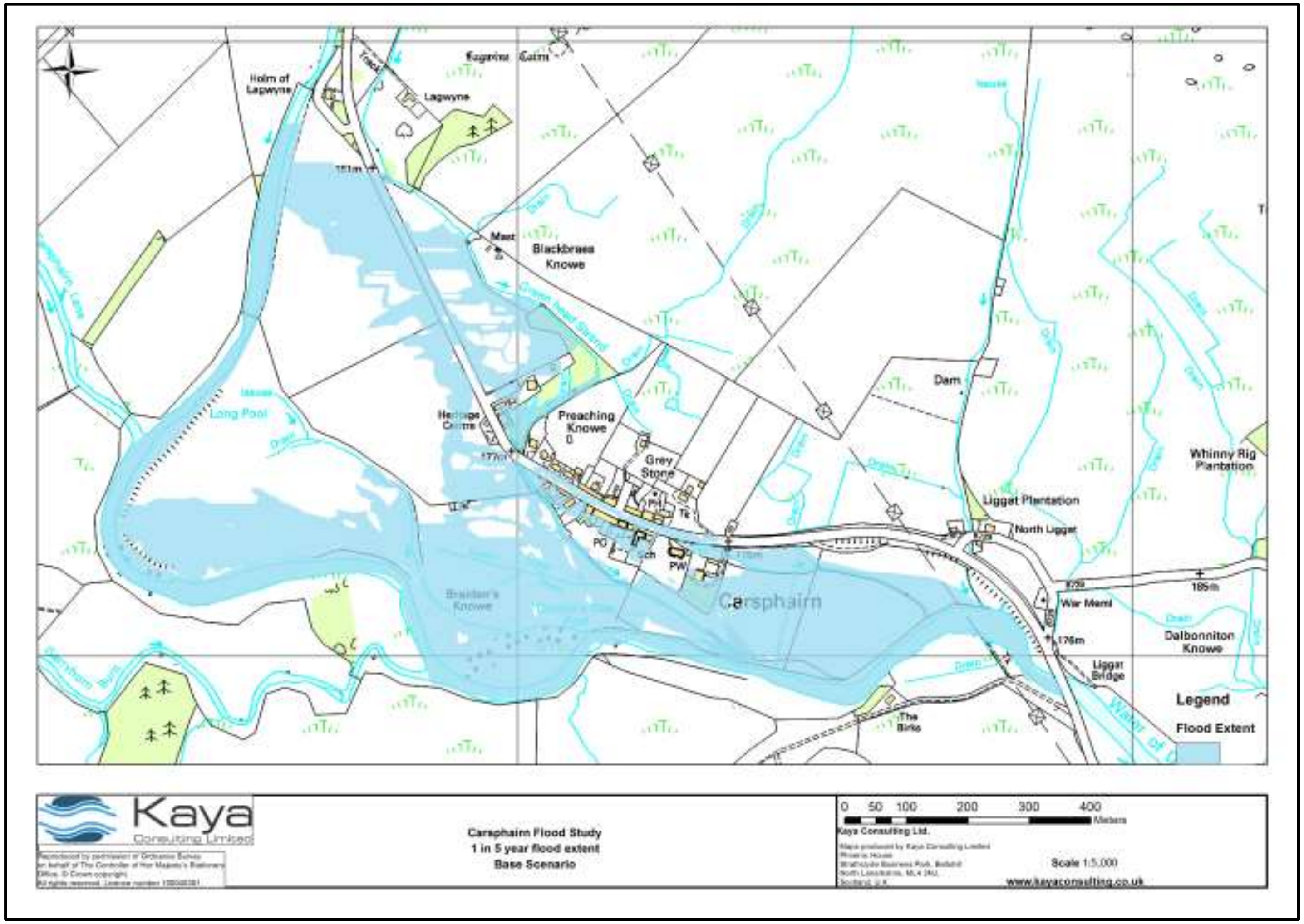


Figure 36: Predicted 10 year inundation

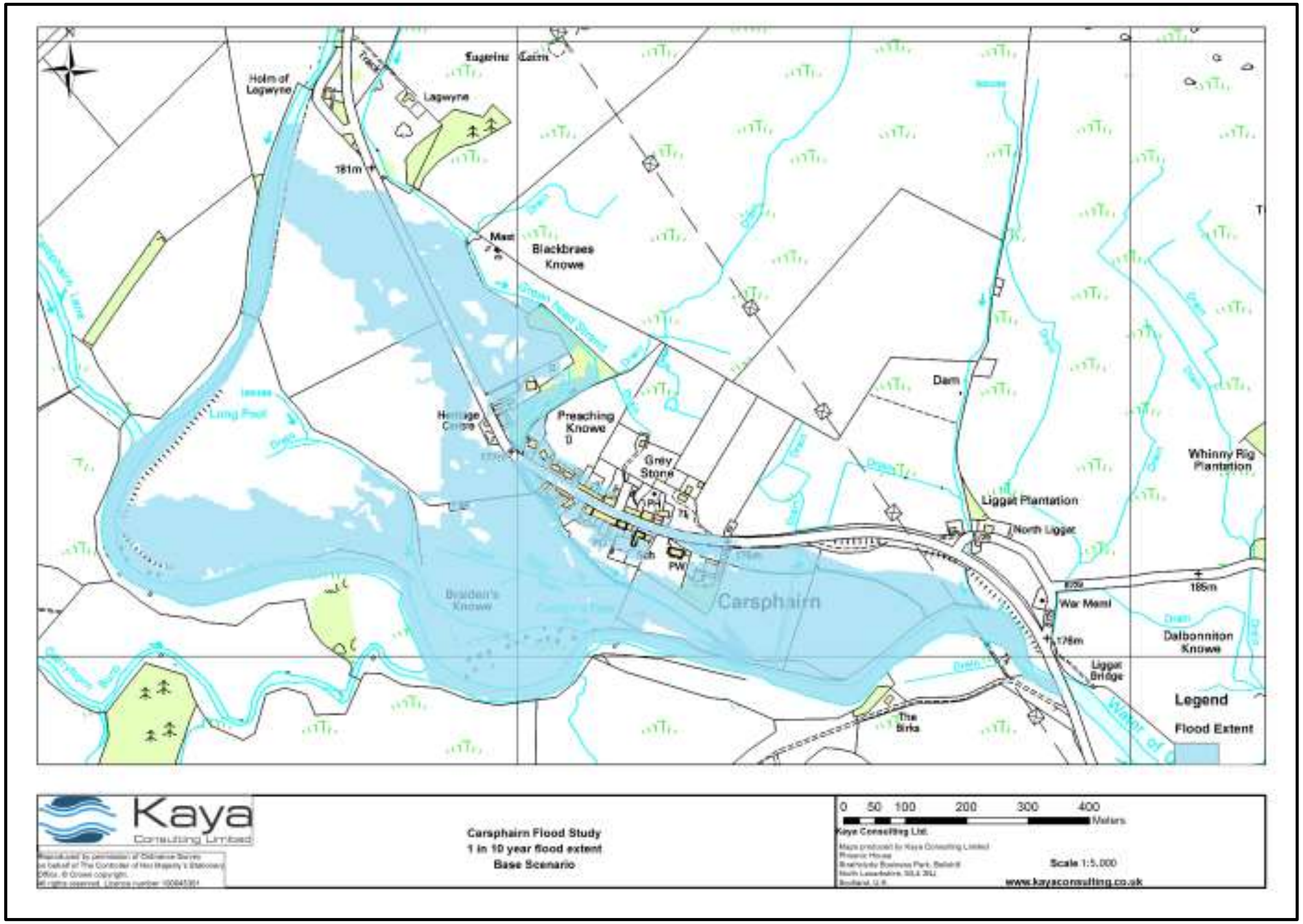


Figure 37: Predicted 25 year inundation

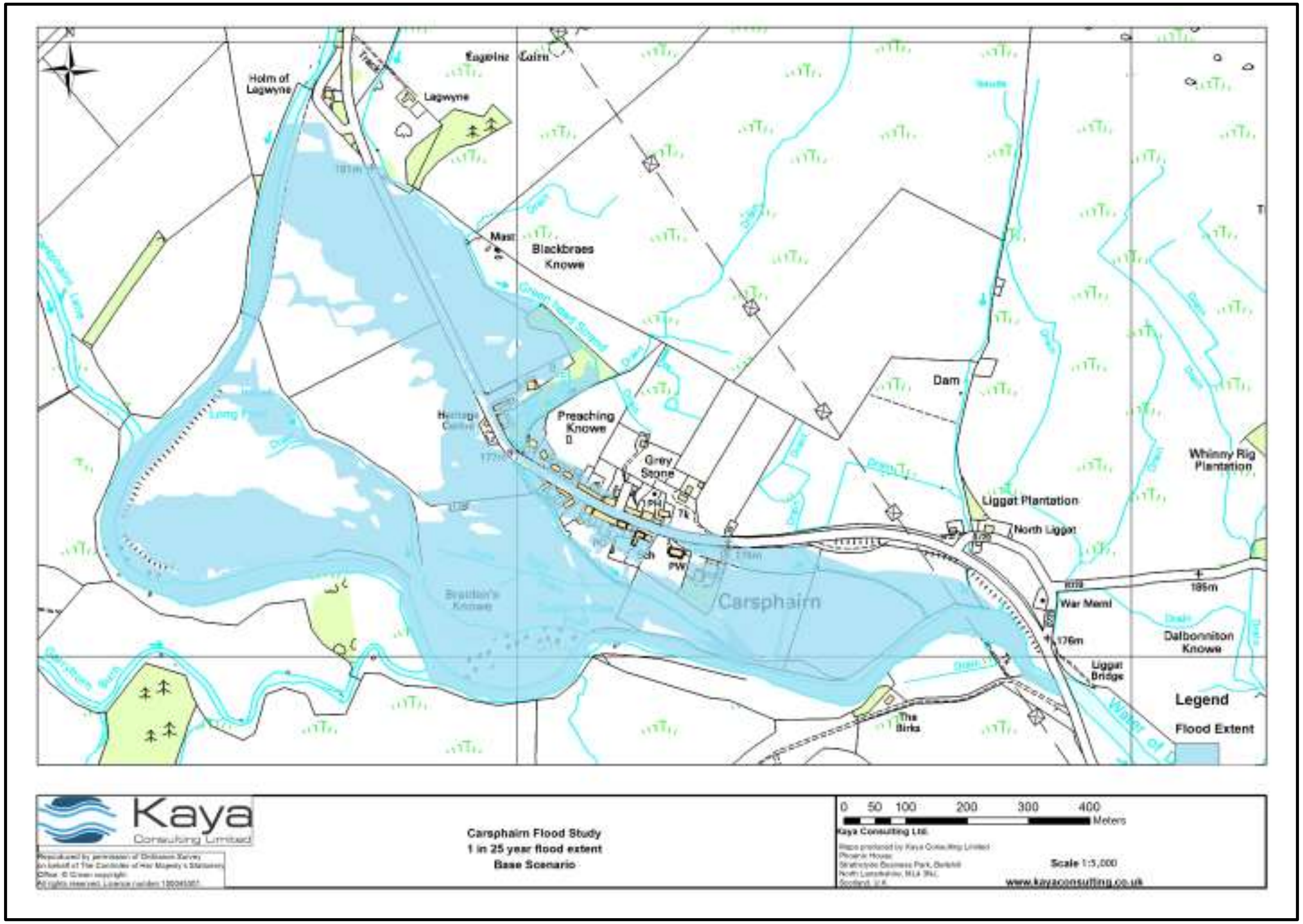


Figure 38: Predicted 50 year inundation

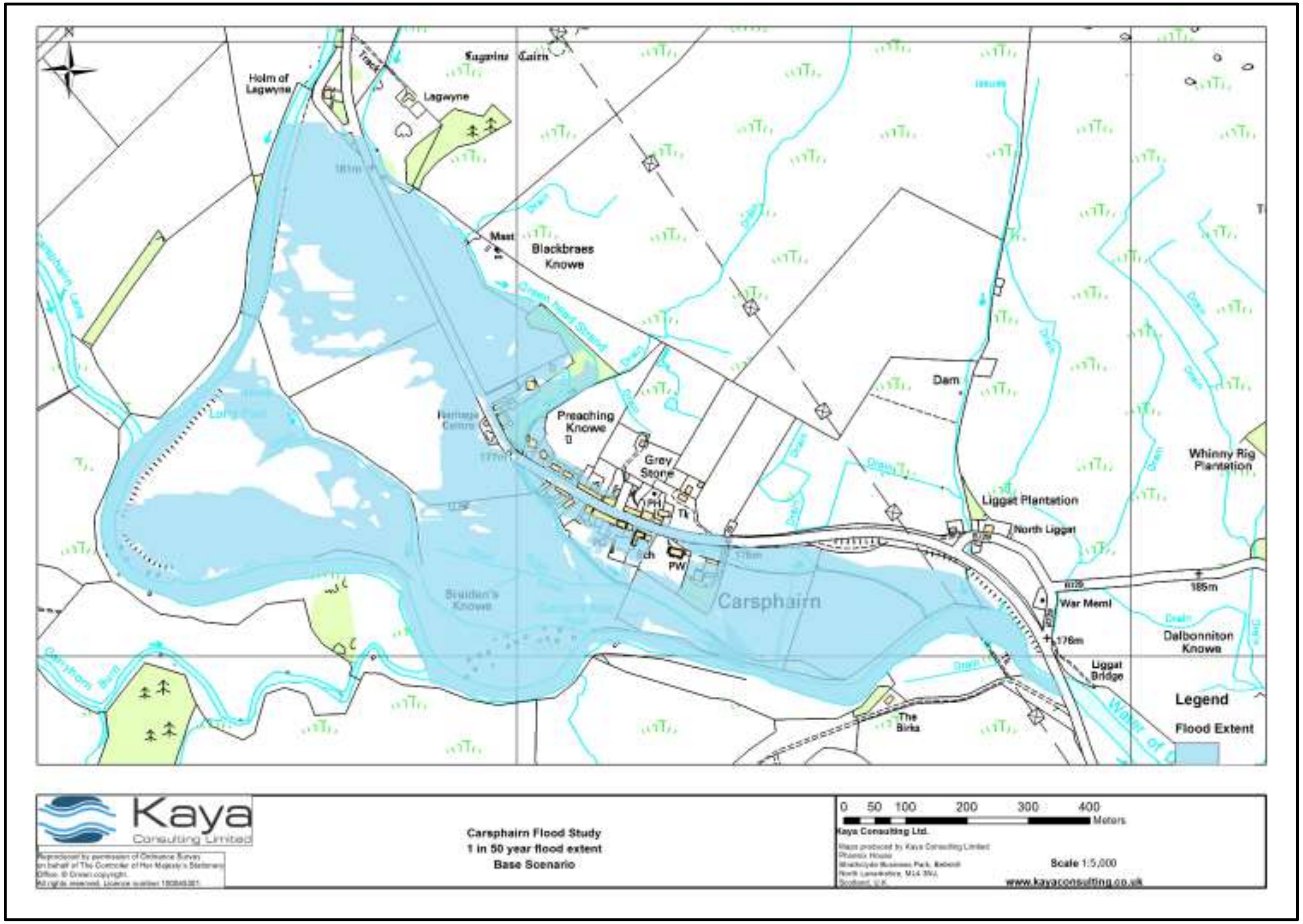


Figure 39: Predicted 100 year inundation

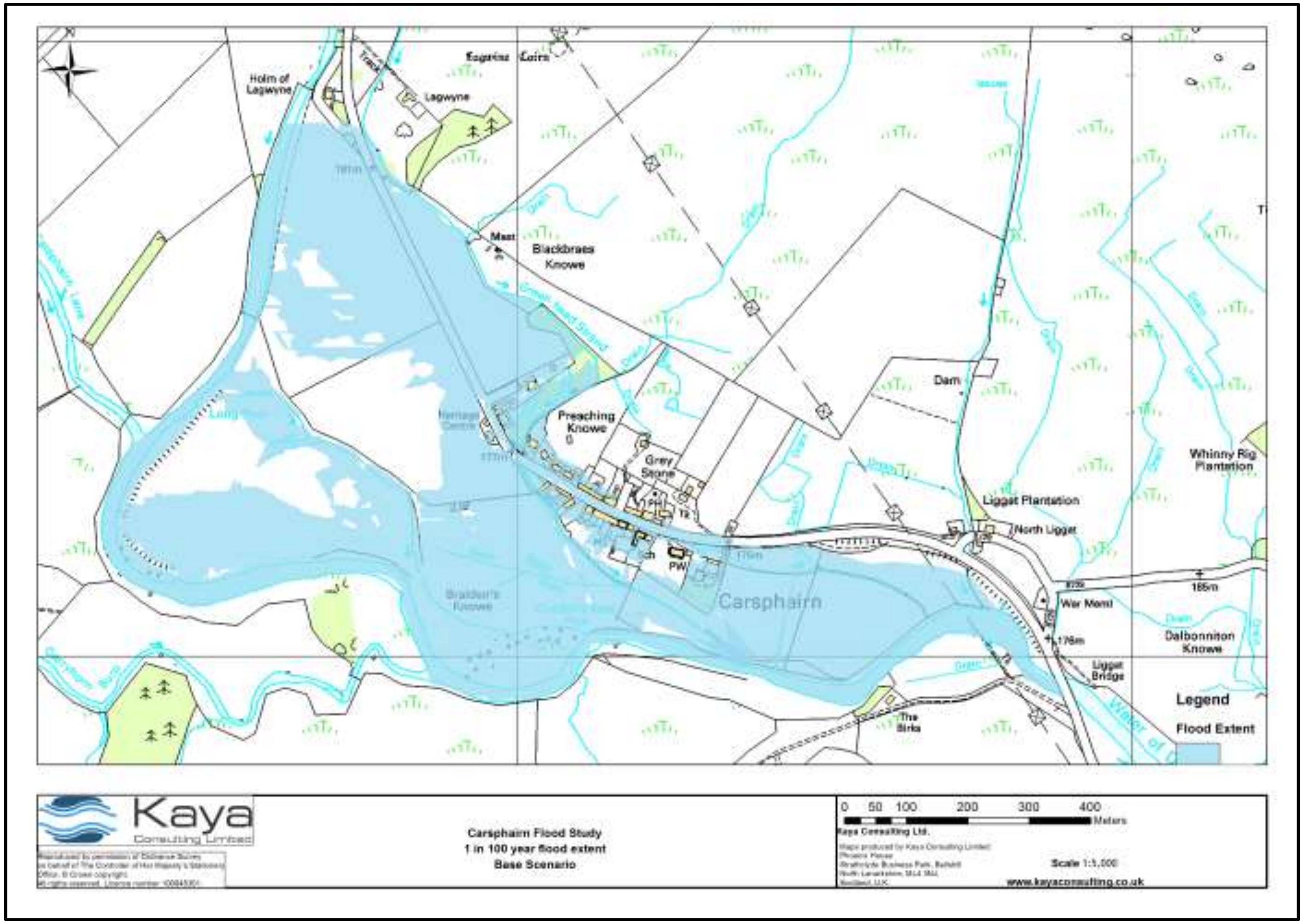


Figure 40: Predicted 200 year inundation

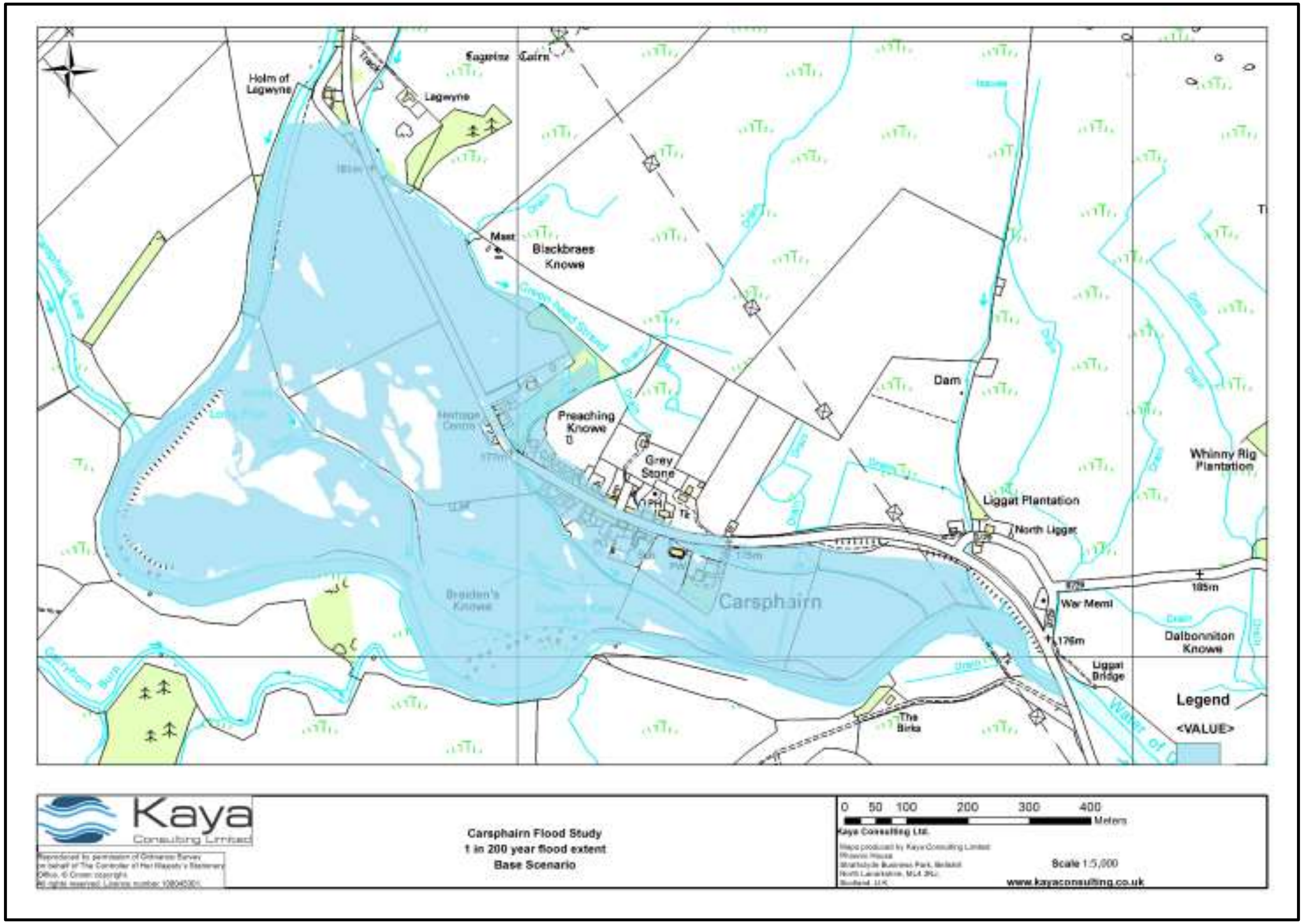


Figure 41: Predicted 200+CC year inundation

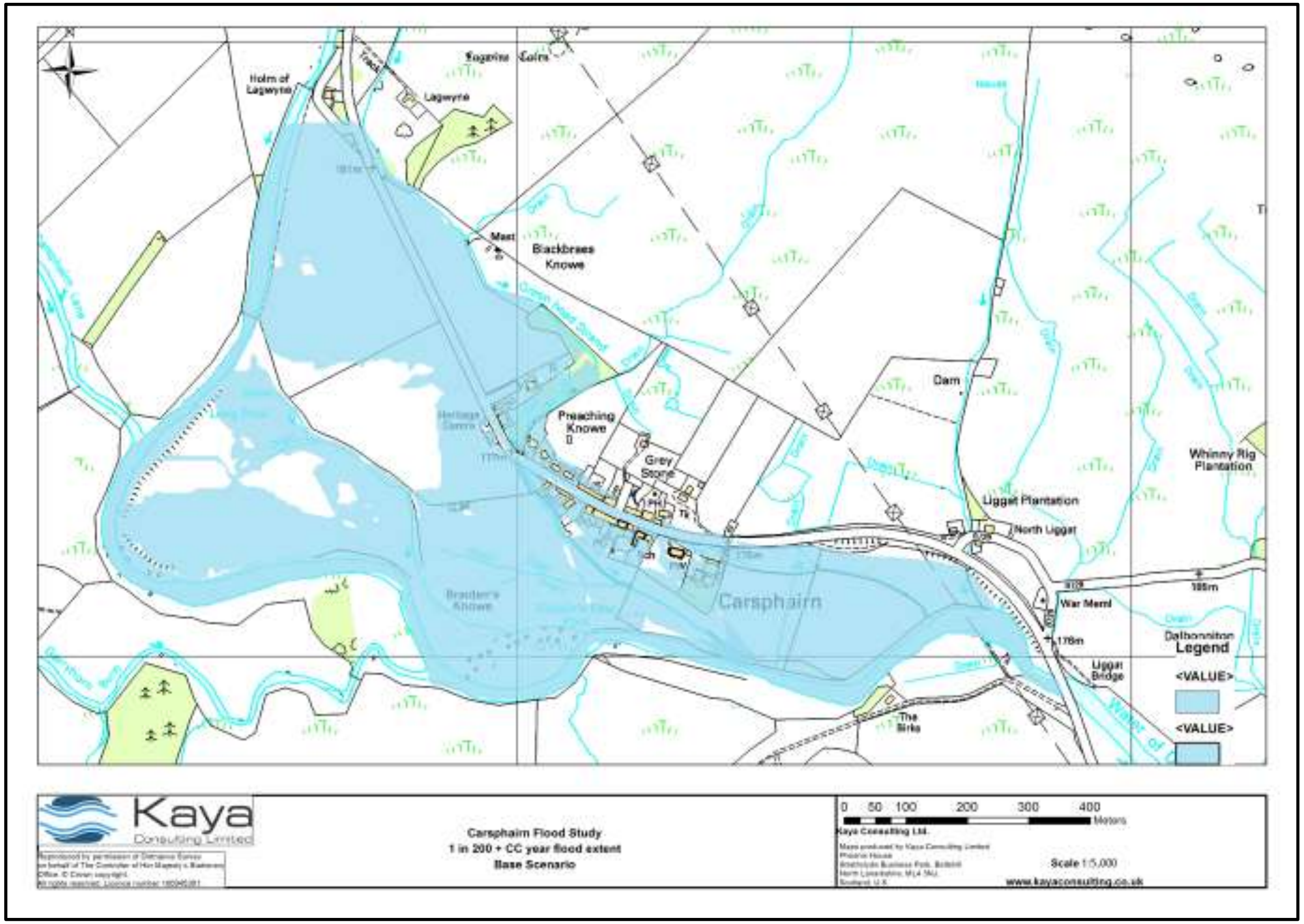
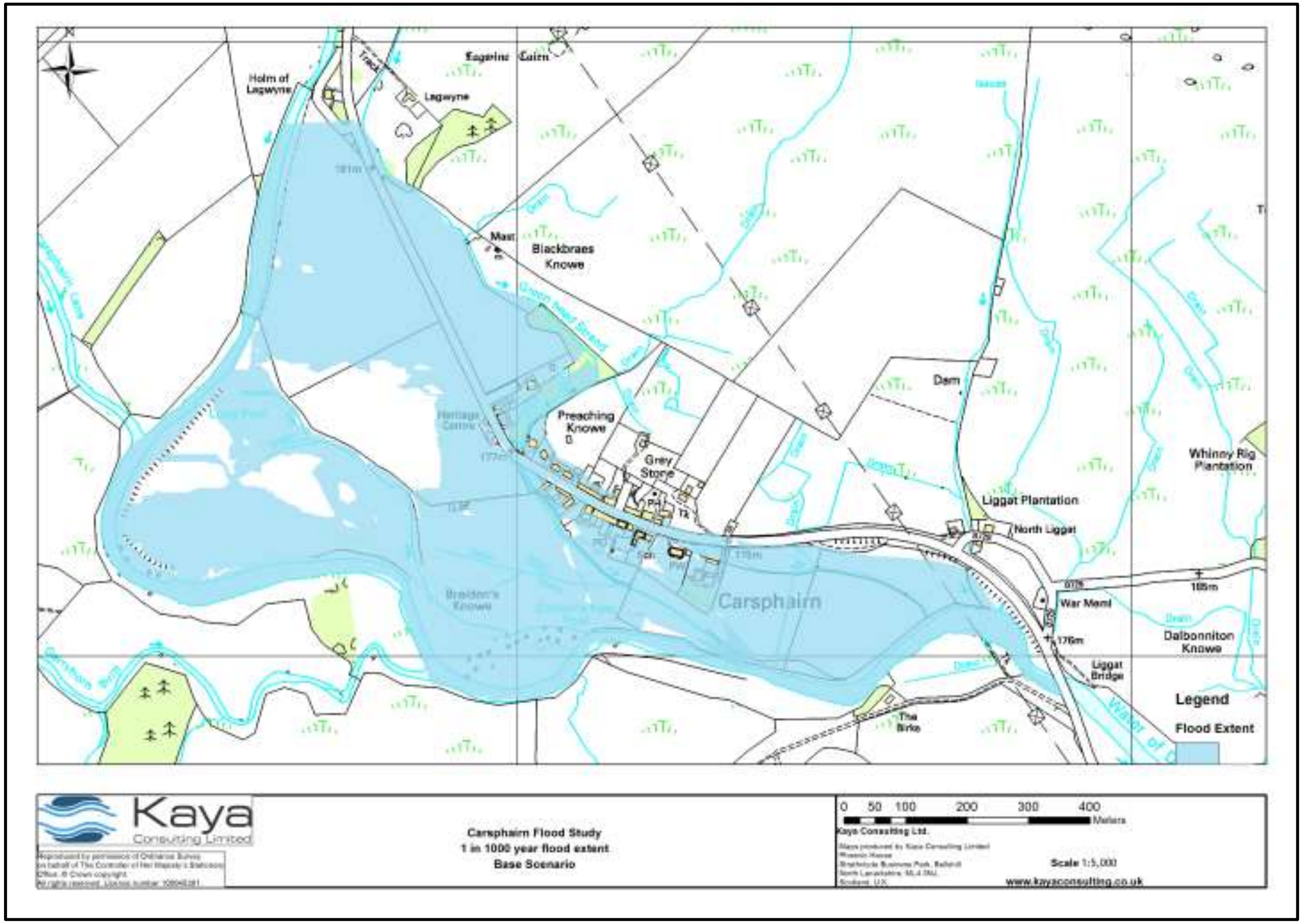


Figure 42: Predicted 1000 year inundation



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