Dumfries and Galloway Council

Moffat Flood Study

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Executive Summary

Dumfries and Galloway Council commissioned Kaya Consulting Ltd. to undertake a study to assess flooding risk within the town of Moffat from fluvial and pluvial sources. The key fluvial sources of flooding are the River Annan, Birnock Water, Crosslaw Burn and Frenchland Burn. The key source of pluvial flooding is runoff from Gallow Hill that sits to the north and north-west of a number of properties in the town.

There is a history of flooding in Moffat, with the most recent extreme flood event occurring in December 2015, when a number of properties were flooded and the main roads in and out of the town were cut-off. SEPA in their 2011 National Flood Risk Assessment study identified Moffat as a Potentially Vulnerable Area (PVA) with 370 residential properties and 50 non-residential properties identified at risk of flooding.

The current assessment undertakes a detailed hydrological assessment for the four watercourses within the study area, develops a linked 1D/2D flood model of the four watercourses through the town, 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 option.

The model predictions for the 1 in 50 year event show a reasonable correlation with the locations of flooding recorded/observed during the December 2015 event. This indicates that the event likely had a return period of the order of 1 in 50 years.

The model predicted that 102 properties would be affected during a 200 year fluvial flood, 45 residential and 57 non-residential. The number of properties predicted to flood is smaller than indicated in the SEPA 2011 study, due to the improved methods and datasets used in the current assessment. Around 50 properties are considered at risk from surface water flooding from Gallow Hill.

A number of flood mitigation options were considered, including; flood storage upstream of Moffat; direct defences where flood risk areas could be protected by flood walls and embankments; increasing the flow passing capacity of the A701 Annan Bridge South; two-stage channel, and lowering of the river bed to increase flow conveyance.

An initial appraisal of the potential options indicated that the most effective and sustainable flood mitigation option is direct defences (i.e. protecting the affected areas by flood walls and embankments) combined with increased conveyance and increasing capacity of culverts receiving runoff from Gallow Hill.

An initial cost-benefit analysis was undertaken, based on the model results and a high-level (conceptual) design of flood alleviation options. Hence, the cost-benefit analysis should be considered as outline 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 a direct defences scheme providing 200 year level of protection is less than unity (of the order of 0.7). This indicates that the scheme would not be economically viable. However, this is based on an estimated scheme cost involving sheet-pile cut-off walls below proposed flood walls and embankments. This is considered necessary due to the expected permeable ground conditions along the line of the defences. Cut-off walls are intended to stop seepage under flood defences. Sensitivity checks undertaken indicated that it may be possible to increase the benefit-cost ratio above unity if there was no or little requirement for sheet-pile cut-off walls below flood defences. Limited ground investigation data available for the Annanside area suggests that ground conditions in this area are permeable in nature at least down to 6m below ground. Therefore, sheet-pile cut-off walls will likely be required, although it may be possible to manage seepage water within the defended areas if the rate of seepage flow was sufficiently low.

Based on the above, it is recommended that the next stage of the project should involve an investigation to assess seepage and refine the estimated cost of the scheme. In addition, the efficacy of flood defences should be assessed for all areas, and in particular in the Annanside and The Glebe area. Given the type and extent of defences involved, it may also be beneficial to involve a contactor to identify possible savings which could be made to reduce the cost of the scheme. Should the cost of defences be able to be reduced below £14M, this would result in a benefit-cost ratio above unity and would indicate that such a scheme would be economically feasible and may be suitable to attract grant aid from Scottish Government.

1 Introduction

1.1 Background

Kaya Consulting Ltd was commissioned by Dumfries and Galloway Council to undertake a detailed flood study for the town of Moffat, focussing on flooding risk of the urban areas from the River Annan, Birnock, Frenchland and Crosslaw Burns, as well as pluvial (surface water runoff) flooding from Gallow Hill.

In 2011, as part of the Flood Risk Management (Scotland) Act 2009, SEPA completed a National Flood Risk Assessment and identified Moffat as a Potentially Vulnerable Area (PVA) with 370 residential properties and 50 non-residential properties identified at risk of flooding. The estimated Annual Average Damages (AAD) was calculated to be £680,000. SEPA identified a number of actions to mitigate flooding risk. These include;

- completion of a Flood Protection Study;
- strategic flood mapping and modelling;
- development of a new flood warning and flood forecasting system;
- development of Community Flood Action Groups; and
- general flood awareness raising, Emergency Plan/Response, review of planning policies, and identification of measures for self help.

The present study addresses the need for flood mapping and modelling, as well as the completion of a Flood Protection Study.

1.2 Past Studies

A number of studies have been carried out to assess flooding risk in Moffat and to assess potential flood mitigation measures. These include the following:

1) Moffat Flood Prevention Feasibility Study – Options for Alleviating Existing Flooding Problems, Dumfries and Galloway Council, 2003
2) Moffat Flood Study, Ewan Group, 2005
3) Moffat Flood Study (Rev A), Ewan Group, 2006
4) Moffat Flood Study – Gallow Hill Runoff - Conceptual Design, Dumfries and Galloway Council, 2011
5) Gallowhill Wood Surface Water Management Option Review, Mouchel, 2013
6) Moffat Flood Study – Report on Phase 2 Ground Investigation, Ian Farmer Associates, 2014

Some of these studies are more than 10 years old (i.e. those going back to 2003-2006). In the last 10 years there have been significant changes to hydrological methods for design flow calculation, mathematical modelling techniques, as well as legislation and guidance related to flooding. Data collected at that time to support flood modelling may not represent the current conditions. Therefore, any information from such studies will be used with caution. More relevant information is available from more recent studies (i.e. those dating back to 2011 to 2014) and use of this information will be made in the current study where relevant.

New topographical survey of the watercourses within the study area was obtained for this assessment, and a full update of hydrological estimates is made.

1.3 Aims and Objectives

The main aim of the study is to identify the risk of flooding from fluvial and pluvial sources within the town of Moffat, to enable Dumfries and Galloway Council to make informed decisions on options available for flood risk management. Therefore, the work will include flood mapping and the development of outline flood mitigation measures, including outline costings for works and associated cost-benefit analyses. The findings of the study will be used by Dumfries and Galloway Council to make a decision on whether further actions can be taken to mitigate flood risk in the town and to identify potential land suitable for development in order to ease the on-going development pressures.

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

Table 1: Key Tasks

No.	Task	Where Addressed in Report
1	Review of previous studies and historical flood data, including door to door survey of properties identified as at risk of flooding.	Section 2
2	A condition assessment of all watercourses within the study area, including culverts, trash screens, structures and artificial and natural bed and banks of the watercourses. This will also include CCTV survey of relevant culverts, recommendations for maintenance, assessment of Scottish Water GIS data for wastewater network affected by flooding.	Section 2.7
3	Topographical survey to enable the construction of the required mathematical models of the watercourses within the study area.	Section 2.3
4	CCTV survey of relevant culverts.	Section 2.4
5	Hydrological assessment of all watercourses within the study area (i.e. River Annan, Birnock Water, Crosslaw Burn and Frenchland Burn).	Section 3
6	Hydraulic assessment of the above watercourses based on mathematical modelling.	Section 4
7	Preparation of flood inundation maps (similar to SEPA maps).	Section 4
8	Development of potential flood mitigation options, both from fluvial and pluvial sources.	Section 6
9	Option appraisal.	Section 6
10	Identify three feasible flood mitigation options to achieve: • A 0.5% AEP (including an allowance for climate change) standard of protection; • A 2% AEP standard of protection (or 1% AEP standard of protection if required by DGC);	Section 6

- 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; and
- "Quick Wins" i.e. options for improvements to the existing assets which will provide an increased standard of protection for relatively low cost.

1.4 Extent of Study Area and Description

Moffat is located around 21 miles north of the town of Dumfries. The town has a population of approximately 2,500 with the main local industries being agriculture, forestry and tourism. The town is situated on the western bank of the River Annan with the tributaries of Birnock Water, Crosslaw Burn and Frenchland Burn all joining the river along the east bank.

The study area extent is shown in Figure 1 and described in Table 2.

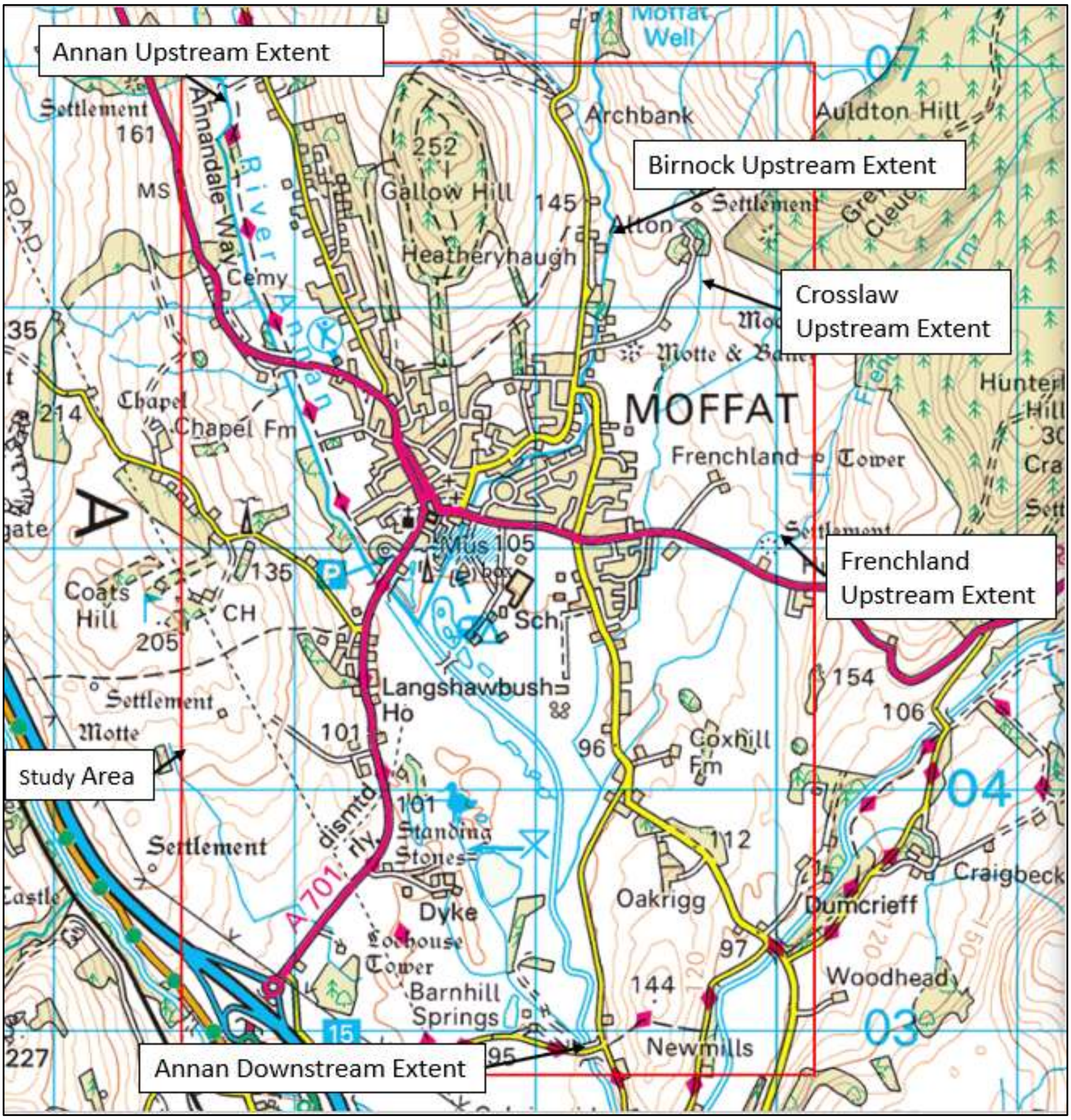
Table 2: Water course model extents

Water Course	Upstream	Downstream
River Annan	Footbridge approximately 1.2miles north of town centre (307685, 606909)	Barnhill Lane Bridge (extended) (309211, 603102)
Birnock Water	Approximately Sparrow Hill (Alton Cottages) (309307, 606336)	Annan intercept at South end of Station park (308493, 604696)
Crosslaw Burn	Approximately Alton Cottages (east side) (309666, 606099)	Approximately Coxhill Farm (309239, 603556)
Frenchland Burn	Approximately 400m north of A708 (310057, 605038)	Approximately Moffat Community Nature Reserve (309047, 603556)

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 Annan catchment is of the order of 1,500mm. Annual mean temperatures are expected to range from 9.4 to 9.7°C (Met Office: Regional Climate: Western Scotland.) The headwaters of the catchments within the study area are relatively steep, rising to the hills to the north and north-west of the town.

The A701 crosses the River Annan twice within the study area, as shown in Figure 1. For the rest of this report, the northern crossing (on Edinburgh Road shown as New Bridge on 1 in 10,000 scale OS maps) is referred to as Annan Bridge North and the southern crossing (shown as Annan Bridge on OS maps) as Annan Bridge South.

Figure 1: Study area for flood mapping and detailed flood modelling



2 Data Collection and Review

Key data obtained for this assessment are described in the following sections.

2.1 LiDAR Data

Filtered LiDAR (Light Detection and Ranging) data were downloaded from the Scottish Remote Sensing Portal. LiDAR is a remote sensing technology that produces high quality topographical point data that is converted into a gridded Digital Terrain Model (DTM) that is used in flood modelling studies. A LiDAR device is normally flown under an aircraft and works by illuminating a target with a laser and analysing the reflected light. LiDAR accuracies vary depending on the equipment used and the height of the aircraft. However, data is usually provided with an absolute spatial (horizontal) accuracy of 1 m and a vertical accuracy of the order of 0.15 m, although the relative accuracy (from point to point) is generally higher.

The raw LiDAR data has been filtered prior to its use in the modelling work, i.e. vegetation, buildings and structures have been removed from the survey data. Hence the DTM used in the modelling work represents “bare earth” elevations. Although the filtering techniques are well tested, there can be errors within dense urban areas, where there may be limited data on ground levels between buildings. In these areas the filtered DTM may be in error. To try and overcome some of these issues a check was made between LiDAR results in the study area with ground survey data at nearby locations. The ground survey was obtained for the purpose of this assessment (Section 4.2). The comparisons indicated that potential errors within the LiDAR data in urban areas did not exceed approximately 20-30mm. This was deemed acceptable for use within the study and no changes were made to the LiDAR data set.

2.2 Mapping

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

- 1:10,000 mapping; and
- 1:50,000 mapping.

2.3 Ground Survey Data

2.3.1 Cross Sectional Survey Including Structures

Although the study area is covered by LiDAR data, LiDAR is unable to penetrate below water deeper than around 0.2 m, so LiDAR surveys do not provide details of the channel form under the water level at the time of the survey. Therefore, in order to construct detailed mathematical models of the four watercourses within the study area, a channel cross-section topographical survey was undertaken. In addition, surveys were taken of in-channel structures that could affect the passage of flood waters. L&M Survey Services were commissioned to undertake these surveys and this work was completed in November 2017. The location of survey sections is discussed in more detail in Section 4.

2.3.2 Top of Bank Survey

A full top of bank survey was also obtained along the left hand bank of the River Annan (looking downstream) and both the right hand and left hand banks of the Birnock Water to identify gaps, low points and any changes in top of bank heights in between surveyed channel sections.

This additional survey work was completed in March 2018.

2.4 CCTV Survey

CCTV surveys are available for the following culverts:

- Hydro Avenue culvert;
- Harthope Place culvert;
- Greenwood Close culvert;
- Annanside culvert; and
- Short culvert under the A701.

2.5 Kaya Site Visits

A series of site visits were undertaken by members of the Kaya team. Site visits are listed below;

- 19/10/2017 – Kaya + Council teams;
- 27/11/2017 – Drop-in Session in Moffat – Kaya + Council teams;
- 23/02/2018 – site walkover by Kaya team;
- 08/03/2018 – Gallow Hill walkover – Kaya + Council teams + local representatives; and
- 15/03/2018 – Presentation of initial findings to local community (at Moffat town hall) – Kaya + Council teams.

2.6 Historical Flood Information

Information on historical flood events were obtained from:

- Public consultation meeting (drop-in session);
- Site visits;
- Internet and social media research; and
- SEPA Evidence and Flooding Advice Service.

Historical flood events were sourced from members of the public at the drop-in session and public consultation meeting, and from internet searches utilising mainly new websites and social media to find incidence and photographs of flood events in the area. These incidences have been mapped and presented in Figure 2 and cross reference to their detail, source and flooding type in Table 3. Related photographs can be found in Appendix A.

The vast majority of these instances of flooding can be attributed to fluvial flooding events, from the River Annan and surface water flooding from Gallow Hill. However, there are also incidences noted from the Birnock Water and from surface water from the golf course south west of the town.

The location of events found from the SEPA Evidence and Flooding Advice Service are shown on Figure 3. Appendix B details flooding events from the SEPA Evidence and Flooding Advice Service.

Figure 2: Historical flood events

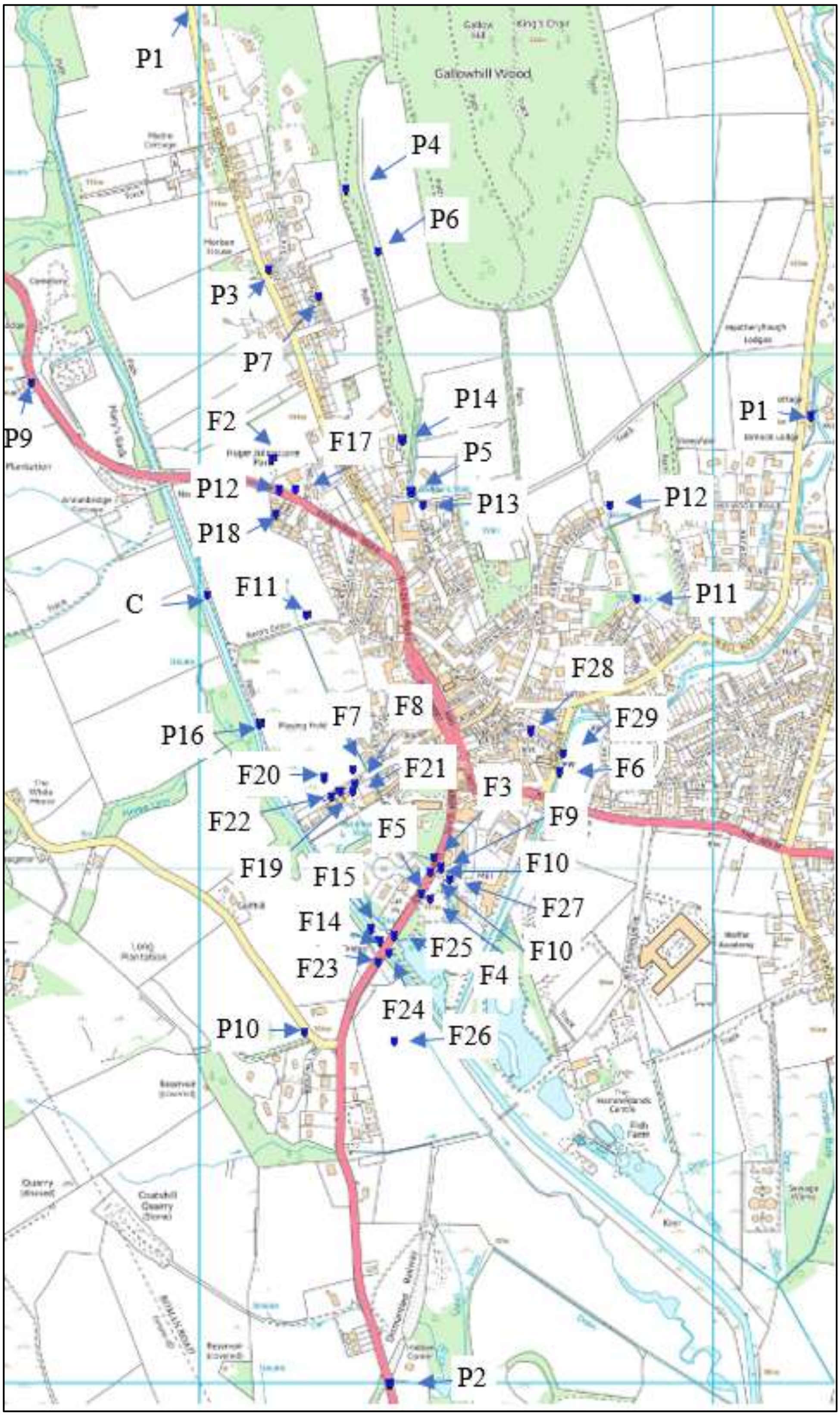


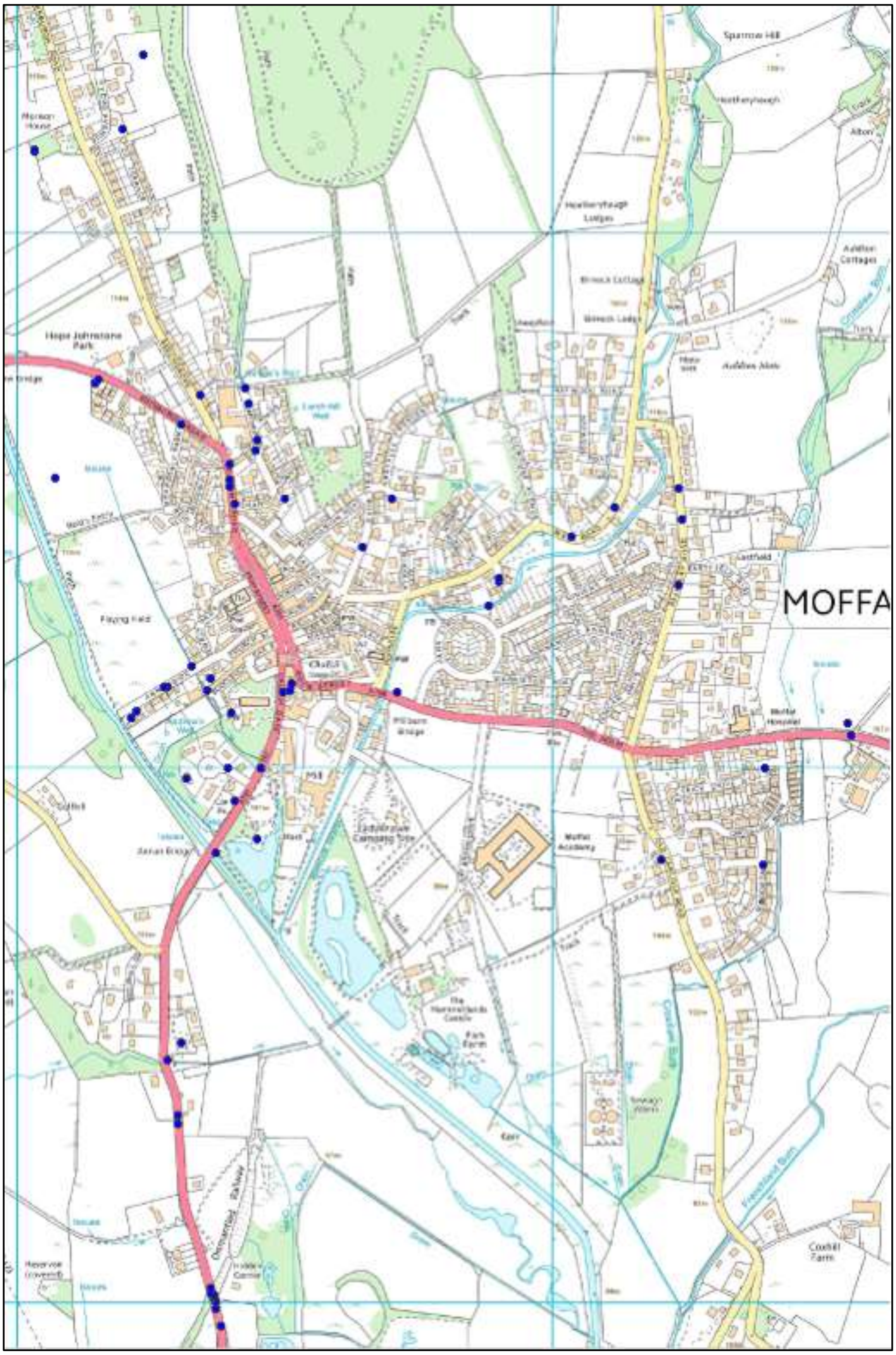
Table 3: Historical Event Details (referring to points in Figure 2. SEPA data provided in Figure 3 and Appendix B)

Map Reference	Appendix A - Figure	Data Source	Flooding identify	Flooding source	Date of event
Unknow exact position on roads	Photo A1: Historical Flood event Ref F2 (http://www.dng24.co.uk/flood-action-snub-for-moffat/)	Dumfries and Galloway what's going on Facebook page	All routes in and out of Moffat blocked by flooding	All Rivers	December 2015
F2	Photo A1	DnG24.co.uk	Deep Ponding in football park	River Annan	March 2016
F3	Photo 3	Boarders forest trust	Road flooding	Fluvial	December 2015
F4	Photo A3	Daily record	Ponding in park	River Annan	December 2015
F5	Photo A4	Daily record	Road flooding	River Annan	December 2015
F6	Photo A5	DnG24.co.uk	River close to bank in park	Birnock Water	December 2015
F7	Photo A6	Youtube	Road and Playing Fields Flooding	River Annan	December 2015
F8	Photo A7	Youtube	Playing Field Flooding	River Annan	December 2015
F9	Photo A8	Youtube	Park Flooding	River Annan	December 2015
F10	Photo A9	Youtube	Road flooding	River Annan	December 2015
F11	Photo A10	Youtube	Field Flooding	River Annan	December 2015
F12	Photo A11	Youtube	Road flooding	River Annan	December 2015
P1 (exact location unknown)	Photo A12	Boarders Forest Trust	Road flooding	Pluvial	December 2015
P2	Photo A13	ITV news	Road flooding	Fluvial	December 2013
F14	Photo A14	Public meeting	Bridge surcharging	River Annan	January 2016
F15	Photo A15	Public meeting	River overtopping	River Annan	January 2016
F16	N/A	Public meeting	Water can't get back into River due to embankment	River Annan	-

F17	N/A	Public meeting	Sports Centre Car park and Road flooding	River Annan	-
F18	N/A	Public meeting	Garden Flooding	River Annan	2015
P3	N/A	Public meeting	Water ponds from manhole, increased culvert capacity stopped issue	Pluvial / manhole from Gallow Hill	-
P4	N/A	Public meeting	Screen to be maintained to stop flooding	Pluvial from Gallow Hill	-
P5	N/A	Public meeting	Drainage system behind old academy inadequate	Pluvial from Gallow Hill	-
P6	N/A	Public meeting	Track included ditch which intercepts overland flows	Pluvial from Gallow Hill	-
P7	N/A	Public meeting	Flooding after trees cut doen 3/4years ago and through cracks in 1.2m retaining wall	Pluvial from Gallow Hill	-
P8	N/A	Public meeting	Lodge, cottage and garage flooding from hill runoff	Pluvial from Gallow Hill	-
F20	N/A	Public meeting	Ponding in playing field	River Annan	-
F19	N/A	Public meeting	Whole street and properties Flooded	River Annan	2009 2015
F21	N/A	Public meeting	Property flooding to sill in 2009 and overtopped threshold 2015	River Annan	2009 2015
F22	N/A	Public meeting	Property flooding	River Annan	2009 2013 2015
F23	N/A	Public meeting	Culvert Undersized	River Annan	-
F24	N/A	Public meeting	Bridge did not overtop in 2015 but was close to invert	River Annan	2015

F25	N/A	Public Meeting	Footpath Flooded	River Annan	-
C	N/A	Public Meeting	River straighten in roughly 1800	River Annan	1800
F26	N/A	Public Meeting	Flooded	River Annan	2015
F27	N/A	Public meeting	Popping manhole allows this side to flood drooping levels upstream	Sewer/ manhole	-
F28	N/A	Public Meeting	Basemen flooding	Birnock Water	-
P9	N/A	Public meeting	Culvert overtopped and water flows down the road towards the bridge	Pluvial	-
P10	N/A	Public Meeting	Surface Water Flooding from Golf Course runoff	Pluvial	-
P11	N/A	Public meeting	Culvert	River Annan	-
F29	N/A	Public meeting	Very close to overtopping the right bank, park has flooded and basements near Burnside flood	Birnock Water	-
P12	N/A	Site Visit	House not flooded but garage close from running off	Pluvial	-
P13	N/A	Public Meeting	Manhole lifted to pass more flow	Pluvial	-
P14	N/A	Public Meeting	Manhole lifted to pass more flow	Pluvial	-

Figure 3: Locations of SEPA evidence and flooding advice service identified events



2.7 Condition of Existing Banks and Flood Defences

A walkover survey was undertaken along the banks of all four watercourses and a visual assessment was made of existing river banks and flood defences. Most defences along the River Annan consists of natural banks and a low embankment along the eastern bank of the river. No significant bank erosion was noticed during walkover.

Birnock Water consists of some gabion walls along both banks. Some damage to gabion walls was noticed in the Park Circle and St Ninians Road area, it is understood that these are scheduled for repair. No significant scouring was noticed along Crosslaw and Frenchland Burns.

3 Hydrological Analysis

Design flow estimates are required for each of the study catchments, namely;

- River Annan;
- Birnock Water;
- Crosslaw Burn;
- Frenchland Burn; and
- Small watercourses draining Gallow Hill.

The assessment needs to calculate target design flows for a range of return periods and it needs to assess how these inflows should be distributed along each of the modelled reaches. The first stage of the analysis calculates design flows, with the second part identifying how the flows will be partitioned for each inflowing catchment.

3.1 Design Flow Estimation

3.1.1 River Annan

Design flow estimates are made for two calculation points along the River Annan; at the upstream and downstream ends of the mathematical model. The locations of these two points are shown in Figure 4. Catchment characteristics for each calculation point were extracted from the FEH Webservice and are shown in Table 4.

The catchment size at the downstream end of the study area is 56.7km^2, which includes all four watercourses. FEH would suggest that statistical methods would be the most appropriate for catchments of this size, although the catchment is at the lower end of the range of catchments that are considered suitable for statistical methods. Design flows for this assessment are based on the FEH Pooling Group methodology and results are compared to values generated using rainfall-runoff methods.

3.1.1.1 Available Data

The River Annan is gauged downstream of the site at Woodfoot (78006) and St Mungos Manse (78001). Both of these gauges are at a point on the river with significantly larger catchment areas than at the site; Woodfoot 217km^2 and St Mungos Manse 730km^2. Data for both gauges are not included in the standard FEH WINFAP dataset. A data request was made to SEPA to obtain data for both gauges;

- Woodfoot – spot flow data and AMAX water level data was provided. FEH would suggest this gauge is not suitable for Q_{med} calculation or Pooling Group assessments. However, the available spot flow data provided by SEPA (Figure 5) would appear to show a large spot flow dataset and data that groups well around a rating curve. Using the rating curve AMAX flows were estimated from the AMAX water level data. Spot flows appear to extend the observed rating curve up to 160m^3/s, compared to a calculated Q_{med} of 146m^3/s. The data was then used to calculate a single site flood frequency curve, shown in Figure 6, with results in Table 5.
- St Mungoes Manse – there was no data available for St. Mungos Manse.

Table 4: Catchment characteristics for River Annan

Parameter	River Annan Upstream	River Annan Downstream
EASTING (m)	307700	309200
NORTHING (m)	606900	602950
AREA (km^2)	32.44	56.72
ALTBAR (m)	361	327
ASPBAR (°)	214	208
ASPVAR	0.2	0.26
BFIHOST	0.47	0.477
DPLBAR (km)	6.21	8.78
DPSBAR (m/km)	214.7	190.3
FARL	0.999	0.999
FPEXT	0.0274	0.04010
LDP	11.07	15.88
PROPWET	0.72	0.72
SAAR (mm)	1518	1496
SAAR4170 (mm)	1557	1523
SPRHOST	40.92	41.12
URBCONC1990	-	-
URBEXT1990	0.0001	0.004
URBLOC1990	-	-
URBCONC2000	-	0.745
URBEXT2000	0	0.0053
URBLOC2000	-	0.324

Figure 4: Study catchments with key flow calculation points as red dots

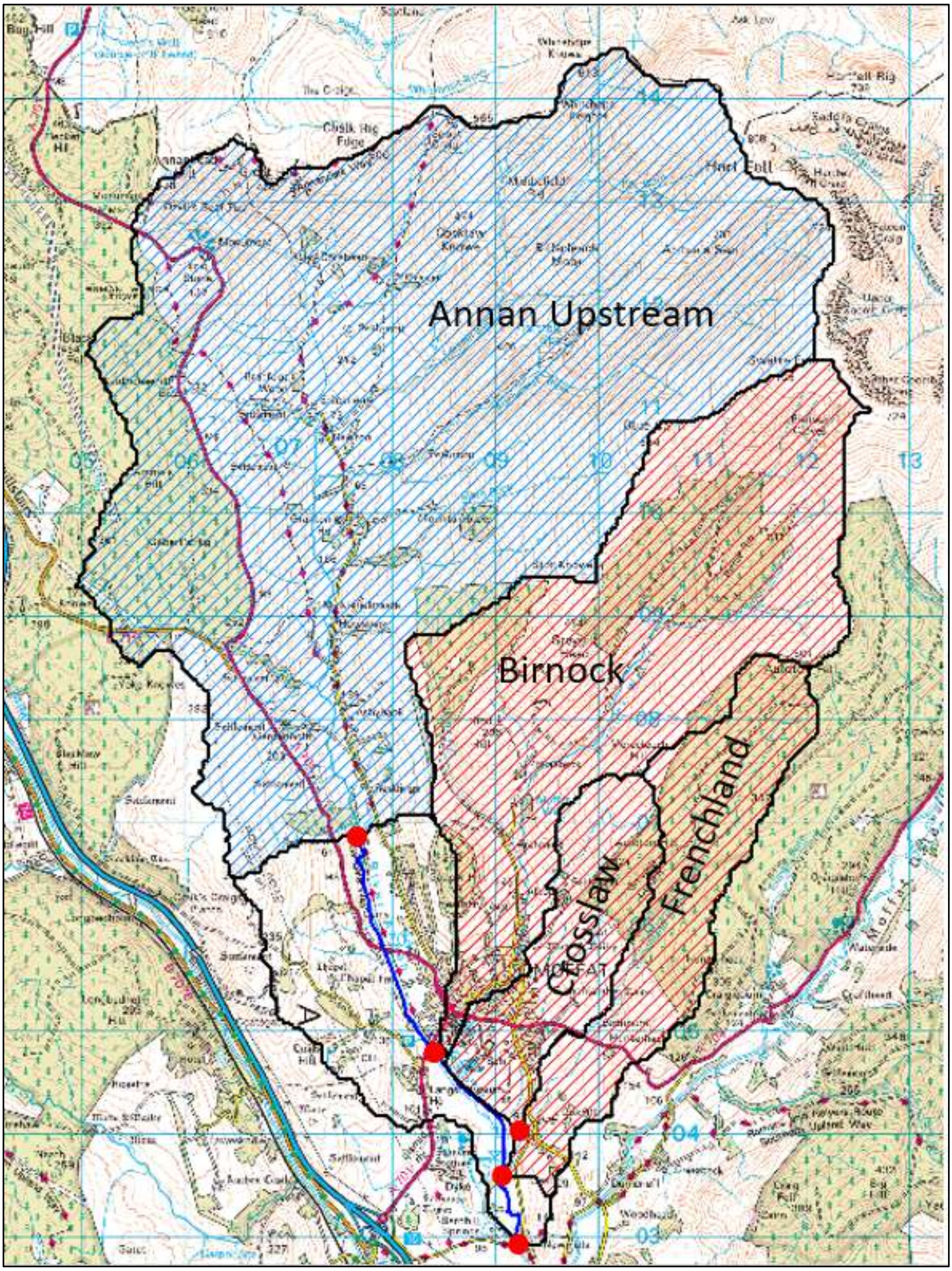


Figure 5: Woodfoot spot flow measurements

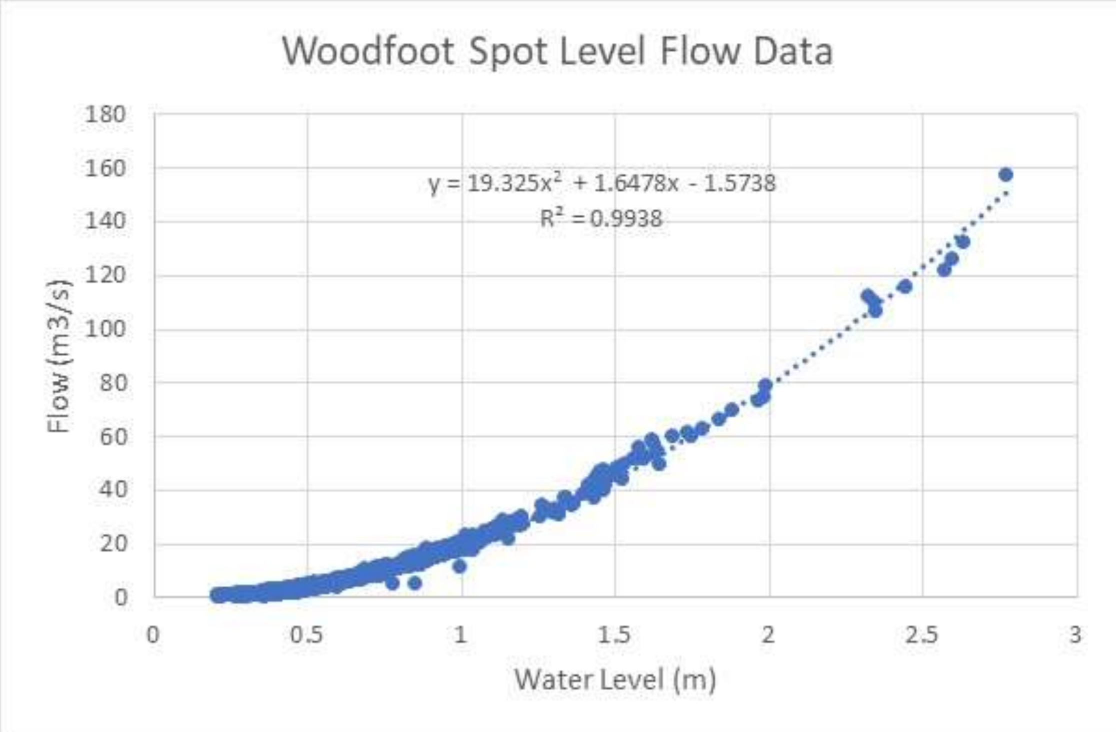
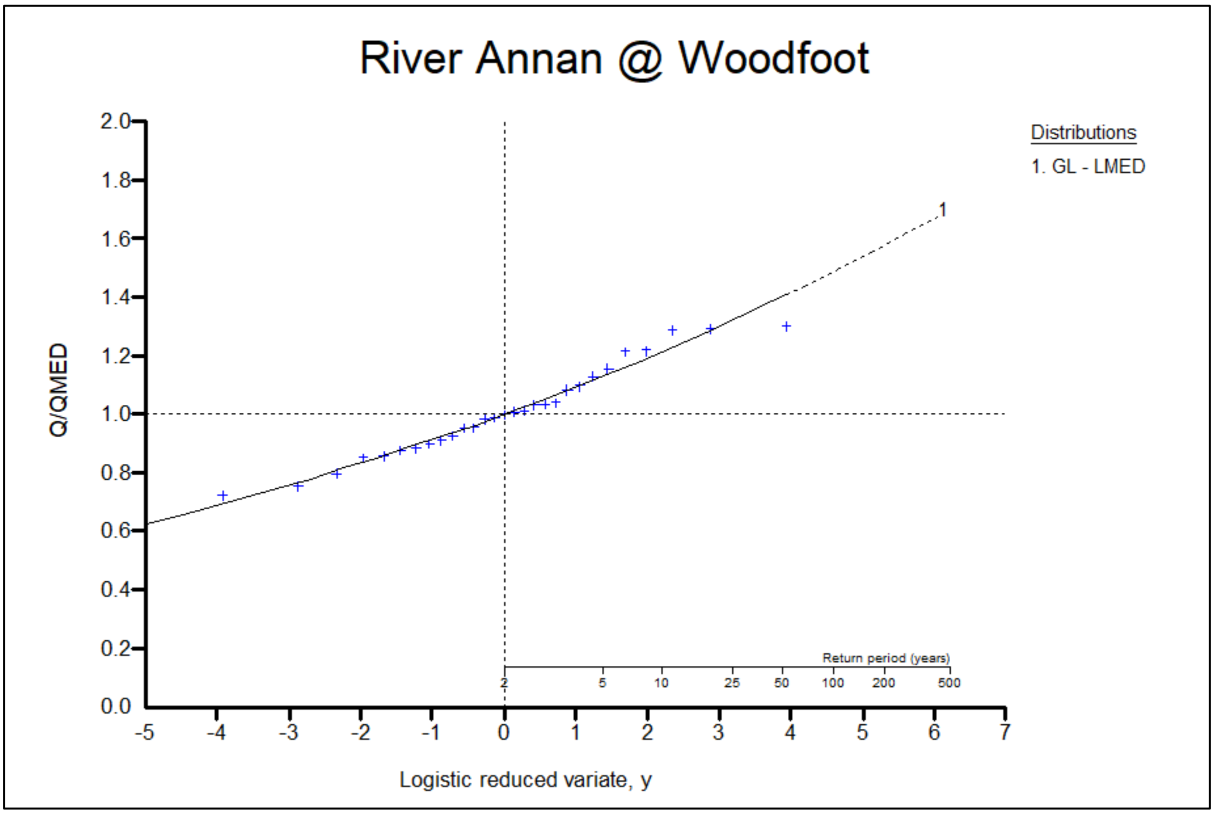


Figure 6: Single site flood frequency analysis for Woodfoot



Data was also requested for other gauged stations located close to Moffat and which measured flows on relatively small catchments, namely;

- Brockhoperig on Ettrick Water (21017). Data is considered suitable for Qmed only and not suitable for Pooling. The data on the WINFAP database was updated using the SEPA gauged flows.
- Redhall on Kinnel Water (78004). Data is considered reasonable for Qmed and Pooling. The data on the WINFAP database was updated using the SEPA gauged flows. A single site analysis using the AMAX series is summarised in Table 5.
- Bridgemuir on Kinnel Water (78005). Data is considered reasonable for Qmed and Pooling. The data on the WINFAP database was updated using the SEPA gauged flows. A single site analysis using the AMAX series is summarised in Table 5.
- Fruid on Fruid Water (21001). No additional data available. Data within WINFAP used for assessment.
- Glenbreck on River Tweed (21029). No additional data available. Data within WINFAP used for assessment.

Table 5: Single Site Analyses for Nearby Stations

Return Period	River Annan at Woodfoot	Kinneil at Redhall	Kinnel at Bridgemuir
years	Scaling Factor	Scaling Factor	Scaling Factor
[a]2	1	1	1
5	1.13	1.20	1.12
10	1.21	1.34	1.18
25	1.32	1.52	1.25
50	1.40	1.66	1.30
100	1.49	1.81	1.34
200	1.58	1.97	1.38
500	1.70	2.20	1.43

All based on GL Distribution

a Based on Q_{med} Donor Method: Gauged Sites 21001, 21029, 21017 and 78004

3.1.1.2 Q_{med} and Pooling Group Assessment

FEH Pooling Group Assessments were undertaken for River Annan upstream and downstream of the study area.

Values for Q_{med} were based on selecting the average of the four closest donor catchments to the site (Fruid Water at Fruid; River Tweed at Glenbreck; Ettrick Water @ Brockhoperig; and Kinnel Water at Redhall). This gave Q_{med} values of;

- River Annan upstream; 32.1 m^3/s
- River Annan downstream; 49.6 m^3/s

Pooling Groups were developed for the two sites, Tables 6 and 7. The Pooling Groups were considered acceptably homogeneous.

Based on the Pooling Groups the return period flows at the two sites are summarised in Table 8.

Table 6: Pooling Group for River Annan Upstream

Station	Distance	Years of data	QMED AM	L-CV	L-SKEW	Discordancy
72007 (Brock @ Upstream of a6)	0.361	36	29.438	0.193	0.236	0.814
47009 (Tiddy @ Tideford)	0.389	45	6.466	0.213	0.236	0.405
48004 (Warleggan @ Trengoffe)	0.395	45	9.983	0.265	0.263	2.014
21017 (Ettrick Water @ Brockhoperig)	0.396	41	60.364	0.203	0.276	0.307
25012 (Harwood Beck @ Harwood)	0.400	45	33.265	0.189	0.247	1.165
47014 (Walkham @ Horrabridge)	0.473	41	38.941	0.215	0.231	0.126
48001 (Fowey @ Trekeivesteps)	0.483	45	17.316	0.226	0.279	0.436
48009 (st Neot @ Craigshill Wood)	0.501	17	7.614	0.251	0.346	0.985
76811 (Dacre Beck @ Dacre Bridge)	0.521	14	35	0.194	0.263	2.274
27032 (Hebden Beck @ Hebden)	0.547	48	3.923	0.206	0.265	0.329
24006 (Rookhope Burn @ Eastgate)	0.606	20	24.62	0.152	0.117	0.779
51003 (Washford @ Beggearn Huish)	0.620	47	6.105	0.189	0.066	1.732
73009 (Sprint @ Sprint Mill)	0.664	45	41.64	0.172	0.157	0.276
28041 (Hamps @ Waterhouses)	0.670	29	26.664	0.221	0.314	1.507
49003 (de Lank @ de Lank)	0.710	48	13.985	0.23	0.22	0.813
84020 (Glazert Water @ Milton of Campsie)	0.718	37	56.483	0.132	0.064	1.671
73015 (Keer @ High Keer Weir)	0.761	24	12.187	0.164	0.008	1.948
54025 (Dulas @ Rhos-y-pentref)	0.773	45	23.241	0.165	0.238	1.128
46007 (West Dart @ Dunnabridge)	0.779	33	74.889	0.173	0.125	0.292
Total		705				
Weighted means		1377		0.199	0.21	

Heterogeneity Measure: Pooling Group is acceptably homogeneous; H2 = -0.6380

Table 7: Pooling Group for River Annan Downstream

Station	Distance	Years of data	QMED AM	L-CV	L-SKEW	Discordancy
84020 (Glazert Water @ Milton of Campsie)	0.209	37	56.483	0.132	0.064	1.119
21019 (Manor Water @ Cademuir)	0.241	39	26.132	0.191	0.149	0.505
73011 (Mint @ Mint Bridge)	0.342	45	54.835	0.193	0.241	1.106
54025 (Dulas @ Rhos-y-pentref)	0.375	45	23.241	0.165	0.238	1.055
47014 (Walkham @ Horrabridge)	0.445	41	38.941	0.215	0.231	0.568
78004 (Kinnel Water @ Redhall)	0.469	40	78.224	0.118	0.011	1.848
23011 (Kielder Burn @ Kielder)	0.481	43	65.78	0.163	0.06	0.962
84009 (Nethan @ Kirkmuirhill)	0.515	36	31.157	0.241	0.155	2.186
55004 (Irfon @ Abernant)	0.550	45	56.542	0.159	0.255	1.703

58006 (Mellte @ Pontneddfechan)	0.603	43	89.48	0.167	0.12	1.121
46007 (West Dart @ Dunnabridge)	0.605	33	74.889	0.173	0.125	0.176
47009 (Tiddy @ Tideford)	0.683	45	6.466	0.213	0.236	0.742
21017 (Ettrick Water @ Brockhoperig)	0.687	41	60.364	0.203	0.276	0.874
25006 (Greta @ Rutherford Bridge)	0.804	52	76.763	0.186	0.183	0.034
Total		585				
Weighted means		585		0.179	0.166	

Heterogeneity Measure: Pooling Group is acceptably homogeneous; H2 = 0.0978

Table 8: Design Flow Estimates – Pooling Group (GL Distribution)

Return Period years	Annan Upstream Peak Flow (m^3/s)	Annan Downstream Peak Flow (m^3/s)	Annan Downstream Scaling Factor
[a]2	32.1	49.7	1.00
5	42.4	63.6	1.28
10	49.9	73.4	1.48
25	60.9	87.1	1.75
30	63.3	90.0	1.81
50	70.5	98.6	1.98
75	76.7	105.8	2.13
100	81.4	111.3	2.24
200	94.0	125.4	2.52
500	113.6	146.8	2.95
1000	131.1	165.2	3.32

Based on GL Distribution

a Based on Q_{med} Donor Method: Gauged Sites 21001, 21029, 21017 and 78004

The use of donor catchments resulted in a higher Q_{med} than would have been produced by catchment characteristics at the study sites. Scaling by area the Q_{med} at the Upstream end of River Annan is equivalent to 0.99 $m^3/s/km^2$. At the downstream end of the study area Q_{med} is 0.87 $m^3/s/km^2$, falling to 0.67 $m^3/s/km^2$ at Woodfoot. A steady decrease in flow per unit area is expected for catchments with increasing area.

Compared to single site analyses at neighbouring sites (Table 5), the scaling factors for the Pooling Group and the downstream end of the site (Table 8) is higher, with the results for the local gauges producing lower than average scaling factors for southern Scotland. This suggests that while the local gauges can be used as donors for Q_{med}, the flood frequency analysis should be based on a Pooling Group analysis and not extrapolation of single site data.

The results of the Pooling Group analysis for the 200 year flood were compared to results using rainfall-runoff modelling approaches, with results in Table 9. The rainfall-runoff model results are predicted to produce higher flows than the Pooling Group. However, as can be seen in Table 9 the flows are all reasonably consistent.

The design flows used in the analysis are based on the FEH Pooling Group method.

Table 9: Comparison of Design Flow Estimates – Downstream River Annan

Method	Critical Storm Duration (hours)	200 year return period design flow (m^3/s)
FEH Pooling Group	-	125.2
FEH Rainfall Runoff – FSR Rainfall	7.1	124.7
FEH Rainfall Runoff – FEH Rainfall	7.1	125.2
ReFH2	3.75	107.2

3.1.2 Birnock Water, Crosslaw Burn and Frenchland Burn

The three main tributaries to the River Annan are considered in this section. As the catchment areas for these watercourses are less than the Annan, design flows are calculated based on rainfall-runoff methods. As the catchments are close to one another they are considered together to allow an assessment as to whether a single critical storm can be used for all the catchments.

Key calculation points for these watercourses are shown in Figure 4. Flows are calculated for the downstream ends of each catchment, where they meet the River Annan. How the design flows are partitioned within the catchments are outlined in Section 4.6.1.

The catchment characteristics for the catchments at their downstream end are summarised in Table 10. The Birnock Water is the largest of the three catchments at 12.05km^2, with the Frenchland at 4.04km^2 and the Crosslaw at 2.32km^2. Although the Birnock is the largest, it is also the steepest and most highly urbanised; although the urbanisation of all catchments is low.

Design flows were calculated based on the FEH Rainfall-Runoff method, ReFH2 method and IH124. The appropriate (and different) storm durations were calculated for each catchment and for each method, with results shown in Table 11.

The results indicate that the FEH Rainfall-Runoff model produces the largest flow estimates. The differences between the various methods is smallest for the Birnock Water (largest catchment) and increases for the smaller catchments.

The ReFH2 model is a more up to date method that has recently been calibrated for Scotland. But to be conservative, the design flow estimates are based on the higher FEH Rainfall-Runoff model predictions. These estimates will be tested during the modelling process, by comparing predicted flood extents for lower return period flows with observed flooding in Moffat.

Based on the above, the proposed design flow estimates for the three tributaries are summarised in Table 12.

Table 10: Catchment characteristics for Birnock Water, Frenchland Burn and Crosslaw Burn

Parameter	Birnock Water	Frenchland Burn	Crosslaw Burn
EASTING (m)	308550	309300	309250
NORTHING (m)	604750	604050	604050
AREA (km^2)	12.05	4.04	2.32
ALTBAR (m)	367	269	199
ASPBAR (°)	205	221	232
ASPVAR	0.38	0.51	0.73
BFIHOST	0.429	0.464	0.509
DPLBAR (km)	5.39	3.32	2.62
DPSBAR (m/km)	205	130.8	121.5
FARL	1	1	1
FPEXT	0.0207	0.0241	0.0743
LDP	8.99	6.06	4.7
PROPWET	0.72	0.72	0.72
SAAR (mm)	1557	1422	1362
SAAR4170 (mm)	1545	1447	1395
SPRHOST	44.48	42.7	40.87
URBCONC1990	0.522	-	-
URBEXT1990	0.0056	0	0.0027
URBLOC1990	0.118	-	-
URBCONC2000	0.759	-	0.5
URBEXT2000	0.0059	0	0.0129
URBLOC2000	0.102	-	0.502

Table 11: Comparison of 200 year Design Flow Estimates – Birnock Water, Frenchland Burn and Crosslaw Burn

Method	Birnock Water		Frenchland Burn		Crosslaw Burn	
	Critical Storm Duration (hours)	Peak Flow (m^3/s)	Critical Storm Duration (hours)	Peak Flow (m^3/s)	Critical Storm Duration (hours)	Peak Flow (m^3/s)
FEH Rainfall Runoff – FSR Rainfall	5.5	34.8	4.9	11.7	4.1	6.9
ReFH2	3.25	33.4	3.25	9.4	2.75	4.5
IH124	-	23.8	-	8.1	-	4.8

Table 12: Design Flows for Birnock Water, Frenchland Burn and Crosslaw Burn

Return Period (years)	Birnock Water	Frenchland Burn	Crosslaw Burn
2	9.2	3.1	1.8
5	13.5	4.5	2.6
10	16.4	5.4	3.2
25	21.3	7.1	4.2
30	22.3	7.4	4.3
50	25.5	8.5	5.0
75	27.8	9.3	5.4
100	29.7	10.0	5.9
200	34.8	11.7	6.9
500	42.9	14.5	8.6
1000	51.6	17.5	10.4

3.1.3 Small Catchments at Gallow Hill

A number of small catchments drain Gallow Hill, a small hill located to the north of Moffat. These catchments enter a number of watercourses that have culverted sections through urbanised areas of Moffat. The general catchments are shown in Figure 7 and have areas of around 50 ha.

To calculate design flows for each of the catchments, runoff rates scaled to a 1ha catchment were calculated using the IH124, FEH Rainfall-Runoff and ReFH2 methods. These runoff rates could then be applied to any sized catchment.

Catchment characteristics used in the assessment are provided in Table 13.

The runoff rate was calculated for a standard 50ha catchment and then scaled by area to give a runoff rate per 1ha. Calculated values are provided in Table 14. The estimated 200 year rainfall runoff rate per hectare is of the order of 52l/s. However, these do not fully account for the steep slope of the catchment and will need to be increased say by 10% to account for this. Based on this, the average 200 year runoff rate becomes 57l/s/ha.

Similar calculations were undertaken by Mouchel in a study of the catchments draining Gallow Hill. They used the FEH Rainfall-Runoff model and obtained typical runoff rates of the order of 65/1ha for the 200 year event.

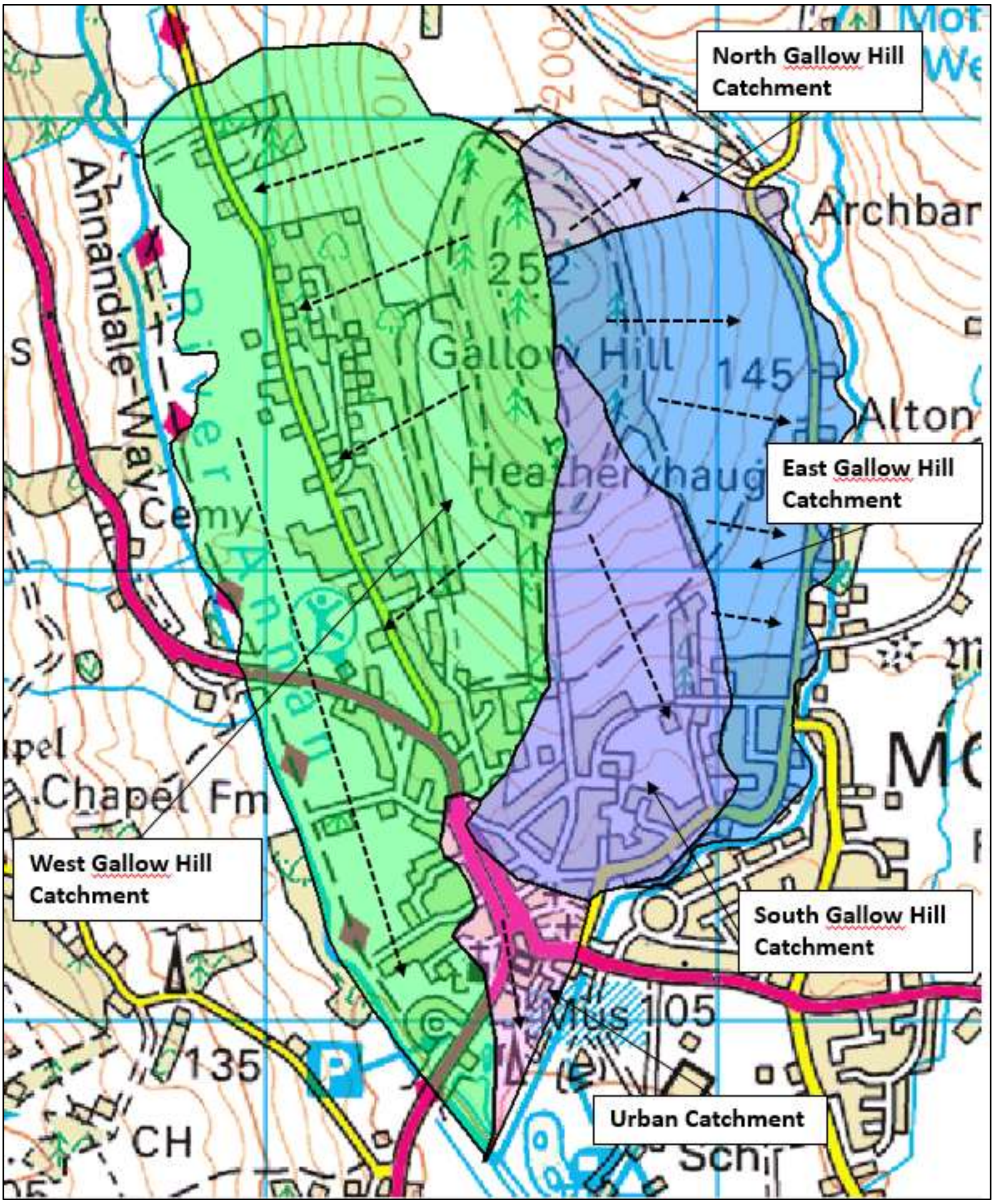
Table 13: Catchment characteristics Gallow Hill catchments

Parameter	Gallow Hill Catchment
AREA (km^2)	0.5
BFIHOST	0.41
DPLBAR (km)	0.75
DPSBAR (m/km)	150
FARL	1.0
PROPWET	0.72
SAAR (mm)	1577
SAAR4170 (mm)	1559
SPRHOST	45.33
URBCONC1990	-
URBEXT1990	0
URBLOC1990	-
URBCONC2000	-
URBEXT2000	0
URBLOC2000	-

Table 14: Predicted runoff rates for Gallow Hill

Return Period (years)	IH124 (l/s/ha)	FEH Rainfall-Runoff (l/s/ha)	ReFH2 (l/s/ha)
2	8.0	13.4	10.2
5	10.4	19.2	14.6
10	12.5	23.6	17.8
25	15.9	30.0	-
30	16.6	32.0	23.2
50	19.1	37.0	26.0
75	21.4	41.1	28.5
100	23.1	44.0	30.3
200	28.0	52.0	35.5
500	-	65.0	-
1000	-	80.0	53.0

Figure 7: Gallow Hill catchments



3.2 Partitioning Flows within the Modelled Catchments

Partitioning of the flows in the model is discussed in detail in Section 4.6.1.

3.3 Flow Distribution for Modelling Scenarios

Design flows for each catchment were outlined in Section 3.1. It is clear that there are three groups of catchments which will experience peak flows in response to different rainfall events;

- River Annan;
- Three main tributaries to River Annan; and
- Small catchments draining Gallow Hill.

The critical storm for River Annan is predicted to be around 7 hours, with a storm duration of around 3 - 6 hours resulting in the highest flows for the three tributaries and a storm of around 1 hour duration resulting in peak flows for the small catchments around Gallow Hill.

Models considering runoff for the small Gallow Hill catchments will be run separately from the models for the main tributaries and the River Annan. However, the other watercourses will be included in a single FloodModeller model. Therefore, care needs to be taken to develop model runs that represent design flow conditions for each of these watercourses. In order to reduce the number of model runs, reduce the need to combine results from different model runs and to make the assessment easier to follow for non-experts, it would be ideal if a single model simulation could be run for each return period, i.e. one that reflected design conditions in all watercourses. The alternative is to run a series of model simulations appropriate to design conditions in each of the inflowing watercourses (Annan, Birnock and Crosslaw).

A series of test runs (range of return periods) were undertaken with different storm durations. Following this assessment, it was determined that if all the catchments were run based on a 7.1 hour design storm (consistent with critical storm for the River Annan upstream of the site), with peak flows scaled to the appropriate design flow a single model simulation was able to be run for each return period that (i) provided the appropriate peak inflow to each catchment, (ii) produced the appropriate return period flow at the downstream end of the model. Table 15 summarises the target flow at the downstream end of the model (based on design flow assessment outlined above) and the predicted peak flow at the downstream end of the model. The modelled flow is within 3% of the target flow for all return periods from 1 in 5 to 1 in 200 years. Above 1 in 200 years the model over predicts the target flow by around 10%. Given the uncertainties in estimating such high return period flows and given that the model over-predicts the target flow (i.e. is relatively conservative) these results were carried forward to the flood mapping exercise.

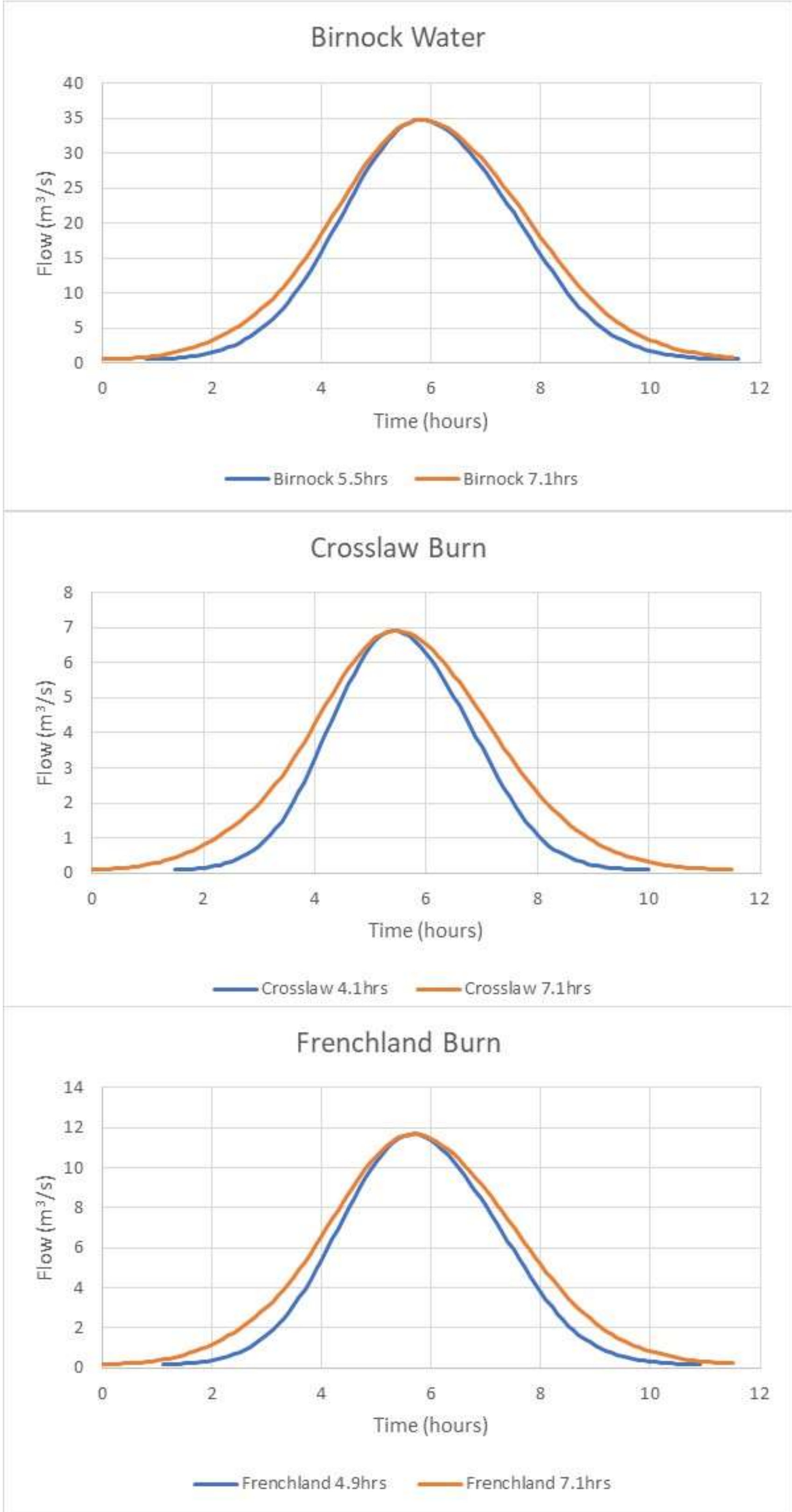
Table 15: Design Flows for Birnock Water, Frenchland Burn and Crosslaw Burn

Return Period (years)	Target flow at downstream Annan (m^3/s)	Model Flow (m^3/s)	Difference (%)
5	63.5	61.9	-3%
10	73.3	71.5	-2%
25	86.9	84.7	-3%
30	90.0	88.9	-1%
50	98.4	100.5	+2%
75	105.8	105.8	-1%
100	111.1	111.3	0%
200	125.2	129.1	+3%
500	146.5	163.2	+11%
1000	165.2	188.0	+14%

Running the models using a 7.1 hour design storm rather than the critical storm for each catchment will result in slightly differently shaped hydrographs for the smaller catchments, compared to the hydrographs produced using the critical storm duration. These differences are shown in Figure 8 where inflow hydrographs, scaled to the design flow, are provided for each of the three tributaries. The 7.1 hour hydrographs will result in higher flow volumes than the critical storm hydrographs, resulting in slightly conservative flood model predictions. However, the differences are relatively small in terms of the total flow volume in the model.

There is uncertainty in any hydrological assessment and especially where we are modelling design flows for catchments of different sizes and which are impacted by floodplain storage (which is not well represented in the hydrological methods used for design flow estimation). Therefore, the results presented above are considered sufficiently accurate for the design flow model runs. They also provide the benefit of allowing all the models to be run together for a single simulation, which has numerous benefits as noted above.

Figure 8: Comparison of design flow (200 year hydrographs based on 7.1 hour storm and critical storm for Birnock Water, Crosslaw Burn and Frenchland Burn



3.4 Climate Change

Current SEPA flood maps used a 67%ile high emissions scenario, with this being regarded as a conservative choice however SEPA also suggest this is for strategic level mapping and that in a flood study for the design of flood defences around a site of critical national infrastructure a more conservative value may be selected.

For the Solway region in which Moffat is within, the 67%ile high emissions scenario is an increase of 44% with the 90%ile being an increase of 60%.

As there is no critical national infrastructure based within the town of Moffat therefore the 67%ile high emissions scenario value of 44% was selected as the most appropriate for this study.

4 Assessment of Fluvial Flooding Risk

In order to assess flooding risk from all four watercourses, design flow estimates outlined in Section 3.1 were translated to water level along each watercourse using mathematical modelling techniques. This involved the construction of a mathematical model incorporating all four watercourses within the area of interest. The work undertaken is outlined below.

4.1 Modelling Approach

A linked 1D-2D modelling approach has been adopted in order to accurately predict the floodplain flows and the exchange of flow between the main channel and floodplains. The model is based on industry standard and widely used Flood Modeller Pro software package.

4.1.1 Schematisation

The main channel of all four watercourses within the study area was represented in 1D based on surveyed channel cross sections and bridge details. The cross-sections are truncated at bank top locations where the 2D floodplain model starts. The 1D and 2D models are dynamically liked using "linklines" which allow exchange of water between the two domains. The 2D floodplain model is constructed based on the available LiDAR DTM.

4.2 Topographic Datasets

4.2.1 Survey

L&M Survey Services were commissioned to undertake a comprehensive river channel survey of all four watercourses. The survey included channel cross-sections and hydraulic structures (i.e. bridges, culverts and weirs) throughout the study area. Although a previous model of the watercourses exists, the data used in its construction is more than 10 years old and was considered out of date. The current model is based on survey work undertaken in 2017/2018.

The topographical survey included the following:

River Annan:

- 33 Surveyed river channel cross sections
- 5 Surveyed Hydraulic structures

Birnock Water

- 30 Surveyed river channel cross sections
- 7 Surveyed Hydraulic structures

Crosslaw Burn

- 37 Surveyed river channel cross sections
- 5 Surveyed Hydraulic structures

Frenchland Burn

- 18 Surveyed river channel cross sections
- 2 Surveyed Hydraulic structures

The locations of surveyed channel cross sections are shown in Figures 9 to 16 inclusive. Sections shown in blue colour are those interpolated from the adjacent surveyed sections for modelling purposes. Sections shown in green colour are those extracted from LiDAR DTM.

4.2.2 Digital Terrain Model (DTM)

Filtered LiDAR DTM data was downloaded from the Scottish Remote Sensing Portal. The data has a 1m horizontal resolution and covers the entire study area.

The LiDAR DTM was augmented by land based topographical survey of left bank of River Annan and both left and right banks of Birnock Water. This allowed more accurate representation of overbank flows.

4.2.2.1 Top of bank survey

A full top of bank topographic survey was commissioned to be undertaken by L&M Survey Services on both the right hand and left hand banks of the Birnock Water, from its confluence with the River Annan to the Birnock Bridge, Ballplay Road, and on the left hand bank of the River Annan from the confluence with the Birnock Water to the top of the study area. The data was used to update the top of bank levels in the LiDAR DTM.

4.2.2.2 Channel cross sections

In addition to the surveyed channel cross sections outlined above, two additional cross sections were used to extend the model downstream of Barnhill Bridge. These were extracted from the DTM. Topography within this area is flat, comprising of fields and open ground, hence LiDAR elevations in this area outside the main channel are expected to be sufficiently accurate enough to derive model cross sections. Comparison was made of surveyed channel cross section data and section data extracted from DTM at the location of surveyed sections near the downstream boundary. This indicates that on average main channel bed level surveyed was 0.6m lower than the DTM extracted bed level. Therefore, an adjustment was made to the two cross sections to reflect this.

The DTM was used to extend cross section A31 on the right hand bank at the top of the Annan model (Figure 9). Topography within this area is flat, comprising fields and open ground. As before, LiDAR elevations in this area are expected to be sufficiently accurate enough to derive model cross section. This cross section was extended to include the low-lying area in the 1D model as opposed to the 2D, as water exited and returned to the 1D model within this small confined area (i.e. no flow to other parts of the 2D domain). This approach increased model stability in this area.

Figure 9: Locations of surveyed channel cross section in the Upper Annan

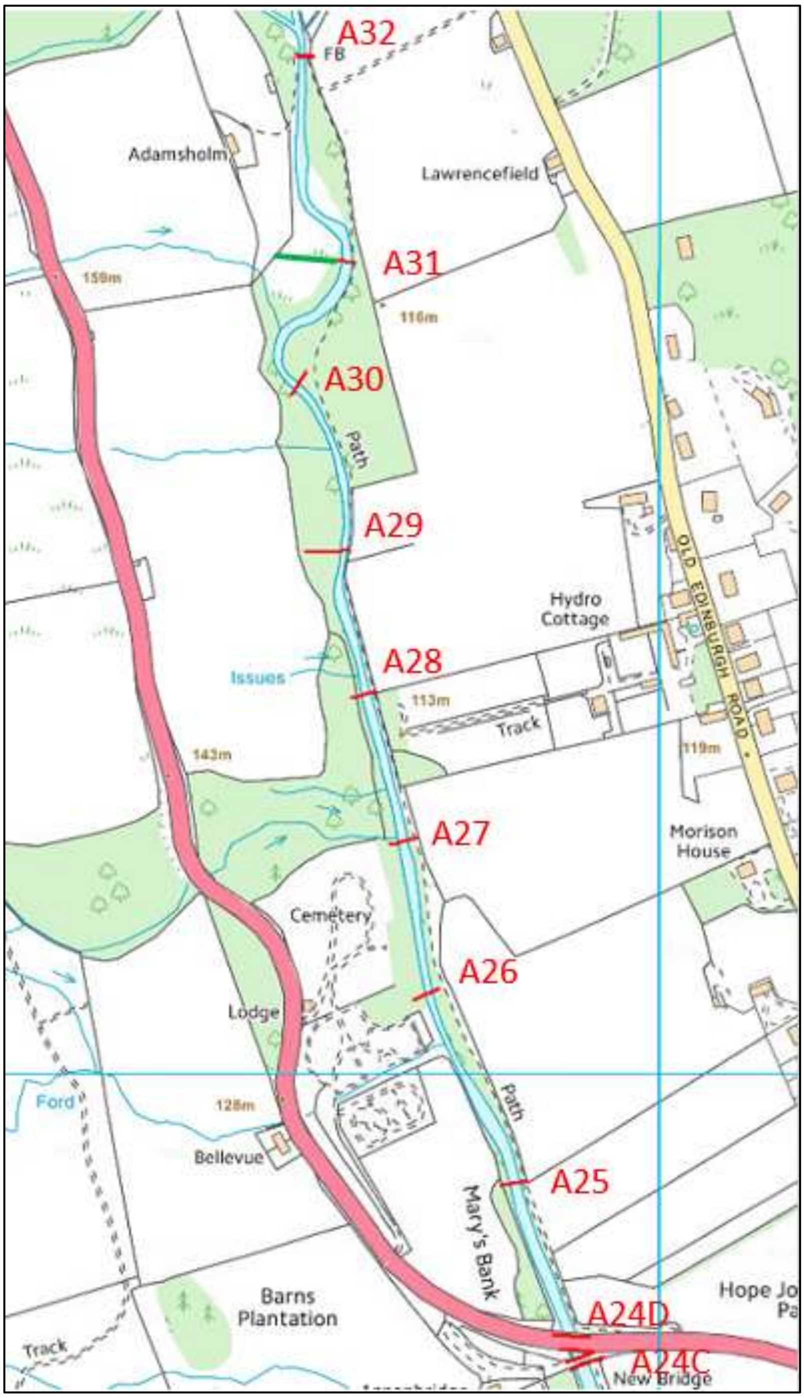


Figure 10: Locations of surveyed channel cross section in the Middle Annan

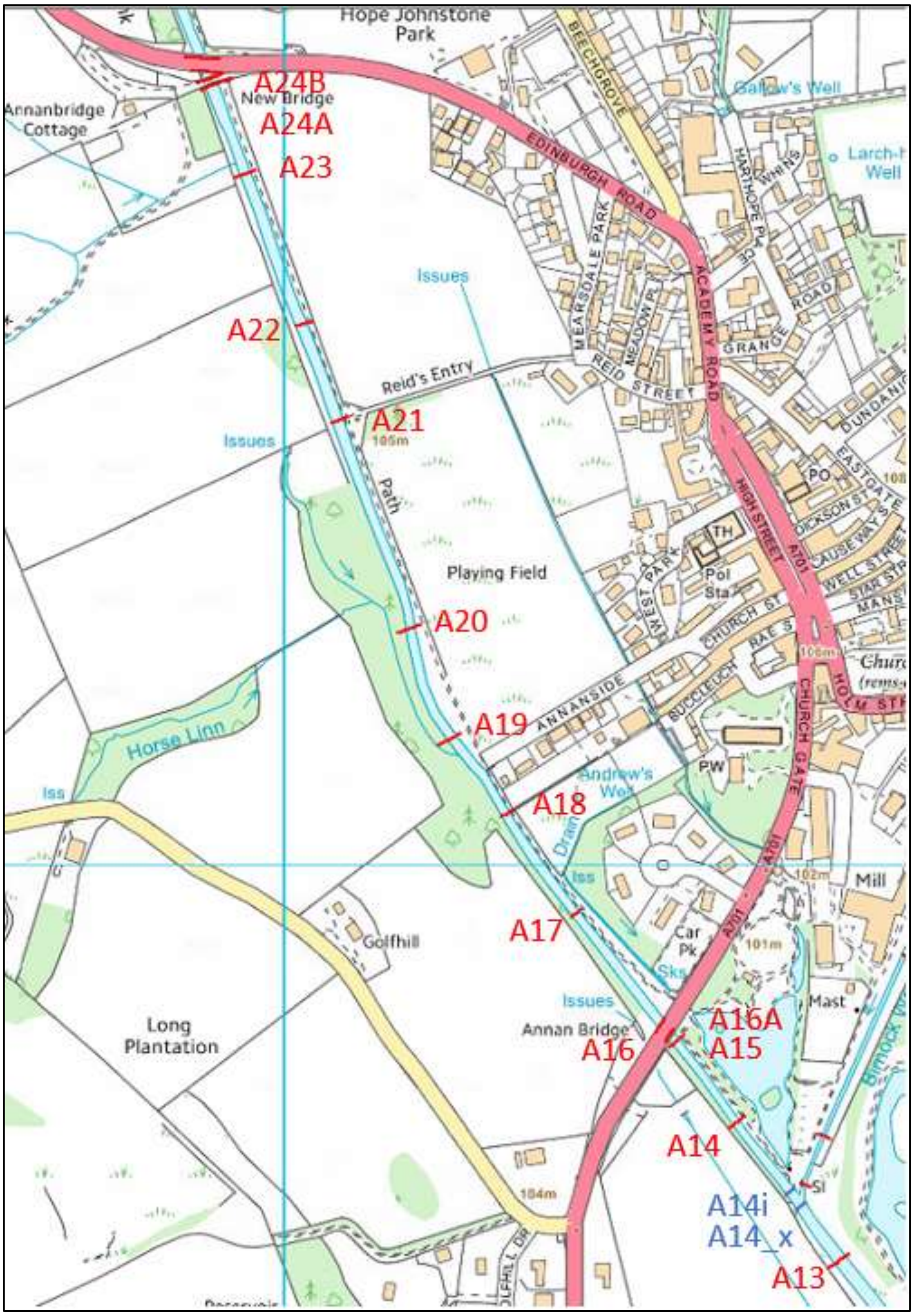


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Figure 11: Locations of surveyed channel cross section in the Lower Annan

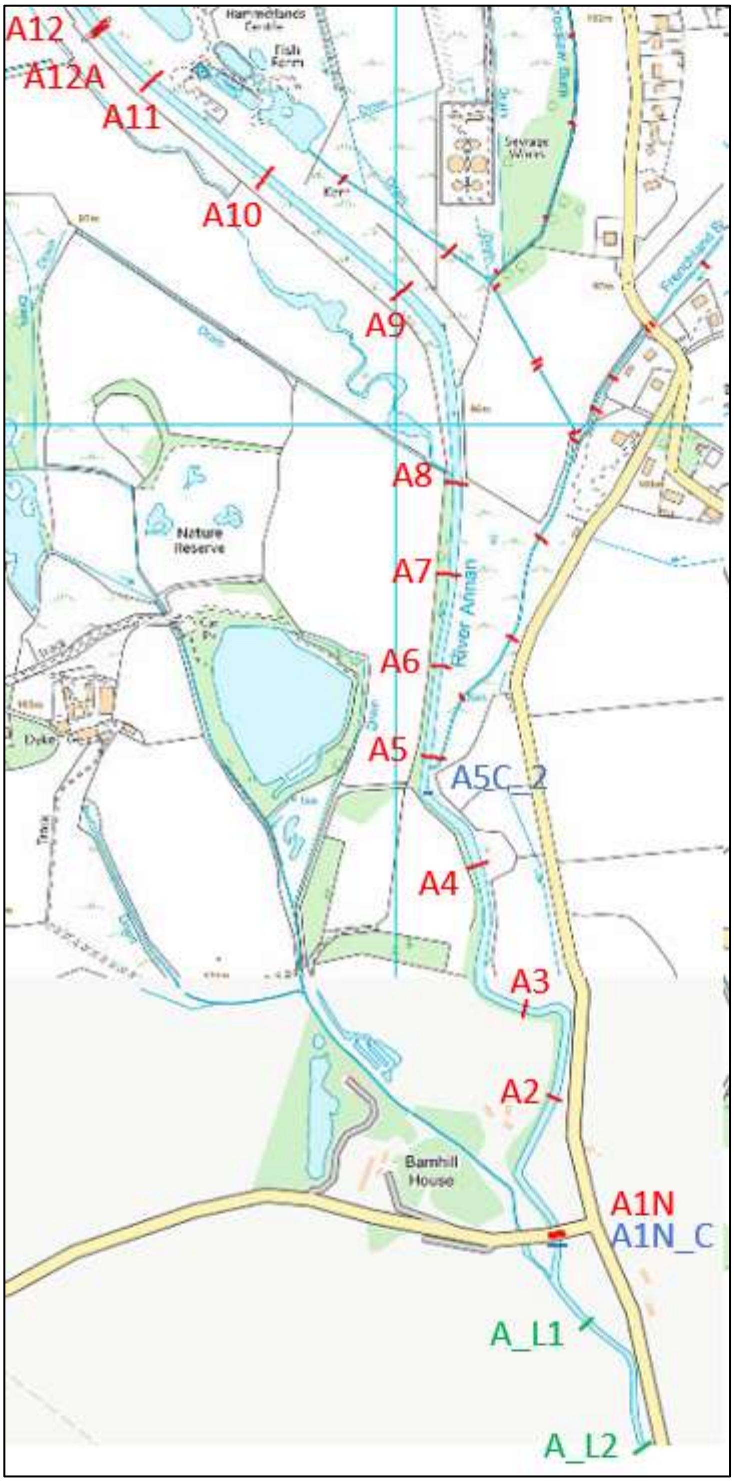


Figure 12: Locations of surveyed channel cross section in the Lower Birnock

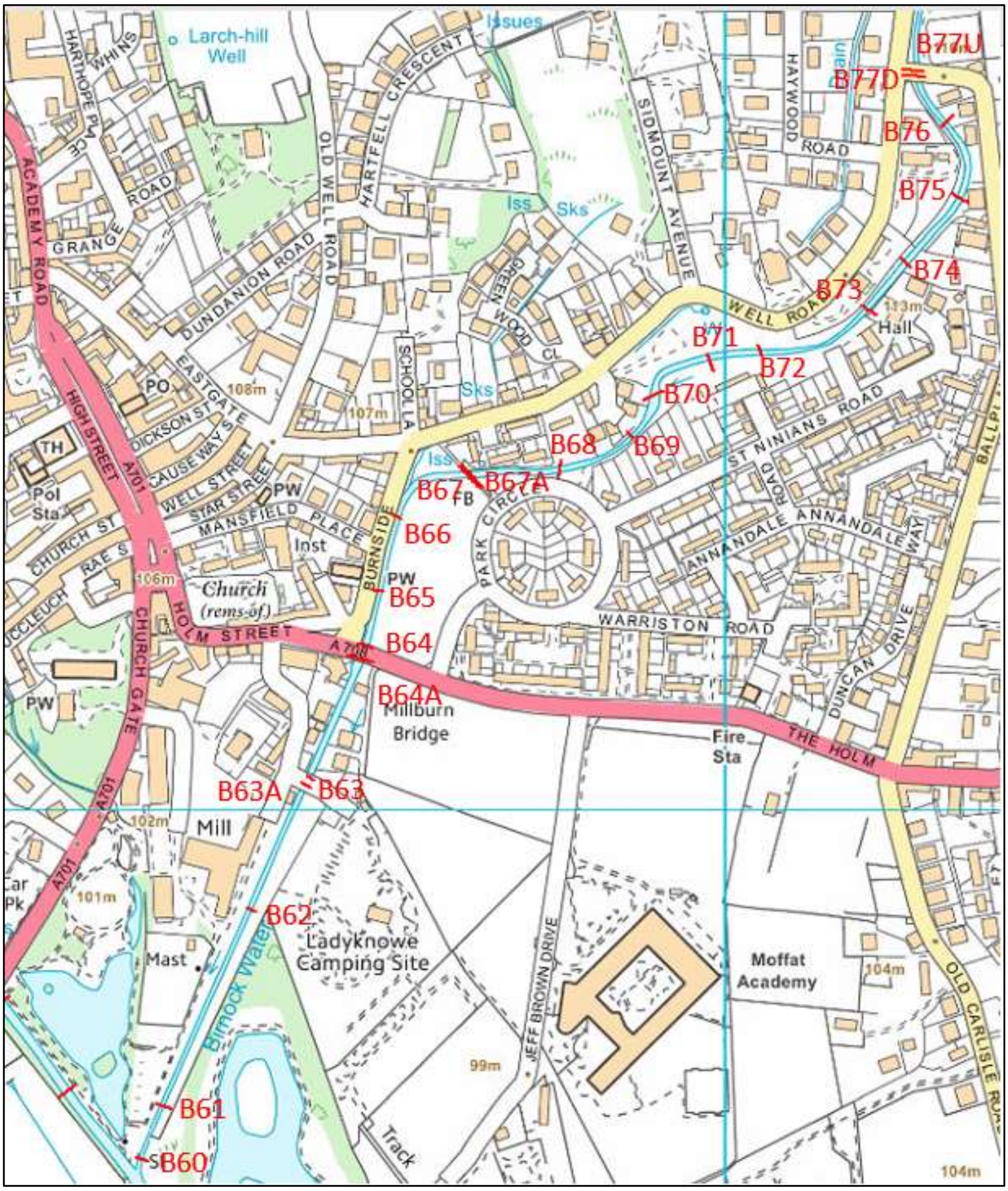


Figure 13: Locations of surveyed channel cross section in the Upper Birnock

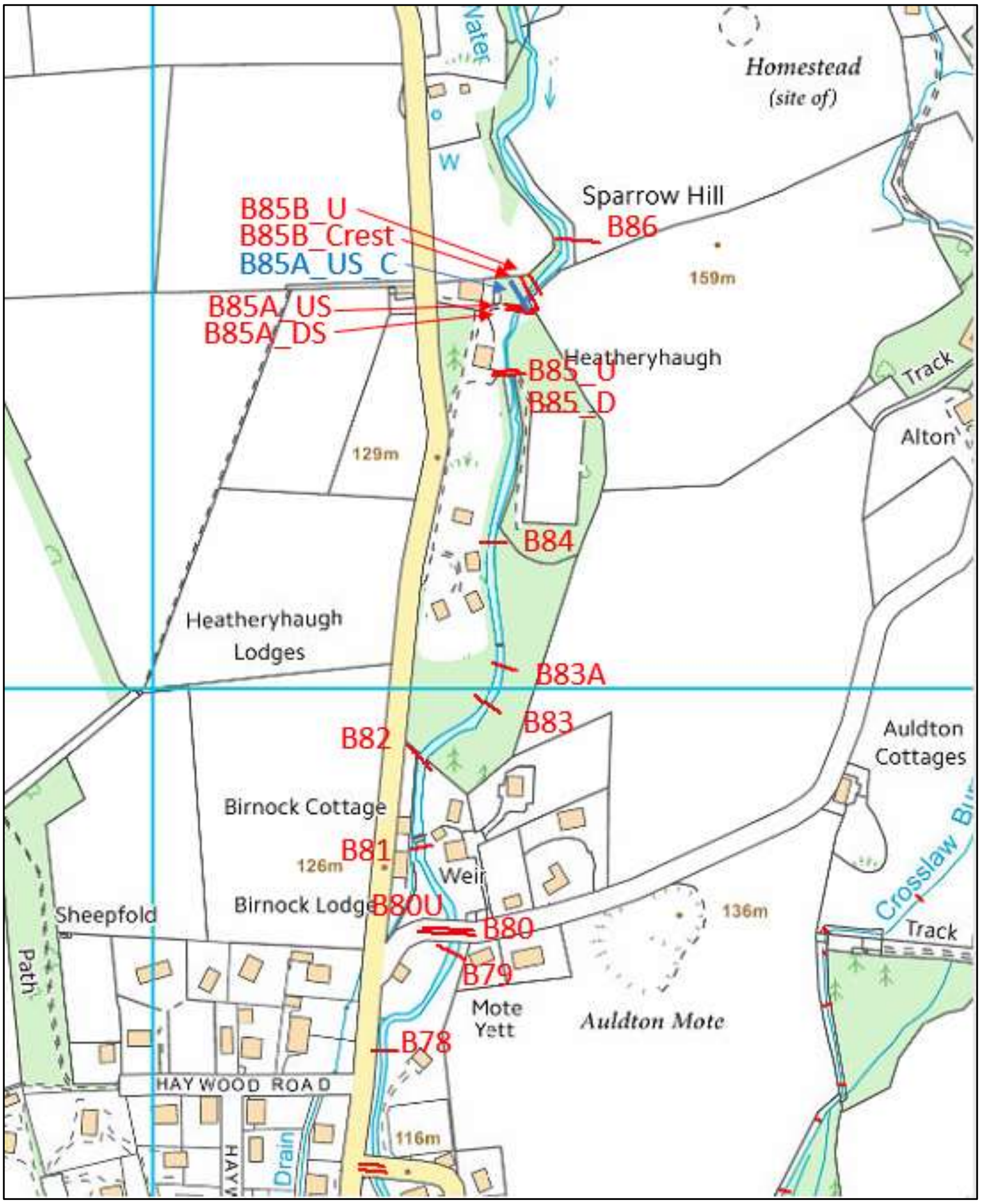


Figure 14: Crosslaw upper cross sections

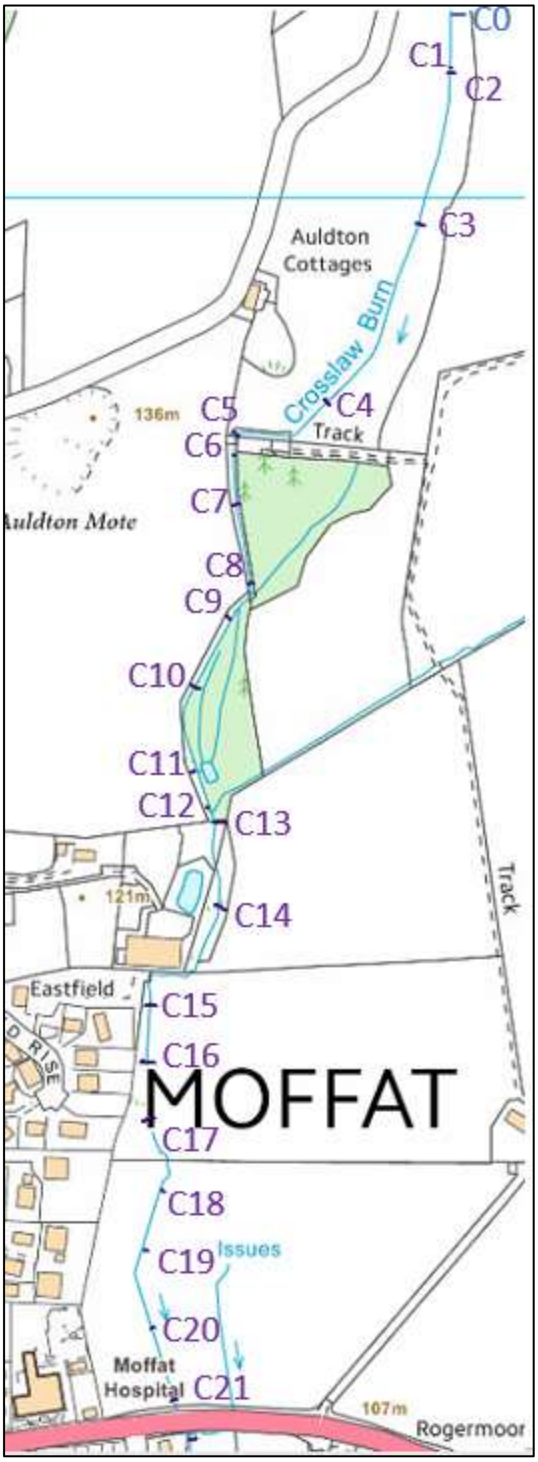


Figure 15: Crosslaw lower cross sections

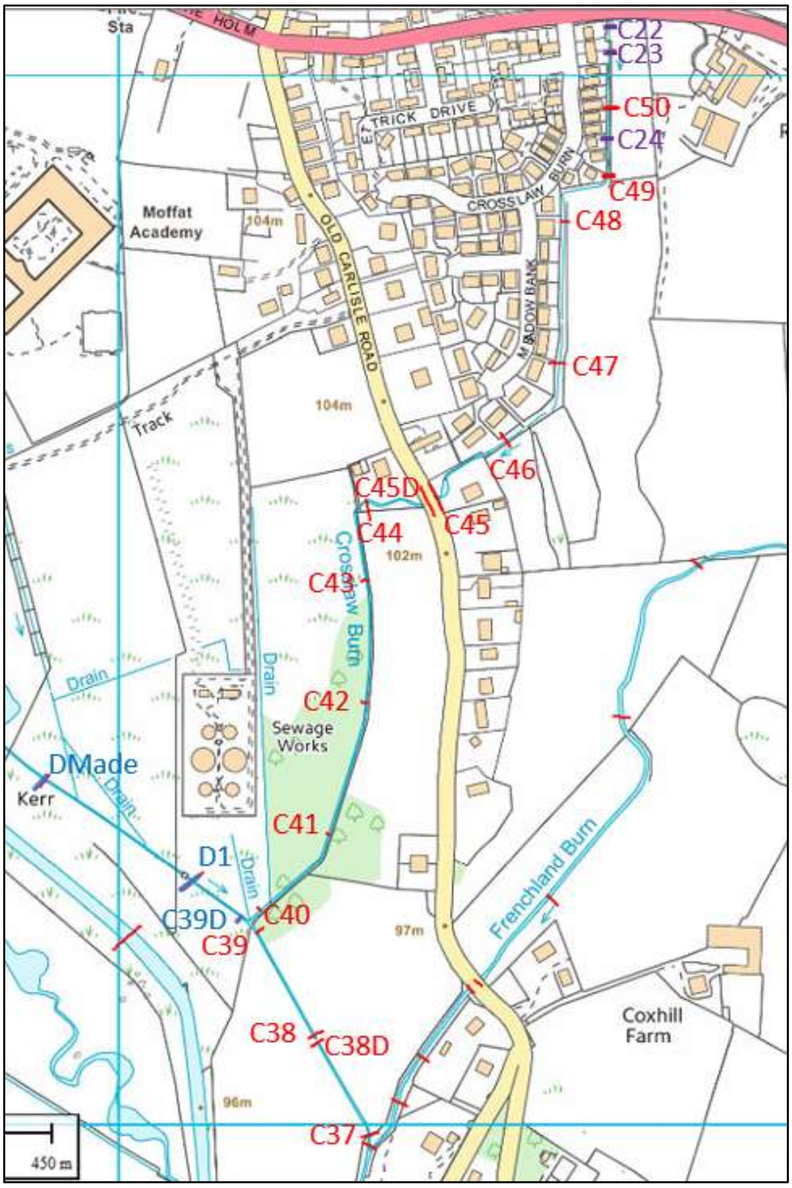
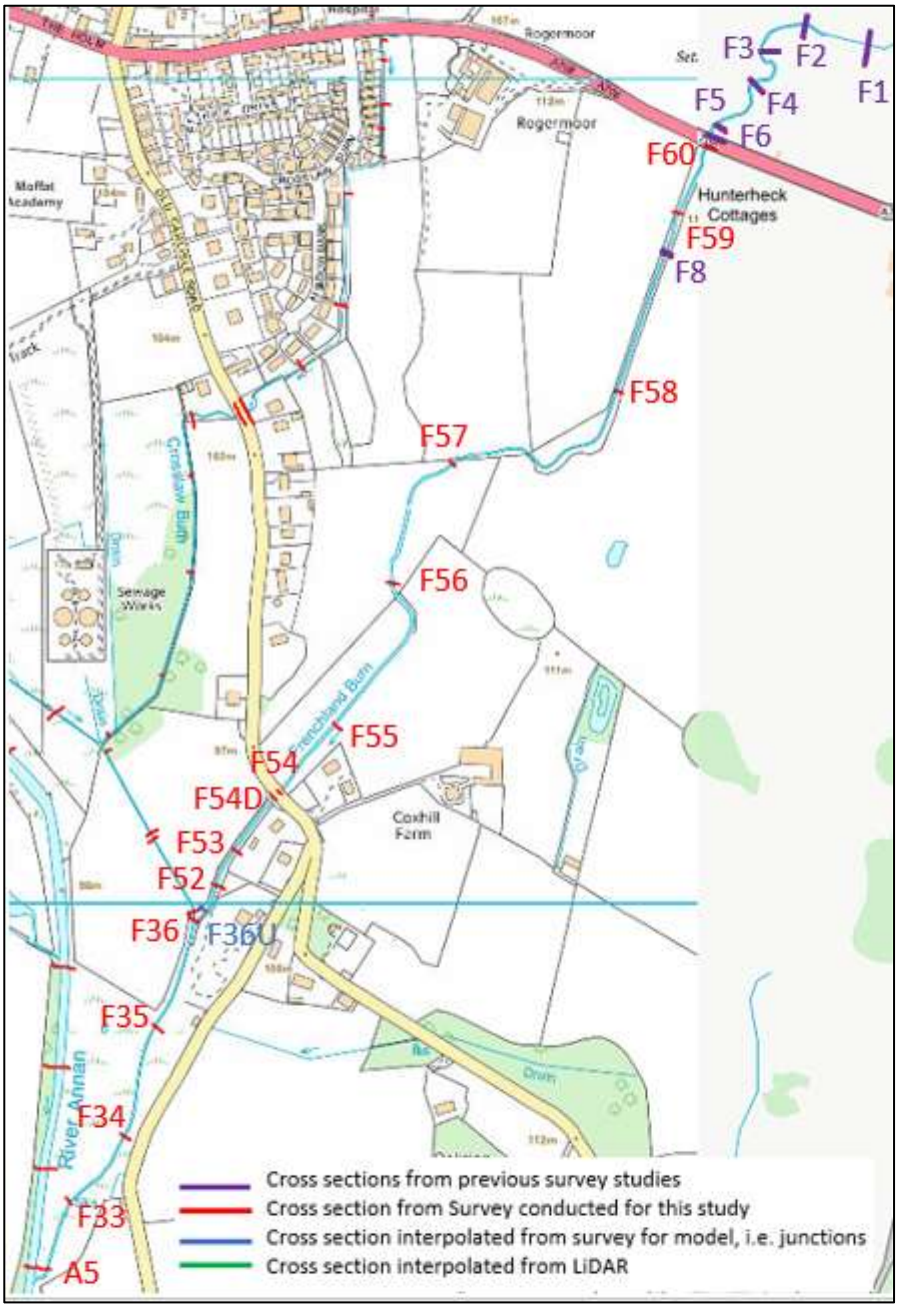


Figure 16: Locations of surveyed channel cross section along Frenchland Burn



4.3 2D Model Domains

Floodplain and over-bank areas within the study area were represented in 2D. These include the floodplains on the right bank of the River Annan, floodplains between the River Annan and Birnock Water, floodplains between Birnock Water and Crosslaw Burn, floodplains between Crosslaw Burn and Frenchland Burn, and floodplains on the left bank of Frenchland Burn. These are shown in Figure 17.

Initial model runs were carried out and the outer boundaries of the 2D domains were adjusted so that flood extent for all the runs were contained within the 2D domain (i.e. the flood extent did not touch the outer boundary of the 2D domain). This optimised the size of the Active Area in the 2D model and reduced run times without sacrificing model accuracy. This allowed a natural flood extent to be generated by the model, unaffected by the domain boundaries.

In Figure 17:

- Domain 1 is the floodplain on the right hand bank of the River Annan;
- Domain 2 is the floodplains between the River Annan and Birnock Water;
- Domain 3 is the floodplain areas between Birnock Water and Crosslaw Burn;
- Domain 4 is the floodplains between Crosslaw Burn and Frenchland Burn; and
- Domain 5 is the floodplains on the left hand bank of Frenchland Burn.

4.4 Linking of 1D and 2D Domains

The 1D model representing the main channels and 2D model representing adjacent floodplains were dynamically linked using “linklines”. For this model, level linklines were used which calculates the exchange of flow between the two domains using a weir type equation (i.e. based on water level difference between the two domains and a standard discharge coefficient).

The over-spill level for each link line was determined based on the available survey data, e.g. from the top of bank survey where available and local ground level from the LiDAR DTM elsewhere.

4.5 Hydraulic Structures

Throughout the study area there are a number of hydraulic structures affecting flows in the modelled watercourses, such as bridges and culverts. The key features have been identified with location and description of the structure in each of the water courses are provided below in Table 16.

Figure 17: 2D model domains

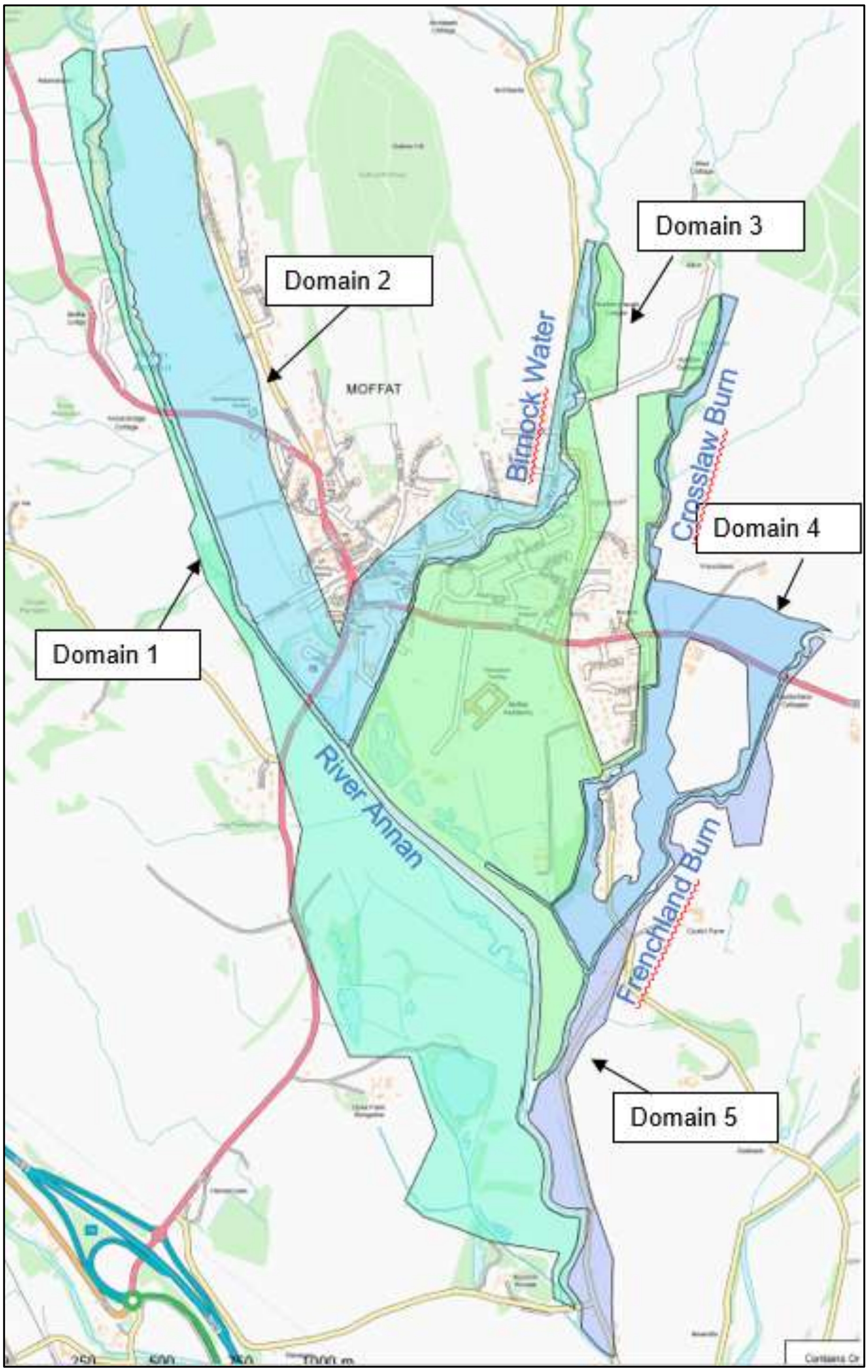


Table 16: Key structures included in the model

River	Feature	Location	Description	Dimensions	Modelled unit
Annan	North A701 Road bridge	307921, 605760	Concrete Road bridge, spanning the entire channel	15m wide, 6m high to the flat deck.	Flat deck bridge
Annan	North A701 Foot bridge	307921, 605760	Old masonry arch bridge	bridge approximately 15m wide and approximately 5.5m high to the middle of the arch.	Arch bridge
Annan	South A701 Road bridge	308356, 604841	Concrete road bridge	11m wide and 2m high to flat deck.	Flat deck bridge
Annan	Barnhill Lane Bridge	309211, 603102	Concrete road bridge	22m wide and 3m high to flat deck	Flat deck bridge
Birnock	Weir	309290, 606285	Weir spanning the entire width of the steep valleyed channel	Width of entire channel, survey taken although weir crest	Spill
Birnock	Private Footbridge	309270, 606282	Footbridge over steep valleyed channel.	3.6m wide 4.6m to flat deck	Flat deck bridge
Birnock	Bridge	309259, 606235	Narrow Arch bridge from steep valleyed channel with an additional by pass opening	6m wide and 5.5m high to middle Arch additional 1m wide and 2m high arch bypass opening	Arch bridge with 2 openings
Birnock	Road Bridge	309222, 605817	Road Bridge	7.36m wide and 2.7m high to flat deck	Flat deck bridge
Birnock	Ballplay Bridge	309163, 605641	Road Bridge	7m wide, and 3m high to flat deck	Flat deck bridge
Birnock	Park Footbridge	308776, 605293	Arch footbridge	15m wide 2.2m to arch middle	Arch bridge
Birnock	A708 Birnock Bridge	308693, 605136	Road Bridge	7.3m wide 2m high to the flat deck	Flat deck bridge
Birnock	Camping and Caravanning Club	308637, 605760	Road Bridge	6.5m wide and 1.8m high to flat deck.	Flat deck bridge
Crosslaw Brun	Field Agricultural	309663, 606093	Track culvert	4.7m long and 0.7m diameter.	Culvert

	Circular Culvert				
Crosslaw Brun	Field Agricultural Circular Culvert	309189, 604082	Track culvert	5m long and 0.8m diameter	Culvert
Crosslaw Brun	A 708 culvert	309462, 605061	Culvert under road	17m long 2m wide and 1m high arch culvert.	Culvert with arch conduit
Crosslaw Brun	Old Carlisle Road Crosslaw road	309300, 604595	stone arch bridge	2.4m wide and 1.5m high to arch middle.	Arch bridge
Crosslaw Brun	Field Agricultural Circular Orifice	309189, 604082	Orifice	1.35m in diameter.	Orifice
Frenchland Burn	A708 Road Bridge	309857, 604926	Stone Arch bridge under road	5m wide and 2.2m to middle of the arch.	Arch bridge
Frenchland Burn	Old Carlisle Road Frenchland Road Bridge	309336, 604136	Stone Bridge under road	4m wide high 0.4m high to flat deck.	Flat deck bridge
2D domain	A708 Road bridge orifice	309462, 605061	By pass opening east of the 708 Road bridge	0.6m diameter	Circular Orifice

*Where bridges have railings 0.3m was added to the spill level to represent the water being able to pass though these railing but inhibited.

4.6 Model Boundaries

4.6.1 Upstream Boundary Condition

The model requires input of flows from the top end of each of the four watercourses, as well as any lateral flows which may enter the watercourses along their modelled lengths. Flows entering the study area from upstream for the River Annan, Birnock Water, Crosslaw Burn, and Frenchland Burn catchments are represented in the model by the flow hydrographs derived in Section 3: Hydrological Analysis. Models were run for the duration of the entire flood hydrograph.

4.6.1.1 Partitioning of flow within the model area

How inflows to the model were partitioned is illustrated in Figures 18 to 21 inclusive. Relevant information regarding flow partitioning is given in Tables 17 to 20.

For each watercourse, the flow contribution from the upper catchment was applied at the top end of the model. Any lateral flows were then added where relevant. Lateral flows were uniformly distributed over a specified length of the watercourses.

A lateral flow entering the 2D domain was connected to a floating 1D unit.

Figure 18: River Annan inflow partitioning

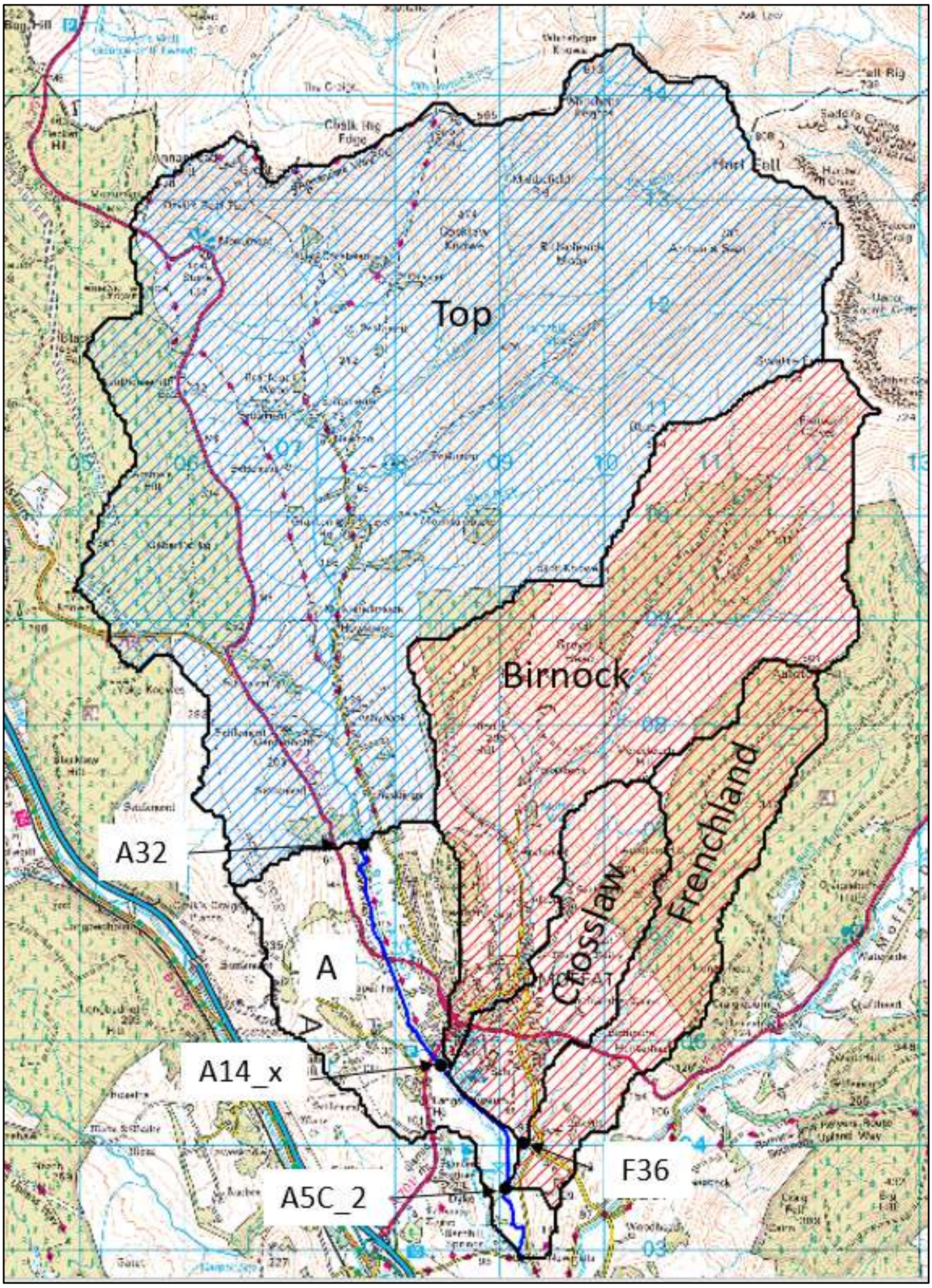


Table 17: River Annan inflow partitioning

Annan Drainage Area	Sq km	Model Inflow type	Inflow Cross Section
Top of model	32.43	Point	A32A_C
Birnock	11.88	Model Junction	A14_x
Crosslaw	3.02	Model Junction	Connected to Frenchland (F36)
Frenchland	4.36	Model Junction	A5C_2
A	5.03	Laterals	A32 to A_L2 proportional to reach length

Figure 19: Birnock Water flow partitioning

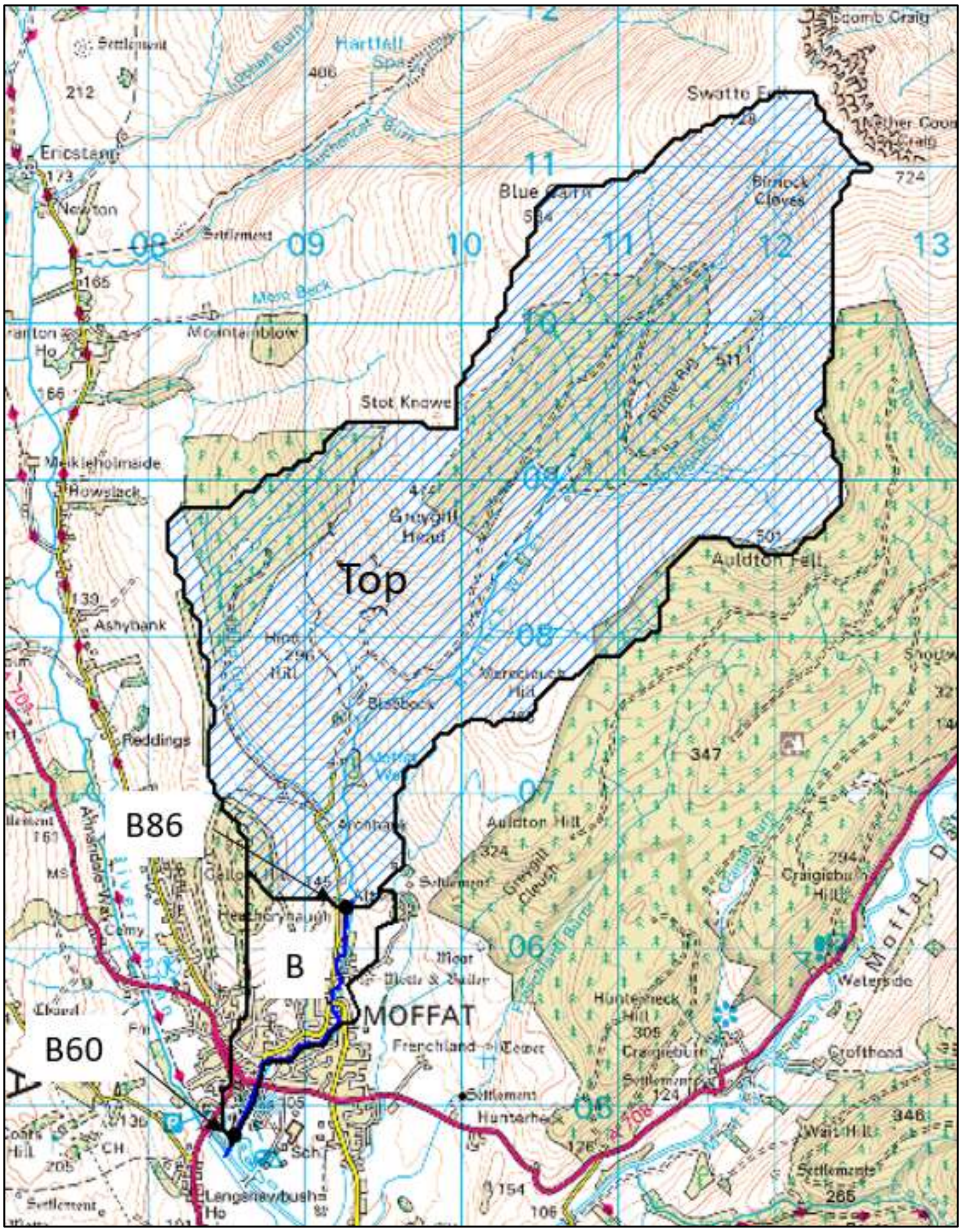


Table 18: Birnock Water flow partitioning

Birnock Drainage Area	Area km^2	Model Inflow type	Inflow Cross Section
Top of model	11.03	Point	B86
B	0.85	Included in Top of model point inflow	B86

Figure 20: Frenchland Burn flow partitioning

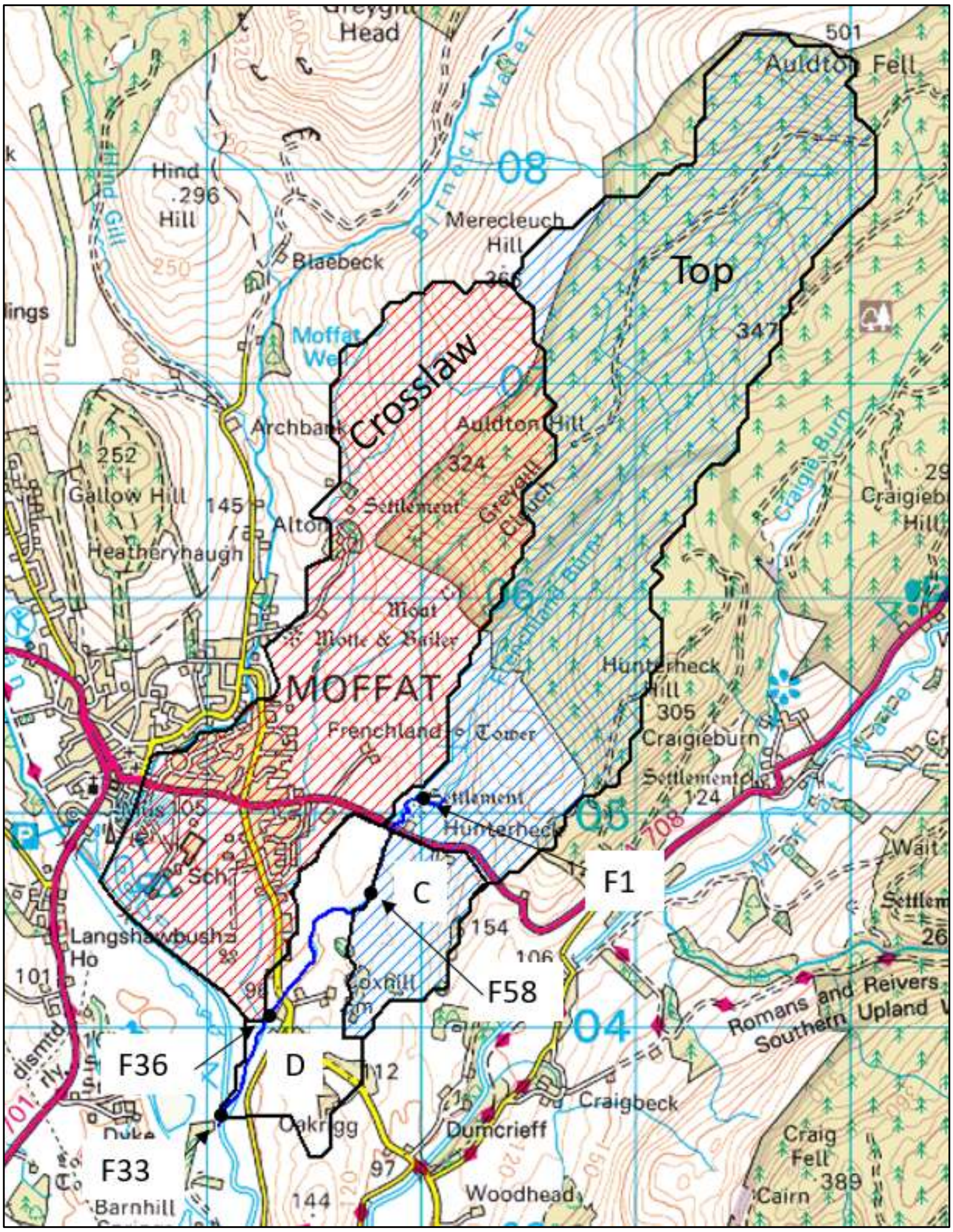


Table 19: Frenchland Burn flow partitioning

Frenchland Drainage area	Area km²	% of total	Model Inflow type	Inflow Cross Section
Top of model	3.36	0.83	Point	F1
Crosslaw	3.02		Model Junction	F36
C	0.367	0.09	Point	F58
D	0.313	0.08	Laterals	F60 – F33 proportional to reach length

Figure 21: Crosslaw Burn flow partitioning

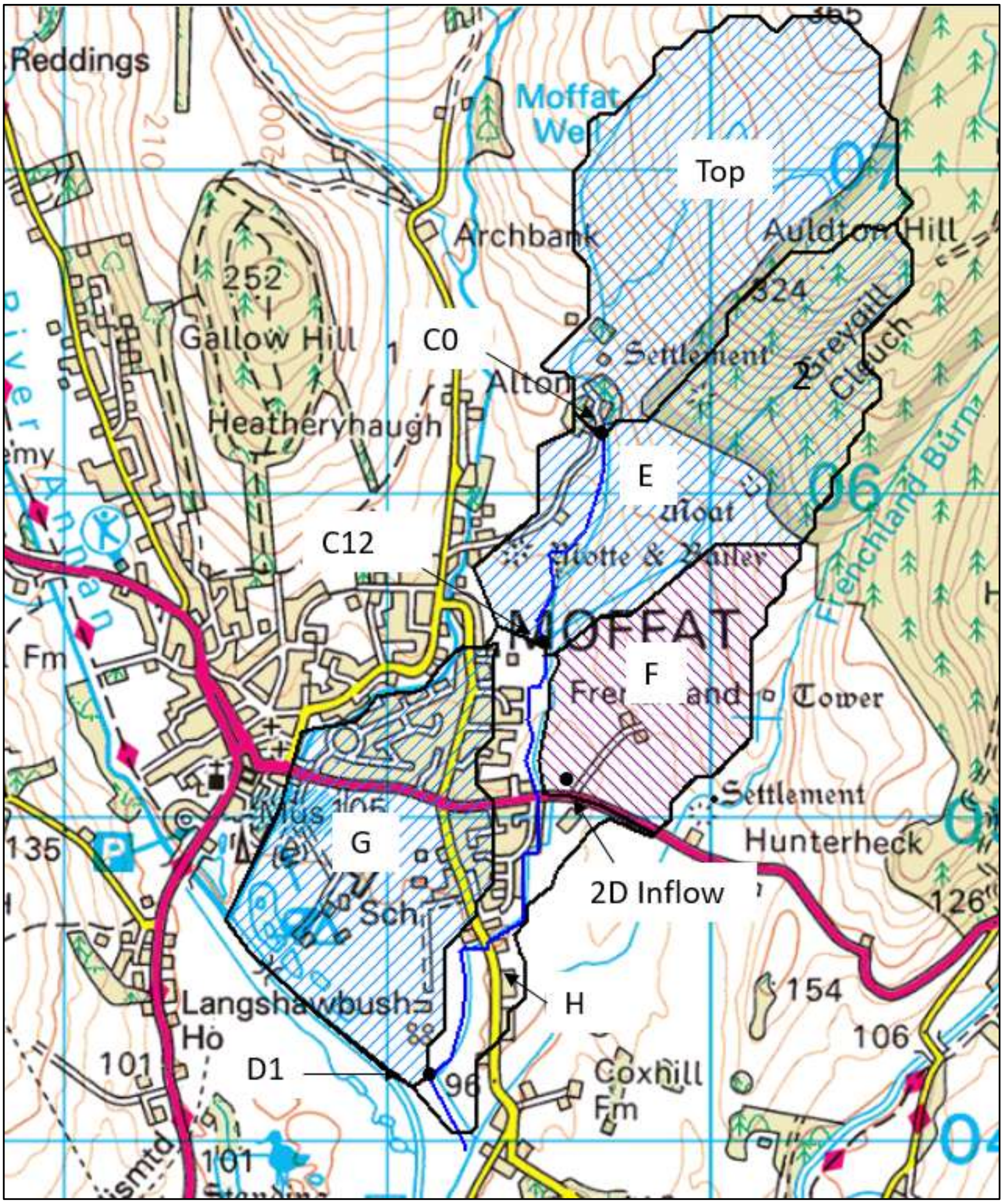


Table 20: Crosslaw Burn flow partitioning

Crosslaw Drainage area	Area km²	% of total	Model Inflow type	Inflow Cross Section
Top of model	0.835	0.36	Point	C0
E	0.776	0.33	Point	C12
F	0.421	0.18	2D inflow	2D inflow
G	0.679	0.29[a]	Point	D1
H	0.288	0.12	Laterals	C23, and C44

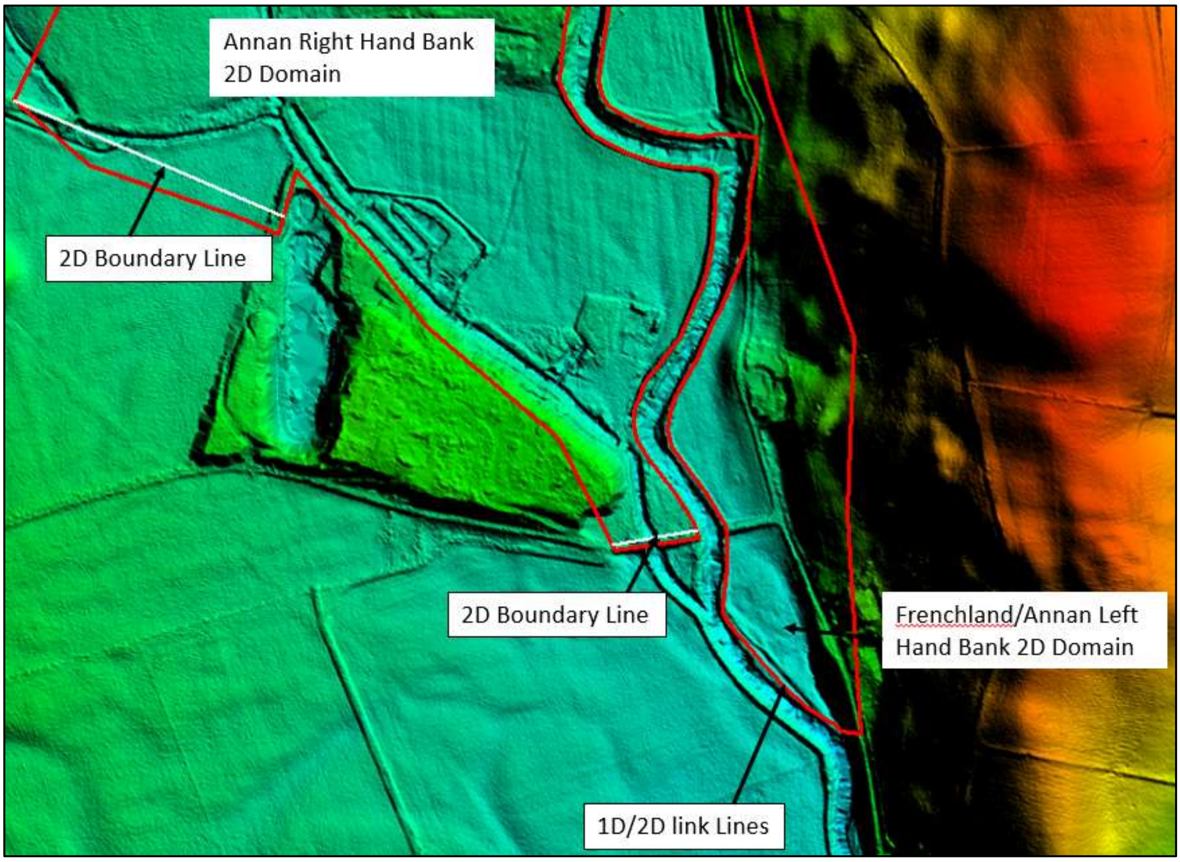
a. Addition to FEH catchment, identified from flow pathway analysis

4.6.2 Downstream Boundary Condition

The downstream model boundaries used in the model are:

- Normal depth boundary at the downstream end of the 1D model (at the last channel cross section on the River Annan). The gradient was set to the average bed gradient in the area.
- The 2D Domain 1 included two downstream boundaries at the downstream end where flood waters are allowed to leave the model domain. These are shown in Figure 22. There is high ground in between these two boundaries and no flow would leave the domain in this area. Normal depth boundaries were used with a slope of 0.01.

Figure 22: 2D downstream boundary



4.7 Key Model Parameters

4.7.1 Roughness

The following global roughness values were used in the 1D model:

- Main channel: 0.040
- Channel banks: 0.050

These were based on field observations and an assessment based on our vast experience in similar projects elsewhere.

Where there were fences across 4 cross sections in the upper part of the Crosslaw Burn and an increased roughness of 0.05 was used in these areas.

For the 2D domains, SEPA roughness grid were used. This consisted of areas with roughness values varying between 0.02 and 1 depending on land use, as shown in Table 21.

Table 21: 2D model friction grid values

Land use	Roughness value (Manning's n)
Roads	0.02
Grass Fields and Urban Areas	0.033
Rough Ground and wooded area	0.1
Buildings	1.0
Friction patches for stability	0.1

In four areas increased friction patches were used to increase model stability:

- The downstream end of the model.
- Land between the junction of Crosslaw Burn and Frenchland Burn.
- The left hand bank of the River Annan for approximately 120m upstream of the Birnock Water confluence.
- Both banks of the River Annan upstream of the Birnock Water confluence for approximately 90m upstream of the A708.

For these areas, a higher Manning's n value of 0.1 was used.

The discharge coefficient for level linklines was 1.2. This coefficient is less critical when peak water levels in the 2D domain approach the water level in the river.

For the 2D domains, a uniform grid size of 2m was used, except for Domain 3 (between Birnock Water and Crosslaw Burn for which a grid size of 1.5m was used.

Computational timestep used for all domains was 0.5 second. A range of timesteps were considered, but this provided a good mass balance and acceptable model run times.

4.8 Model Calibration

Historical flood information was summarised in Section 2.6. The information generally provided information on the location of flooding with no information on the extent and depth. Table 3 indicates that much of the available information relates to flooding in December 2015, however, reference is also made to flooding in 2009, 2013, and 2016. Some of the areas where flooding has been reported relate to pluvial (surface water) flooding.

As most historical flood information available relates to the December 2015 flood event (Storm Frank), the mathematical model should be calibrated against this event. However, flows are not recorded in any of the four watercourses in Moffat. Therefore, it would be necessary to initially estimate the peak flows and shape of the flood hydrograph for each watercourse for the 2015 event. This would require a detailed hydrological modelling exercise, the outcome of which could not be guaranteed.

Instead of the above approach, it was considered more appropriate to compare model results for a range of return period flows with available flood data from the December 2015 event. This would indicate likely return period of the event, as well as how well the model predictions correlate with observed/anecdotal flood data. This aspect is discussed in more detail in Section 4.11.

4.9 Model Runs

The linked 1D-2D model was initially tested for a range of flow conditions and varying model parameters. This exercise was carried out to improve numerical stability and robustness of the model. The 1D-2D linked model was then run for a range of return period flows ranging from 1 in 2 years to 1 in 1000 year, with and without the effects of climate change. Model runs were carried out for the following:

- 1 in 2 years
- 1 in 5 years
- 1 in 10 years
- 1 in 25 years
- 1 in 30 years
- 1 in 50 years
- 1 in 75 years
- 1 in 100 years
- 1 in 200 years
- 1 in 500 years and
- 1 in 1000 years

4.10 Model Results – Base Case Condition

Model results for the 11 flow conditions listed above are presented in Appendix C. The predicted flood extent for the 1 in 200 year event is also shown in Figure 23. Based on this, a summary of location of flooding and flow mechanism is given below.

4.10.1 Flooding Mechanisms

4.10.1.1 River Annan

The model results show that the low-lying fields to the north and south of the Annan Bridge South (A701) and the nature reserve site to the south flood first. These areas flood during a 1 in 2 year flood.

As flow increases, flooding of the north bank of the Annan starts on both the upstream and downstream sides of Annan Bridge South. During a 1 in 10 year event, properties at Annanside start to flood.

With increasing flow, the floodplains to the north of Annanside and the New Bridge (A701 Edinburgh Road) flood as well as The Glebe.

During a 1 in 20 year event, flooding is predicted to occur at Hydro Cottage and properties on the west side of Old Edinburgh Road, Hope Johnstone Park and properties to the north and south of Edinburgh Road, properties at the west end of Reid Street, at West Park and Annanside. Flooding is also predicted at The Glebe. In the Hope Johnstone Park area, flood waters are predicted to overtop Edinburgh Road.

4.10.1.2 Birnock Water

There is no overtopping of the channel of the Birnock Water predicted for flows up to 1 in 5 year event. The first area to flood is a land just upstream of the footbridge at Park Circle. At higher flows, the flood extent in the footbridge area becomes larger. For a 1 in 50 year event, flood waters spill south, overtop The Holm (A708) and run south towards Ladyknowe Camping site. Part of the playing fields adjacent to Park Circle and the lower part of Burnside Road are predicted to flood.

For a 1 in 75 year event, flooding of properties at Park Circle and School Lane is predicted. No flooding is predicted upstream of Park Circle until a 1 in 100 year event, when flood waters overtop the river bank at the back of St Ninians Road, where Well Road is closest to the river on the opposite bank.

For a 1 in 200 year event and higher, most properties at St Ninians Road are predicted to flood. Flood waters overtopping The Holm (A708) flow south and affect the new Moffat Academy.

4.10.1.3 Crosslaw Burn

It should be noted that although the upper part of The Crosslaw Burn is included in the model (the reach between cross sections C0 and C13 in Figure 14), there are a number of field crossings along this reach some of which are included in the model and the others are not. The main reason for missing crossings was due to access difficulties at the time of the survey. The flood maps representing this reach of the watercourse contained in this report should therefore be regarded as indicative only and should be used with caution. This simplified representation in the current model is considered sufficient for the present study, however, if detailed flood mapping along this reach is required, a detailed local model should be set up which should include all field crossings. Flood mapping downstream of this reach are not affected from this.

For the 1 in 2 year flood event, some flooding of the fields to the south of the Sewage Works is predicted from the Crosslaw Burn, as well as flooding of a small area to the east of Moffat Hospital on the north side of the A708.

The extent of flooding in these areas increases with increasing flow. For a 1 in 25 year event, some flow is predicted to overtop the west bank of Frenchland Burn and flow towards Crosslaw Burn to the north of the A708.

Flows backing up from an undersized culvert under the A708 inundate the low-lying areas on the north side of the A708, along with the additional overland flood flows from the west, sourced from the overtopping of the Frenchland Burn.

Flows overtopping the east bank of the burn south of the A708 accompanied by flows from the bypass culvert (under the A708), are conveyed south towards the Frenchland Burn along the low-lying land and presumed natural course of the burn before man-made intervention created the current route.

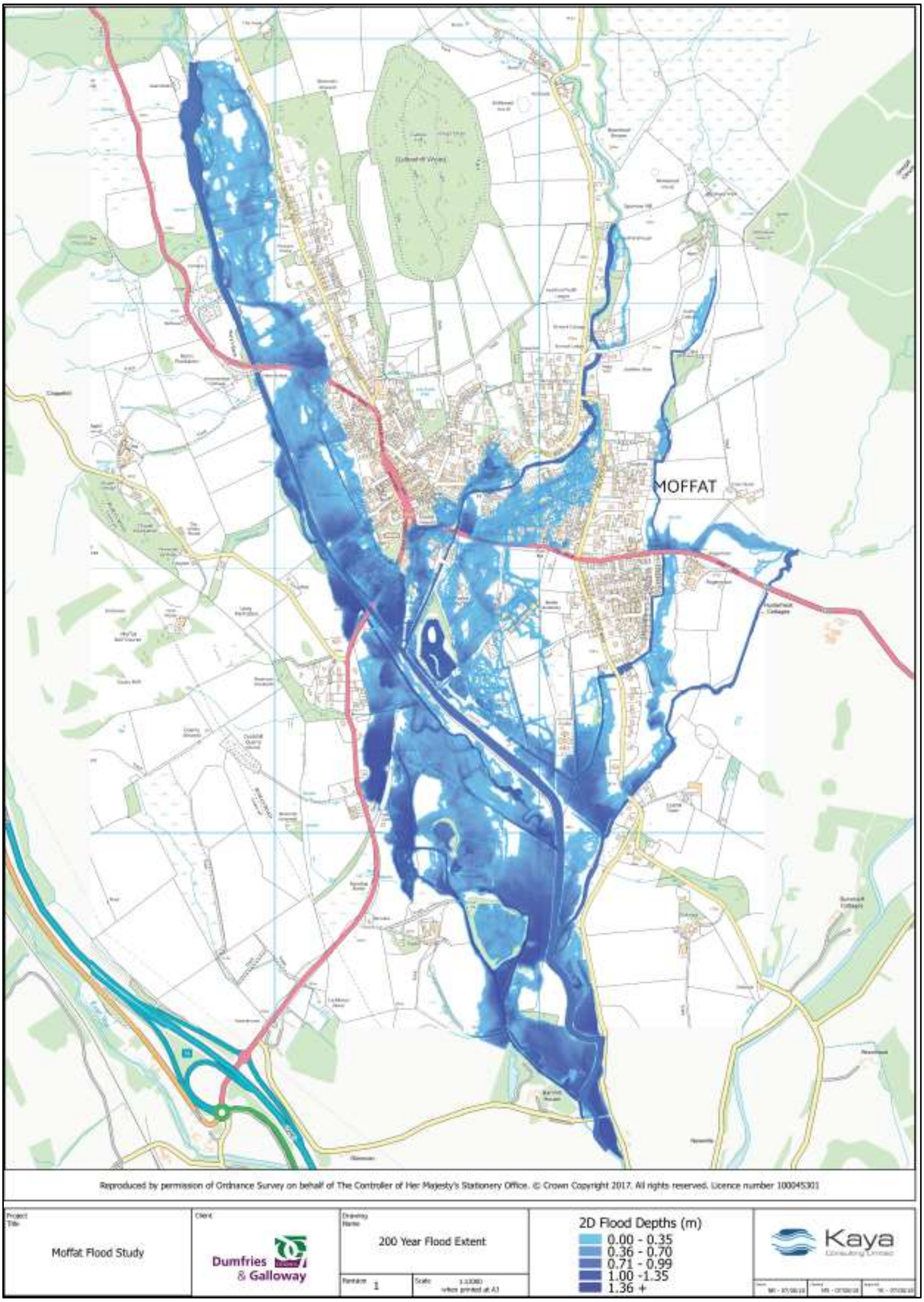
Flooding occurs on the low-lying land on both banks of the burn as it approaches the Frenchland Burn. No flooding of properties is predicted up to 1 in 200 year event, except flooding of a barn at Eastfield.

4.10.1.4 Frenchland Burn

Flooding from the Frenchland Burn starts for the 1 in 5 year event at Old Carlisle Road due to the under capacity of the culvert. At the 1 in 25 year event, flood waters are predicted to overtop the road in this area. The west bank of the burn is predicted to overtop with flood waters flowing west towards the Crosslaw Burn.

As flow increases, the flooding extent in these areas becomes larger, but no flooding of any properties is predicted for the 200 year and 1000 year events.

Figure 23: Predicted 200 year extent of inundation



4.11 The December 2015 Event

Comparison of available data for Storm Frank (December 2015) and model results indicate that, the flood event may have a return period of the order of 1 in 50 years. The estimated return period of the December 2015 event on the Cree at Newton Stewart was between 1 in 50 and 55 years. Therefore, a similar return period for Moffat is not unrealistic.

Comparing the locations of flood incidents associated with the December 2015 event shown in Figures 2 and 3 and the predicted flood extent for the 1 in 50 year and 1 in 75 year events indicates that the December 2015 flood event from the River Annan may had a return period of the order of 1 in 50 years. The model predictions for the 50 year event show some flooding from Birnock Water in the Park Circle and Burnside Road area. Historical flooding incidents shown in Figure 2 also show some flooding in this area. A photograph shows water level close to overtopping the A708 in this area, consistent with the predictions for the 1 in 50 year event.

Although there are no peak water level data available for the December 2015, the model predictions are consistent with the available flood information, providing some confidence in the performance of the model and its ability to predict flooding in the correct areas of the town.

4.12 Model Sensitivity Analysis

A model sensitivity analysis provides an illustration of the effect of changing key model parameters on the important model outputs (in this case flood levels, extents and depths). If model parameters are varied within the range of possible input values, then a sensitivity analysis can also provide an indication of uncertainty associated with the model predictions.

A sensitivity analysis was undertaken considering the following parameters;

- An increase in flow of 44% to represent future climate change;
- Manning's "n" values for the channel, floodplain, and culverts within the 1D and 2D environment were increased by 20% from design values; and
- Downstream boundary slope was reduced by 20%.

The results of this sensitivity analysis can be seen in Appendix E showing the corresponding flood maps and a table containing the predicted changes in water level at each cross section. The model is shown to perform as expected, with changes in model parameters producing expected changes in modelled levels. The results also show that the model is reasonably insensitive to changes in Manning's n and not sensitive to changes in the downstream boundary. The model is sensitive to changes in flow, as would be expected.

4.13 Summary of Fluvial Flooding Risk

The modelling work outlined above indicates that large areas along both banks of the River Annan would flood, even for relatively low return period flood events. At higher return periods properties are predicted to flood at

- Hydro Cottage;
- the west side of Old Edinburgh Road;
- Hope Johnstone Park;

- to the north and south of Edinburgh Road;
- at the west end of Reid Street;
- at West Park and Annanside;
- The Glebe; and
- the church.

The A701 road would be overtopped in two places; at Annan Bridge South and Annan Bridge North (Edinburgh Road).

Large areas of the town are also predicted to flood from the Birnock Water. This would largely be in the St Ninians Road, Park Circle and Burnside area, including the playing fields. Flood waters are predicted to overtop the A708, with flood waters flowing south to Ladyknowe Caravan Park and towards the Moffat Academy, which would be affected for the 1 in 200 year and higher events.

Limited flooding from Crosslaw Burn and Frenchland Burn was predicted, with no significant properties affected. A flow pathway between the Crosslaw Burn and Frenchland Burn was identified.

The number of properties predicted to flood over a range of return period flows are summarised in Table 22. SEPA in their 2011 assessment indicated 370 residential and 50 non-residential properties at risk of flooding during a 200 year event (see Section 1.1). In addition to number of properties presented in Table 22, over 50 residential properties would also be at risk from pluvial flooding. SEPA estimated flooding of significantly more residential properties than predicted in the present study. This may be due to present study only counting ground floor flats, whereas SEPA may have counted upstairs flats as their access/egress would also be affected, and flood extents being slightly different.

Table 22: Predicted number of properties at risk of fluvial flooding

Type	2 year	5 year	10 year	25 year	50 year	75 year	100 year	200 year	500 year	1000 year
Residential	0	1	2	9	20	28	34	44	60	78
Non-Residential	1	4	10	25	49	55	61	84	107	117
Total	**1**	**5**	**12**	**34**	**69**	**83**	**95**	**128**	**167**	**195**

The A701 is predicted to flood at both Annan Bridge South and Annan Bridge North (Edinburgh Road) and the A708 is predicted to flood at Millburn Bridge. The main access road to Moffat is the southern A701 providing access from the M74 Motorway in both the north and south directions, as well as towards local towns such as Lockerbie and Dumfries. The nearest hospital is located in Dumfries. Should this access route be blocked the northern A701 access is an approximately 30 mile diversion and the A708 route a 20 mile diversion to the hospital. Furthermore, both of these access routes are predicted to flood. It was indicated during the public consultation that the town has historically been cut off for vehicular access at certain times of flooding. Therefore, mitigation of flooding risk to the A701 road should be considered as an important aim for any flood mitigation measures.

5 Assessment of Pluvial Flooding Risk

Moffat experiences significant flooding risk from pluvial (surface water) sources. This is due to the local topography where Gallow Hill rises up from about 130m AOD (Above Ordnance Datum) to 250m AOD in the north of the town. It forms the prominent hill overlooking the town. The average ground slope on the west side of the hill is of the order of 1 in 3.5, while to the south it is of the order of 1 in 7. Although Gallow Hill is largely forested and vegetated, rain falling on such steep slopes does not have much time to percolate into the soil and there will be high runoff rates, with rainfall turning into overland flow and running towards properties at the bottom of the hill.

A number of studies have been carried out to assess flooding risk from Gallow Hill and develop mitigation measures. The relevant studies were listed in Section 1.2, with the most relevant studies listed below:

- **Moffat Flood Prevention Feasibility Study – Options for Alleviating Existing Flooding Problems, Dumfries and Galloway Council, 2003**: This considered minor improvements to culverts entrances, repairing of damaged river banks, and also upsizing of some culverts.
- **Moffat Flood Study, Ewan Group, 2005 (updated 2016):** This considered assessing flooding risk from River Annan, Birnock Water and Crosslow Burn using mathematical modelling. It also considered flooding risk from Gallow Hill, and estimated capacity of the culverts draining surface water from Gallow Hill.
- **Moffat Flood Study – Gallow Hill Runoff - Conceptual Design, Dumfries and Galloway Council, 2011:** This considered possible options to managing runoff from Gallow Hill.
- **Gallowhill Wood Surface Water Management Option Review, Mouchel, 2013**: This also considered runoff from Gallow Hill and developed mitigation options.

Information available from the previous studies, observations made during site visits and calculations undertaken as part of the current study indicate that the main cause of pluvial flooding originating from Gallow Hill is due to undersized surface water culverts unable to cope with rapid runoff from the hillside. There is also a risk of blockage of the culvert entrances due to their relatively small sizes.

The existing LiDAR DTM was used to delineate Gallow Hill catchment and this is shown in Figure 24. Areas of these sub-catchments and estimated 200 year runoff rates from each are shown in Table 23.

Table 23: Estimated sub-catchment areas and 200 year flows

Sub-catchment	1	2	3	4	5	6	7	8
Area (ha)	6.42	5.39	14.09	7.67	1.25	4.03	12.95	1.45
200 year flow (m^3/s)	0.36	0.31	0.80	0.44	0.07	0.23	0.74	0.08

Sub-catchments 1 and 2 drain through Hydro Avenue, Sub-catchments 3, 4, and 5 drain through Harthope Place, and Sub-catchments 6, 7, and 8 drain through Greenwood Close.

Should the culvert running through Hydro Avenue to substantially block, 8 to 10 properties could potentially be at risk of flooding.

Should the culvert running through Harthope Place to substantially block, in excess of 30 properties would potentially be at risk of flooding.

Should the culvert running through Greenwood Close to substantially block, 10 to 12 properties would potentially be at risk of flooding.

The above indicates that in excess of 50 properties could potentially be affected from surface water runoff from Gallow Hill.

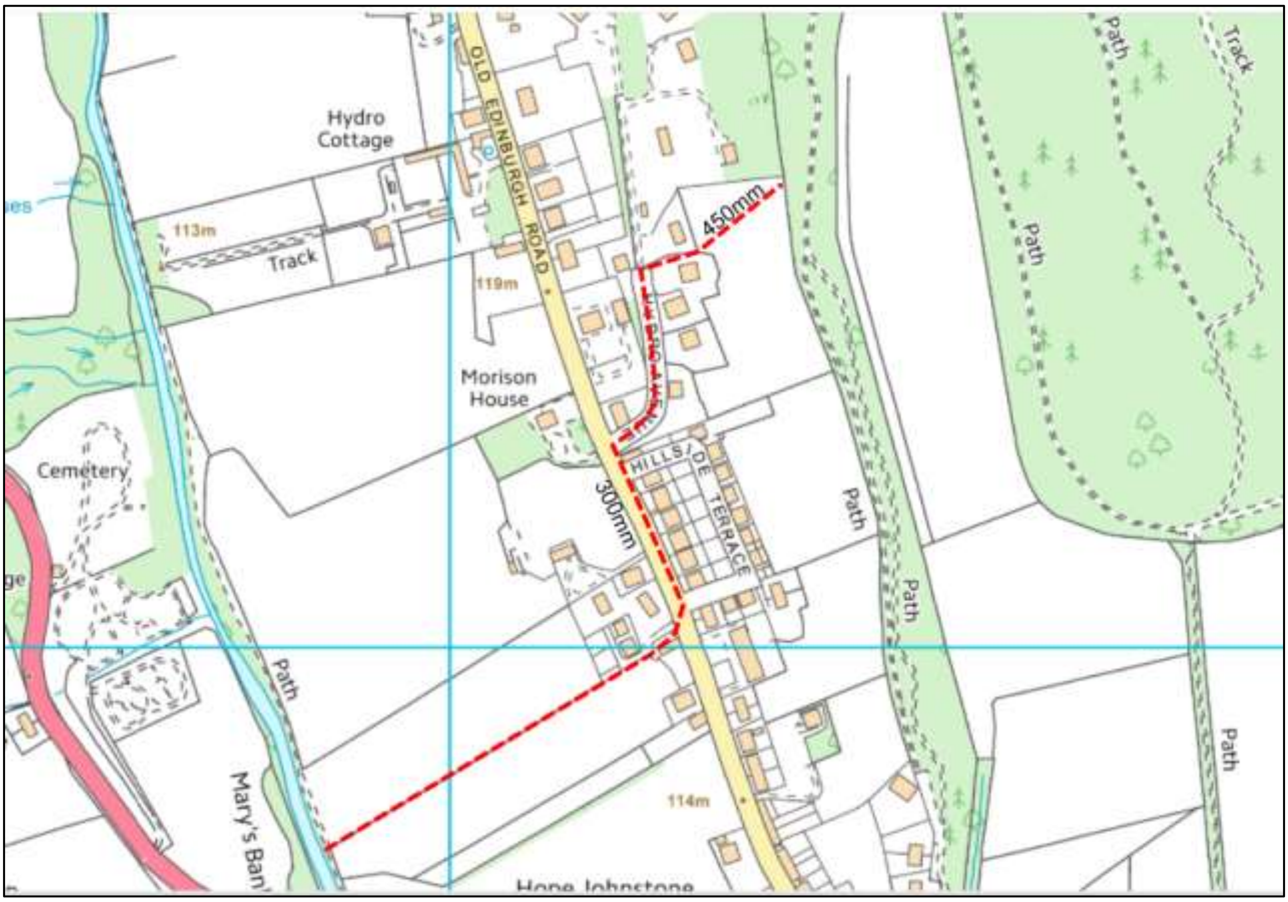
Figure 24: Gallow Hill Sub-catchments draining towards urban areas

5.1 Culvert Capacity Estimation

5.1.1 Hydro Avenue Culvert

The indicative line of the Hydro Avenue culvert is shown in Figure 25.

Figure 25: Indicative line of Hydro Avenue culvert



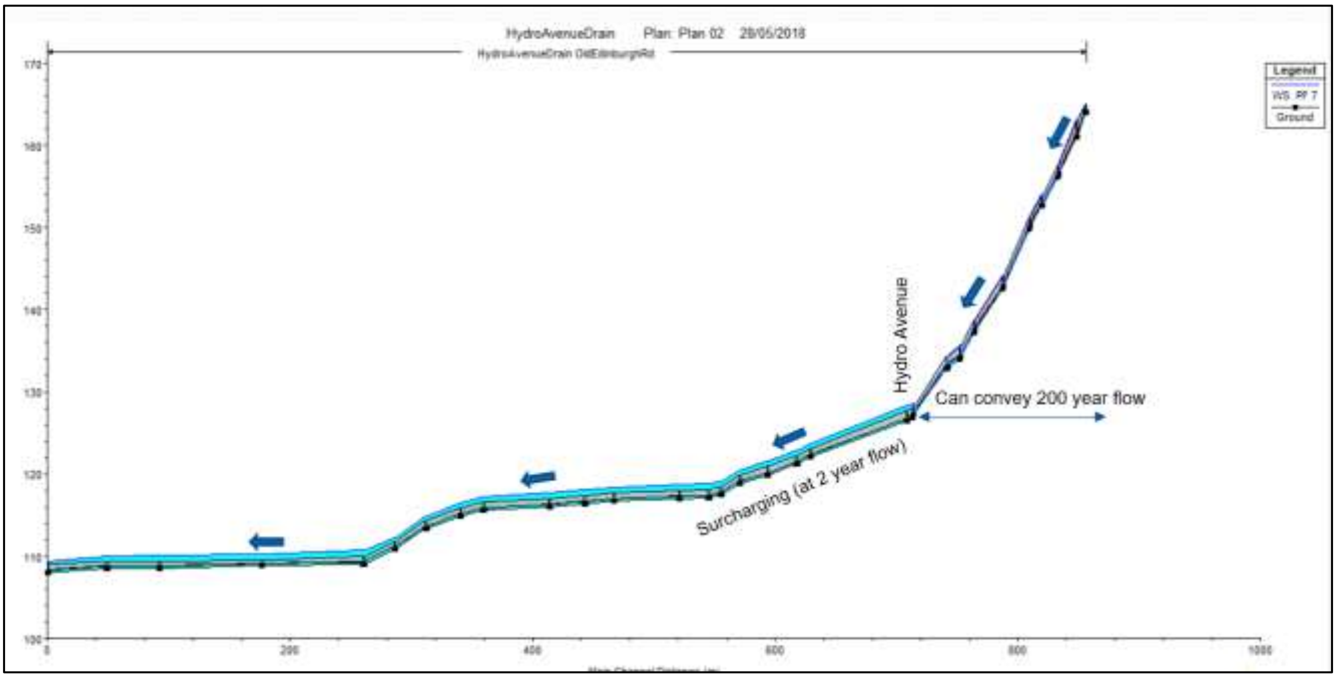
The top part of the culvert (upstream of Hydro Avenue) was replaced with a 450mm culvert in 2014. Downstream, the culvert is in generally 300mm diameter from the top of Hydro Avenue.

Table 23 indicates that the 200 year flows arriving at the culvert entrance is of the order of $0.67m^3/s$ (i.e. flows from combined sub-catchments 1 and 2).

The culvert was modelled using HECRAS. The model long profile is illustrated in Figure 26 and indicates that the new 450mm part of the culvert (upstream of Hydro Avenue) is capable of conveying the estimated 200 year flow. Through Hydro Avenue and Old Edinburgh Road the culvert capacity is reduced to approximately $0.2m^3/s$, further reducing to less than $0.1m^3/s$ as it approaches the River Annan.

It was predicted that the section of the culvert through Hydro Avenue and Old Edinburgh Road would flood on average once every 2 years (assuming no blockage) and more frequently with blockage.

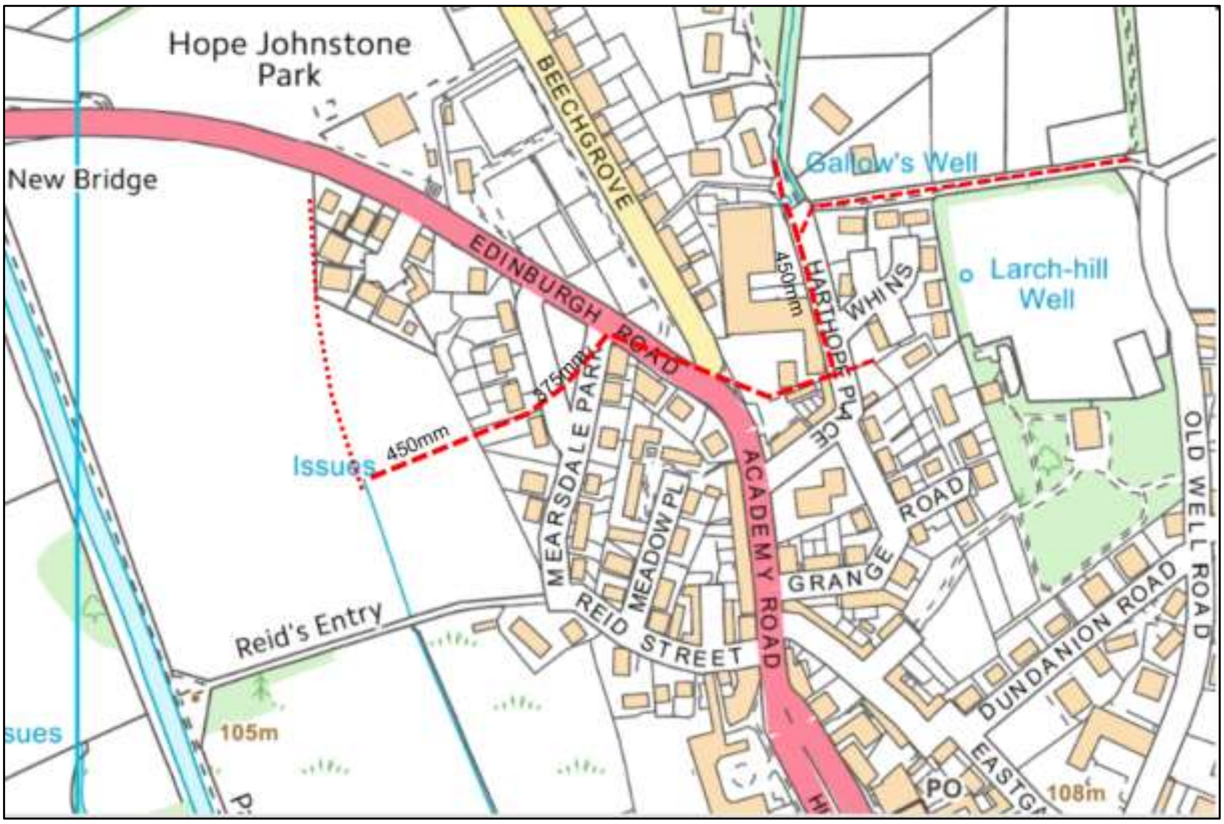
Figure 26: Longitudinal plot of Hydro Avenue culvert



5.1.2 Harthope Place Culvert

The indicative line of the culvert passing through Harthope Place is shown in Figure 27.

Figure 27: Indicative line of Harthope Place culvert



The culvert size is 450mm through Harthope Place, reducing to 375mm before becoming 450mm again at its downstream end, see Figure 27.

Total flows arriving at the culvert could be of the order of 1.31m^3/s (total of sub-catchments 3, 4 and 5 in Table 23).

It was estimated that the culvert would surcharge for flows in excess of 1 in 2 years. During a 200 year event, properties at Harthope Place, Edinburgh Road, and Mearsdale Park would be affected.

The full-bore capacity of the culvert was estimated to be approximately 0.5m^3/s through Harthope Place, reducing to 0.4m^3/s through Edinburgh Road and reducing to less than 0.2m^3/s further downstream toward the outlet. These flow rates are considerably less than the potential peak flow which could arrive at the culvert during a 200 year event.

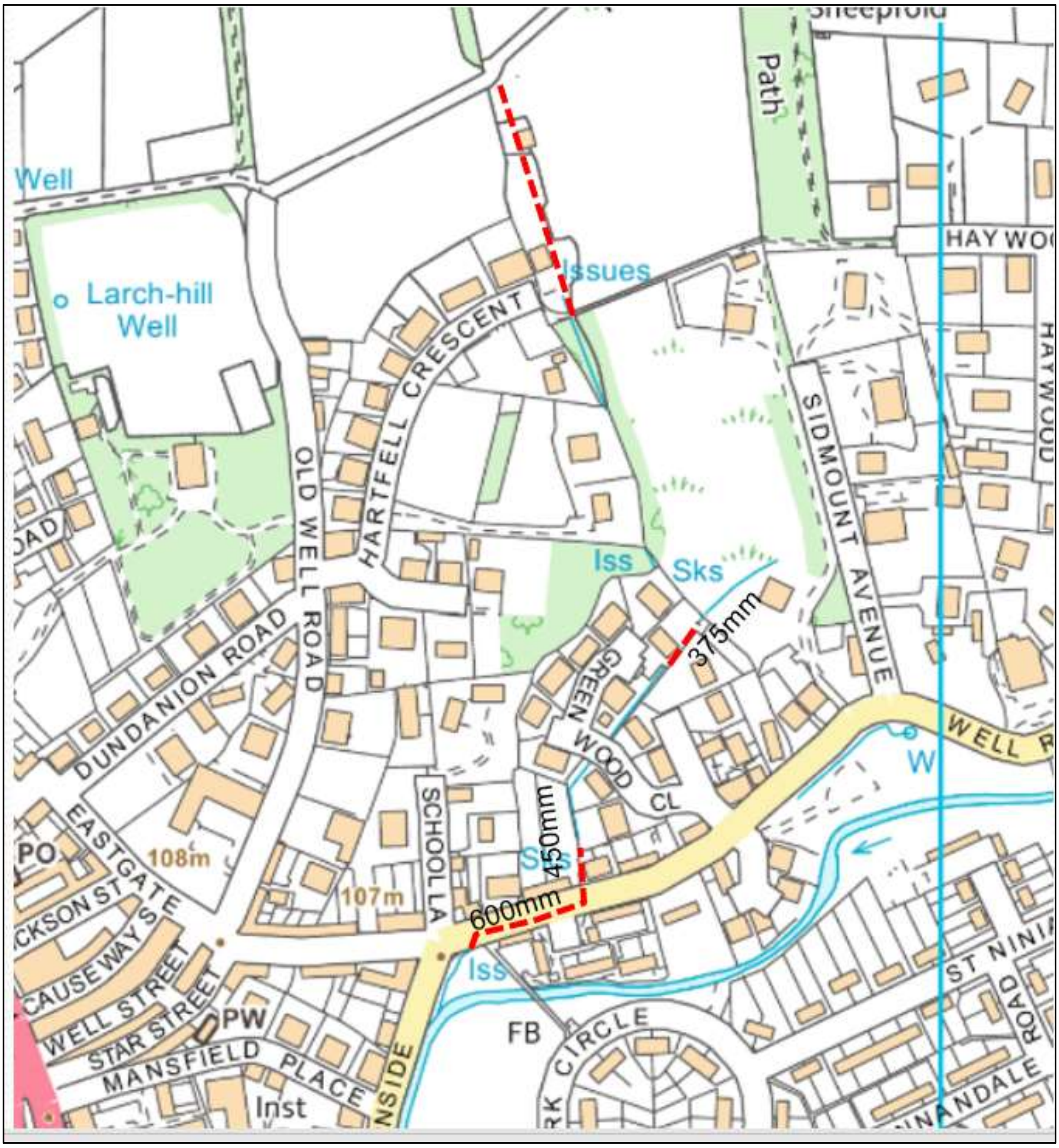
5.1.3 Greenwood Close Culvert

The indicative line of the Greenwood Close culvert is shown in Figure 28. The culvert has varying sizes as shown in Figure 28.

Table 23 indicates that total flows arriving at the culvert could be of the order of 1.05m^3/s (sub-catchments 6, 7 and 8 in Table 23), plus runoff from an area between these catchments and Greenwood Close of 5.3ha, giving a total flow of 1.36m^3/s for the 200 year event.

It was estimated that culvert capacity would be exceeded for flows exceeding 1 in 4 to 1 in 5 year return period. During a 200 year event, properties at Greenwood Close and Well Road would be affected.

Figure 28: Indicative line of Greenwood Close culvert



6 Flood Mitigation Options

Flooding of properties in Moffat is caused by three main sources; flood waters overtopping banks of the River Annan and Birnock Water, and surface water runoff from Gallow Hill.

A detailed assessment of flooding risk from all sources indicated that during a 200 year event 102 properties could be flooded from fluvial sources (i.e. Annan and Birnock) and up to around 50 properties could be affected from pluvial (surface water) sources.

An initial assessment has been carried out to identify possible flood mitigation options. SEPA in their high-level assessment in 2011, identified a number of actions to mitigate flooding risk in Moffat, outlined in Section 1.1

The flood mitigation options considered in this study include:
1) Provision of upstream storage;
2) Increasing capacity of bridges and culverts;
3) Direct defences;
4) Lowering of river bed; and
5) Property level protection.

A review of the upstream catchment of the River Annan indicated that there are no obvious areas where sufficient volumes of flood waters could be stored to reduce flooding risk in Moffat. The design flows in the River Annan at Moffat are high, requiring significant volumes of flood storage to make any impact on flood peaks. No obvious areas were noticed within the upper catchments of the other three watercourses where flood waters could be stored. The headwaters of the catchments are relatively steep, providing little scope for the attenuation of large volumes of water. In addition, low-lying land adjacent to the River Annan is already floodplain, with little scope for increasing flood storage volumes. Given the limited scope for flood storage options, this potential flood management measure has not been taken forward. An upstream storage option was considered for managing flooding risk from Gallow Hill and this is discussed further later in the report.

Model results indicated that the A701 Annan Bridge South and the A708 Millburn Bridge over Birnock Water are both under capacity. Widening and raising of these bridges is taken forward as a potential flood management option and is discussed later.

The most effective option for mitigating flooding risk from surface water runoff from Gallow Hill appears to be an increase in the capacity of the culverts draining the hill. This option is taken forward and discussed in more detail below.

The conventional method of flood mitigation is by way of direct defences, involving the construction of flood walls and earth embankments to protect flood risk areas. In some cases, this may be the most effective way of reducing flood risk to an acceptable level. However, containment of the entire flood flow within the main channel (i.e. due to embankments/walls preventing overtopping) would increase flood levels both upstream and downstream of the area protected. Any increase in water level due to direct defences will need to be included in the design of the defences, so that the protection of one area did not increase flood risk to others.

Lowering of the river bed can increase flow conveyance and lower water levels in the river. This is usually considered in areas where sediment deposition is taking place. Both the River Annan and Birnock Water in Moffat appear to have reached their regime or near regime conditions. These means that no significant erosion and deposition takes place along this reach of the watercourse. Although sediment will be transported through the reach there is a general balance between material arriving from upstream and leaving the reach downstream, so that the bed level in any location does not change markedly over time. Lowering the bed level in any location could disturb the stable regime conditions and the watercourse would try to return back to the existing conditions over a period of time. This would require monitoring the river bed, with re-lowering once the bed level rises to a predefined level. Therefore, such works would need to be undertaken on a regular basis. As such an option would have significant environmental impact on the river corridor, SEPA and SNH would not normally allow such engineering of the channel. Therefore, this option has not been considered further.

Property level of protection include, but not necessarily limited to:

a) Manual/Automatic door guards;
b) Manual/Self-closing airbricks and covers;
c) Non-return valves on sewer pipes;
d) Re-pointing external walls (up to 0.6m above ground level with water resistant mortar);
e) Silicone gel sealant around service and cable entry points;
f) Sump pump; and
g) Resilient plaster (up to 1m); resilient doors; windows and frames; resilient kitchen; raised electrics and appliances; and concrete/sealed floors.

A recent study commissioned by DEFRA[1] showed the benefits of such defences where a wider flood mitigation scheme is not technically feasible or financially viable. This followed by a study for Scottish Government[2] which aims to quantify how many properties and businesses might benefit from property level protection (PLP), now and in 2035, and what the costs and benefits of providing PLP within Scotland may be. The results have been presented at both a national level (to inform policy decisions) and at a regional level (to assist local authority decisions). However, the analysis is based on SEPA indicative flood mapping and more detailed analysis will need to be carried out for specific watercourses. However, these remain options to be considered for areas where more formal flood protection schemes are not viable due to engineering and cost limitations.

6.1 Level of Protection

In Scotland, the standard level of protection, from a Scottish Planning Policy perspective, 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 types of developments including residential and commercial/industrial, except for sensitive infrastructure (e.g. schools or hospitals) for which a higher level of protection is required (i.e. 1 in 1,000). To allow re-development behind a flood scheme, based on the most recent SEPA guidance a flood scheme would need to provide a 1 in 200 year + climate change level of protection.

[1] Establishing the Cost Effectiveness of Property Flood Protection: FD2657, August 2012, JBA.
[2] Assessing the Flood Risk Management Benefits of Property Level Protection: Technical and Economic Appraisal Report - Final Report v2.0 November 2014

Although providing a flood scheme with a level of protection of 1 in 200 year + climate change would be the ideal level of protection for residential and commercial areas in Moffat, sometimes it may not be cost effective to provide such a level, or indeed acceptable to local residents. 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 (i.e. unacceptably high flood walls) or does not produce a sufficiently high benefit cost ratio (showing the scheme does not provide sufficient protection for its cost), a lower level of protection may be more acceptable. Hence, in this assessment, a range of levels of protection are considered.

Model runs undertaken 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 2 year flood only one property was predicted to flood. This does not mean that this property would flood every other year. Taken over a long period of time, say 50 years, the property would be expected to flood of the order of 25 times. Some of these flooding incidents could occur in less than two year intervals and other may be less frequent, but the overall total would not change significantly.

6.2 Freeboard Allowance

A freeboard allowance accounts for uncertainties in the derivation of flood level. It is the height above the modelled flood level that the top of a wall or embankment would be set. A standard 0.3m is normally made for hard defences like flood walls and 0.6m for soft defences such as earth embankments. Variations from these values are allowed based on justifiable reasons and backed up by calculations and consultation. For the flood defences considered, a standard freeboard allowance of 0.3m has been made.

6.3 Fluvial Flood Mitigation Options

Options considered include:

- Increasing flood storage within Hope Johnstone Park;
- Increasing flow capacity through Annan Bridge South;
- Increasing conveyance along Birnock Water (two-stage channel); and
- Direct defences

6.3.1 Increasing Flood Storage in Hope Johnstone Park

Model results indicate that flood waters inundating Hope Johnstone Park overtop the A701 Edinburgh Road and spill onto the fields south of the road, affecting some of the residential properties on the south side of the road. The road dips close to the residential properties and Beechgrove Sports Centre where flood waters overtop first. The road level rises to the west (Annan Bridge North) and east.

This mitigation option involves the construction of an earth embankment on the north side of Edinburgh Road, tying into high ground to the west approaching the bridge and to the east approaching Beechgrove Road. An indicative location of the embankment is shown in Figure 29. The top of the embankment level is set above the predicted flood level, so that there is no overtopping of the embankment.

The embankment blocks the flow path overtopping the A701 Edinburgh Road and causes water level in Hope Johnstone Park to rise by approximately 0.3m, pushing all flood water through the bridge and increasing water levels in the river by approximately 0.1m. Although this embankment protects Beechgrove Sports Centre, Edinburgh Road and residential properties on the south side of Edinburgh Road from flooding, no flooding of the fields on the south side of the road between Edinburgh Road and Reid's Entry was predicted. This is a large floodplain area and flood waters that would be stored within this field now pass downstream, with this option in place. In order to utilise this floodplain, a section of the left hand bank downstream of Annan Bridge North was lowered (over a length of some 30-40m. This allowed flood waters to spill onto this field, although the flood extent is not as large as that predicted for present day case (i.e. no embankment in Hope Johnstone Park). The predicted extent of inundation is shown in Figure 30. In order to maximise flood storage in these fields without flooding adjacent properties, the level of the lowered east bank of the river and length of it will need to be optimised. This work will need to be undertaken as part of detailed design, should the scheme be taken forward.

Figure 29: Indicative location of flood embankment in Hope Johnstone Park

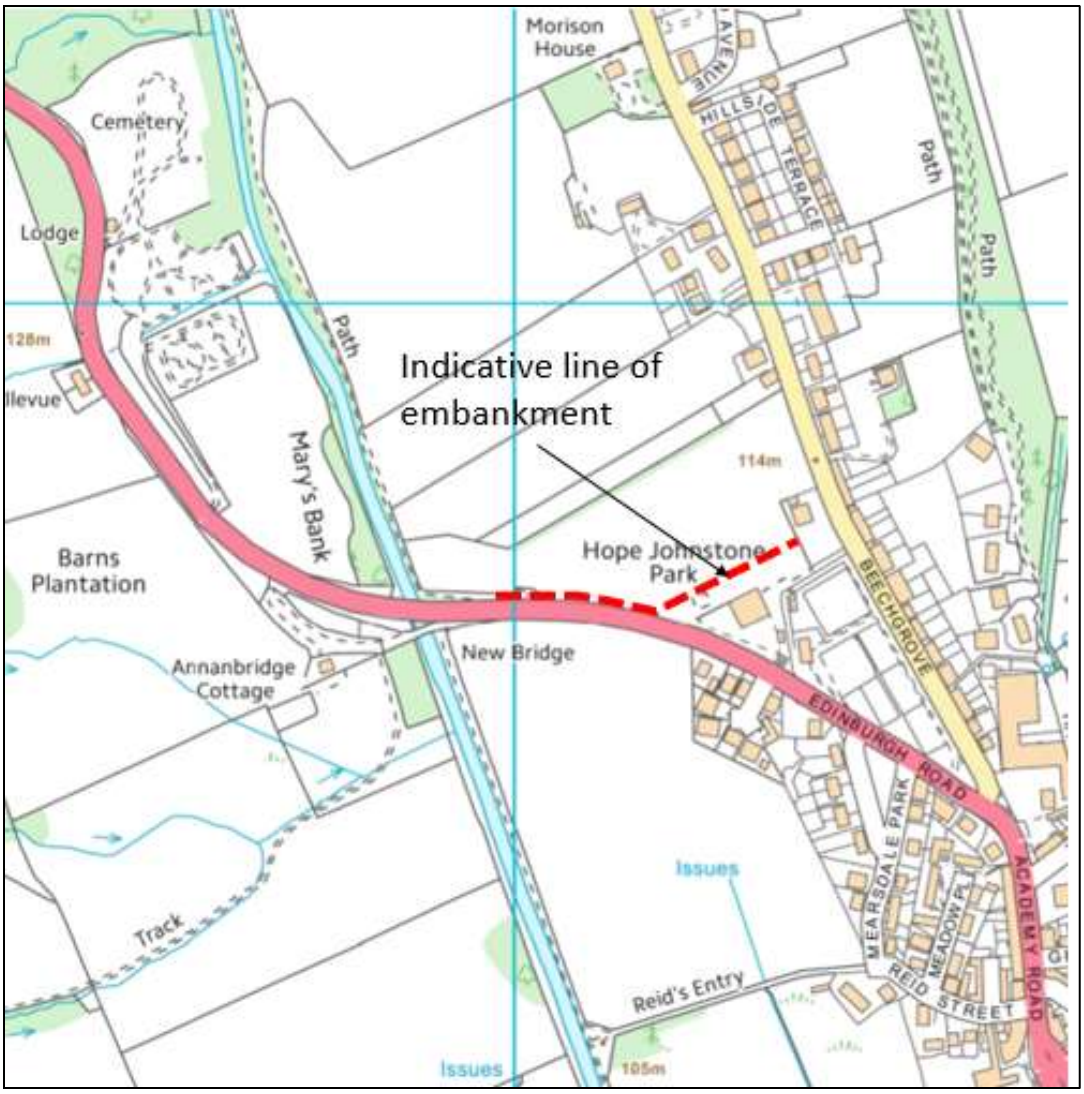
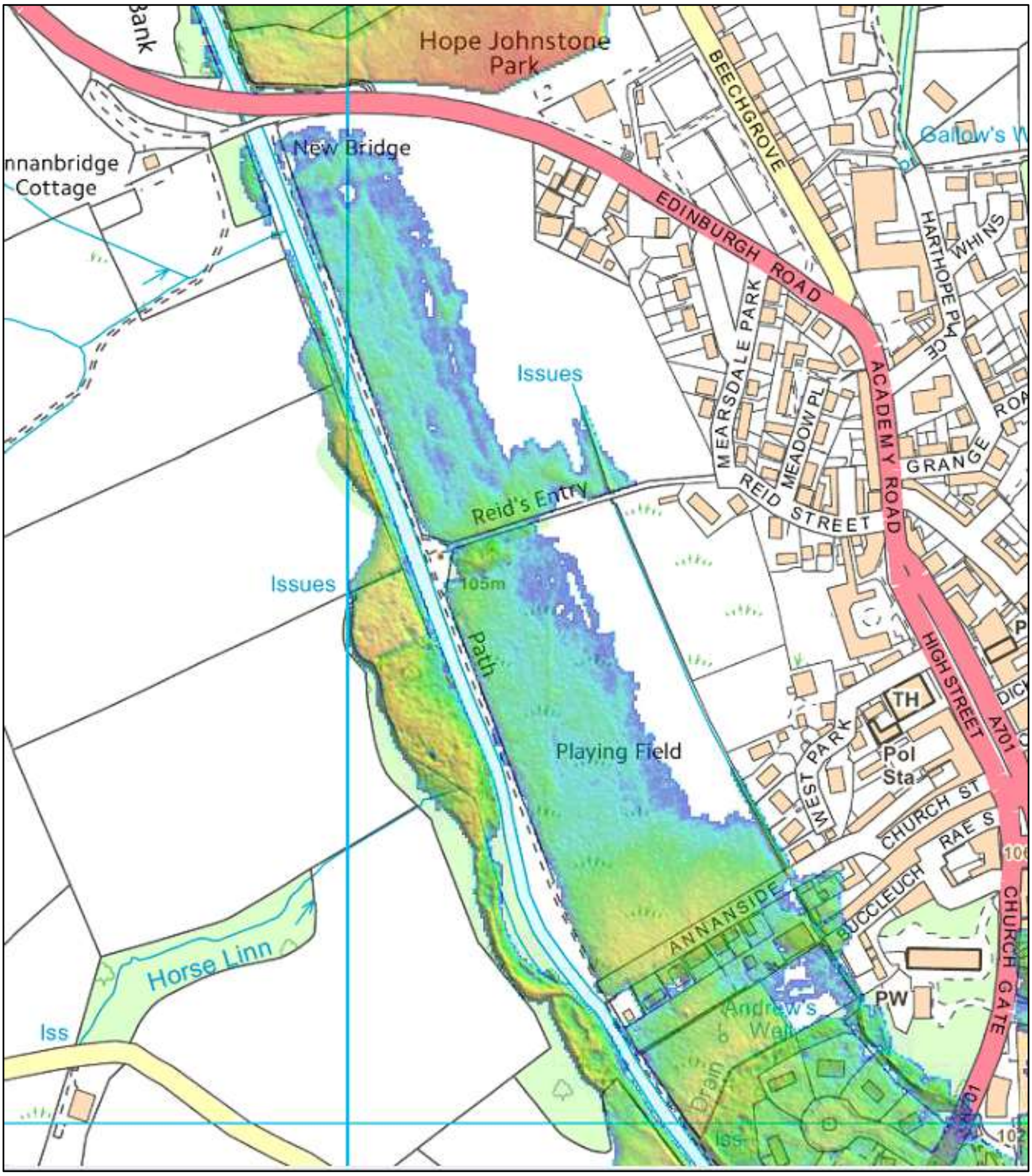


Figure 30 indicates that the proposed embankment in Hope Johnstone Park would prevent the A701 Edinburgh Road from flooding during a 200 year event.

Consideration was given to lowering existing ground levels within Hope Johnstone Park, to allow more storage within the park area. Although, this allowed some extra water to be stored within the park, its effect on peak water levels and flows passing downstream was limited. Therefore, it has not been considered further.

The above indicates that an earth embankment approximately 230m long along the southern edge of Hope Johnstone Park provides significant flood mitigation benefit downstream.

Figure 30: Predicted 200 year flood extent with embankment in Hope Johnstone Park and lowered left hand bank embankment downstream of bridge



6.3.2 Increasing Flow Conveyance at Annan Bridge South (A701)

Figures 23 and 30 indicate that properties at Annanside and The Glebe flood during a 200 year event. Model runs undertaken for a range of flow conditions indicated that Annan Bridge South is under capacity. This causes flood waters to back up and increase water level upstream. During a 200 year event, less than half of the flow arriving at the bridge passes under the bridge and a small amount (no more than 5m^3/s) flows through the bypass culvert to the south of the bridge (on the right hand bank). The remaining flow overtops the road/bridge on the east (left hand) bank, causing flooding. This indicates that in order to pass all flows arriving at the bridge during a 200 year flood under the road, significant extra flow capacity would need to be provided (equivalent to the existing bridge and culvert), either through the bridge and/or on the right hand bank to prevent flooding of the road and adjacent areas on the left hand bank. This could be achieved in two ways:

a) Construction of a wall/embankment along the left hand bank to keep flood waters on the river side and passing more flows through the bridge; and/or
b) Increasing flows passing down the right hand bank.

As the existing bridge can only pass less than half of the design flow arriving at the bridge location, construction of walls/embankment to protect The Glebe and the A701 does not appear practical unless flow conveyance through the bridge and right hand bank of the river is significantly increased. Due to the local topography, raising of the bridge deck to allow more flow under the bridge does not appear to be a practical option.

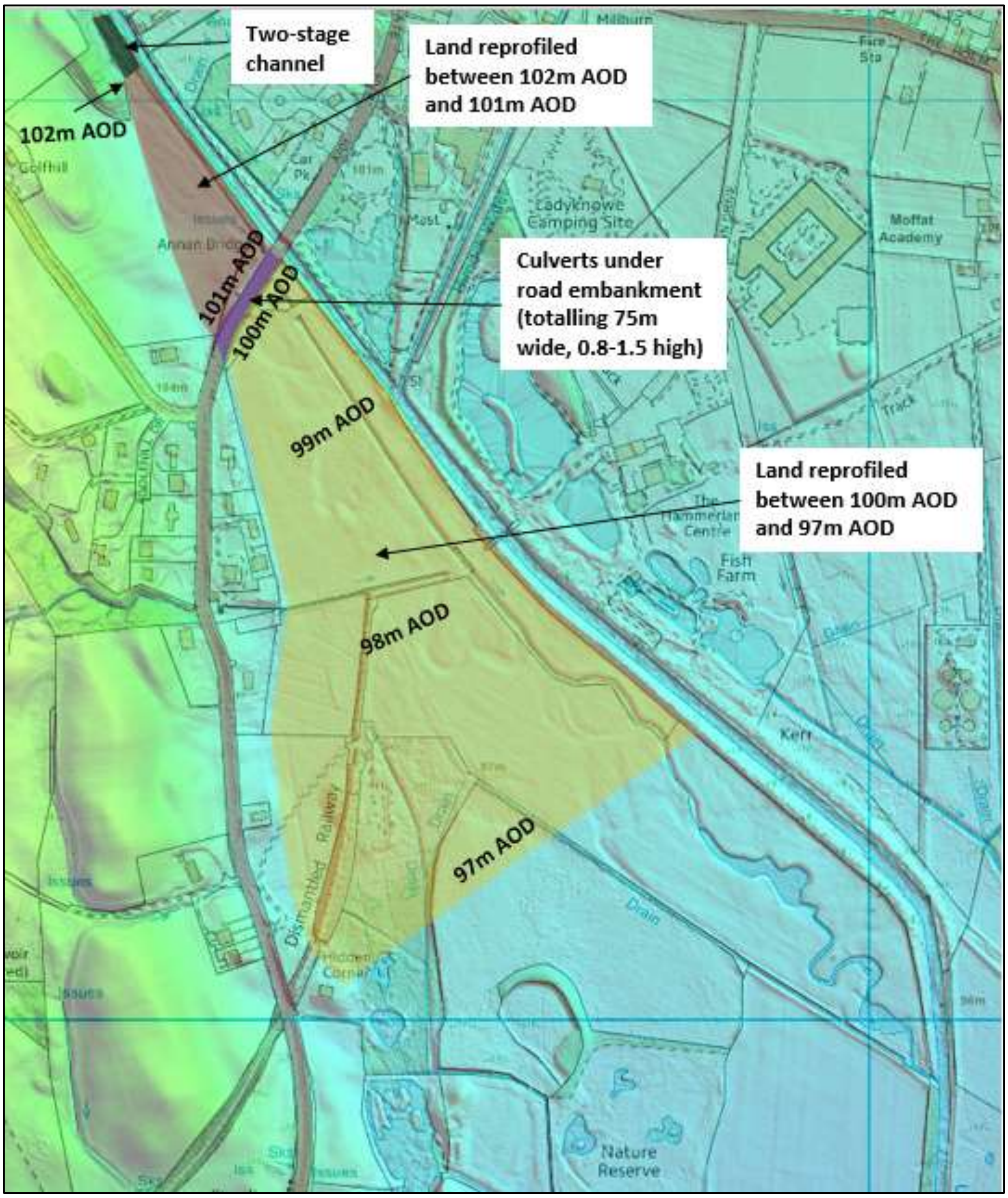
In order to convey large volumes of flow along the right hand (west) bank would require lowering of the west bank approaching the road from upstream. However, the road embankment is approximately 2m high and as a result, culverts through the embankment will be required to pass such flows downstream (instead of embankment lowering). Lowering of the fields on the downstream (east) side of the road will also be required to streamline flows passing through the culverts to minimise downstream effect on culvert capacities and maximise flows passing through the culverts. Initially, the following work has been considered and modelled (Figure 31):

1) The shaded area upstream of the road embankment is reprofiled with ground level lowered to linearly change between 102m AOD and 101m AOD. Any areas lower than the specified level are left as they are.
2) Similarly, the shaded area downstream of the road embankment is reprofiled with ground levels lowered to linearly change between 100m AOD and 97m AOD.
3) Banks of the river both upstream and downstream of the road bridge are also lowered.
4) A series of culverts is placed under the road embankment with the width of the culverts totalling 75m and height of the culverts varying between 0.8m near the river to 1.5m at the far end. The invert level of the culverts at their inlet was set to 101m AOD.

The predicted flood extent based on the above still shows a large extent of flooding on the left hand bank affecting the entire Annanside and the Glebe. Model results indicate that approximately 30m^3/s flow is conveyed along the right hand bank (through the new culverts), approximately 25m^3/s is conveyed through the existing bridge, with the remaining flow in excess of 35m^3/s conveyed along the left hand bank. The predicted peak water level on the right hand bank is approximately 1m lower than the corresponding water level on the left hand bank. This indicates that the assumed reprofiling of land and lowering of the right hand bank was not able to direct sufficient flows onto the right hand bank. Less than half of the capacity of the proposed culverts under the road embankment is used. Therefore, if more flows could be passed onto the right hand bank, this would reduce flows on the left hand bank.

The right hand bank floodplain is narrowest at Annanside (as shown in Figure 30). Consideration was given to lowering the right hand bank in this area to create a two-stage channel. The existing channel cross section at Annanside is shown in Figure 32. This indicates that it may be possible to lower the part of floodplain above the dotted black line over a length of some 20m to generate a two-stage channel. The two-stage channel would start a short distance upstream of Annanside and extend downstream into the area where land is lowered, and floodplain gets wider.

Figure 31: Work required to increase flow conveyance along right hand bank



Model runs were carried out with two-stage channel at Annanside, with the right hand bank approaching the A701 lowered, a series of culvert provided under the A701 embankment, and land downstream of the A701 embankment lowered, as indicated above. Model results for this, combined with flood defences upstream and along Birnock Water are given in Section 6.3.4 below.

Figure 32: Typical two-stage channel at Annanside (bank above dotted black line is to be removed)

6.3.3 Increasing conveyance along Birnock Water

It was shown in Section 4.10.1.2 that Birnock Water overtops its banks for flows in excess of the 1 in 5 year return period. The main channel of the river is under capacity for flows in excess of this.

Consideration was given to providing a two-stage channel along the length of the river where overtopping is predicted. A two-stage channel could potentially be provided along most of the reach of the river where overtopping is predicted. The initial assessment is based on a two-stage channel upstream of Park Circle footbridge. Due to limited available space along the banks of the river, the higher level channel can be provided on either the left bank or the right bank (and not necessarily on both banks). A typical two-stage channel is shown in Figure 33. This provides a higher level channel approximately 3m wide on the right hand bank. For consistency, the higher level channel level is set to 1 in 5 year water level.

The predicted 200 year flood extent with two-stage channel is shown in Figure 34. This shows significantly less overtopping along the reach upstream of Park Circle. It is possible to refine this to reduce overtopping further. However, a low wall in the areas where overtopping is predicted may still be required.

As this option still requires direct defences, it has been considered further in Section 6.3.4 Direct Defences.

Figure 33: Typical two-stage channel along Birnock Burn

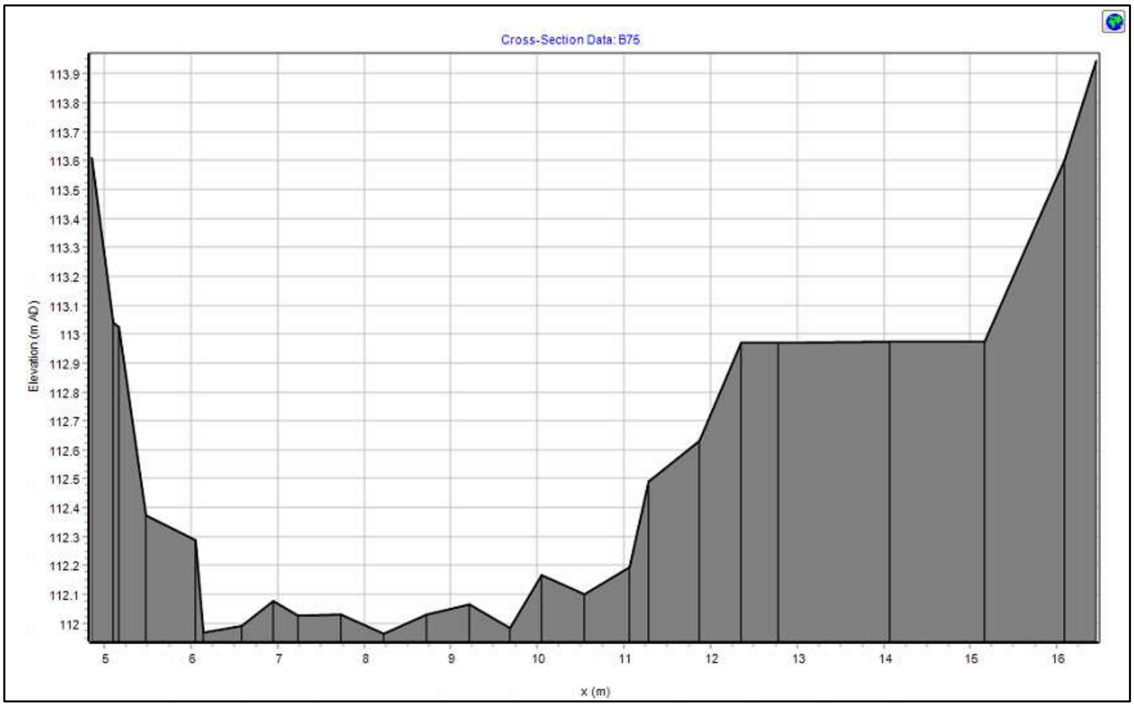
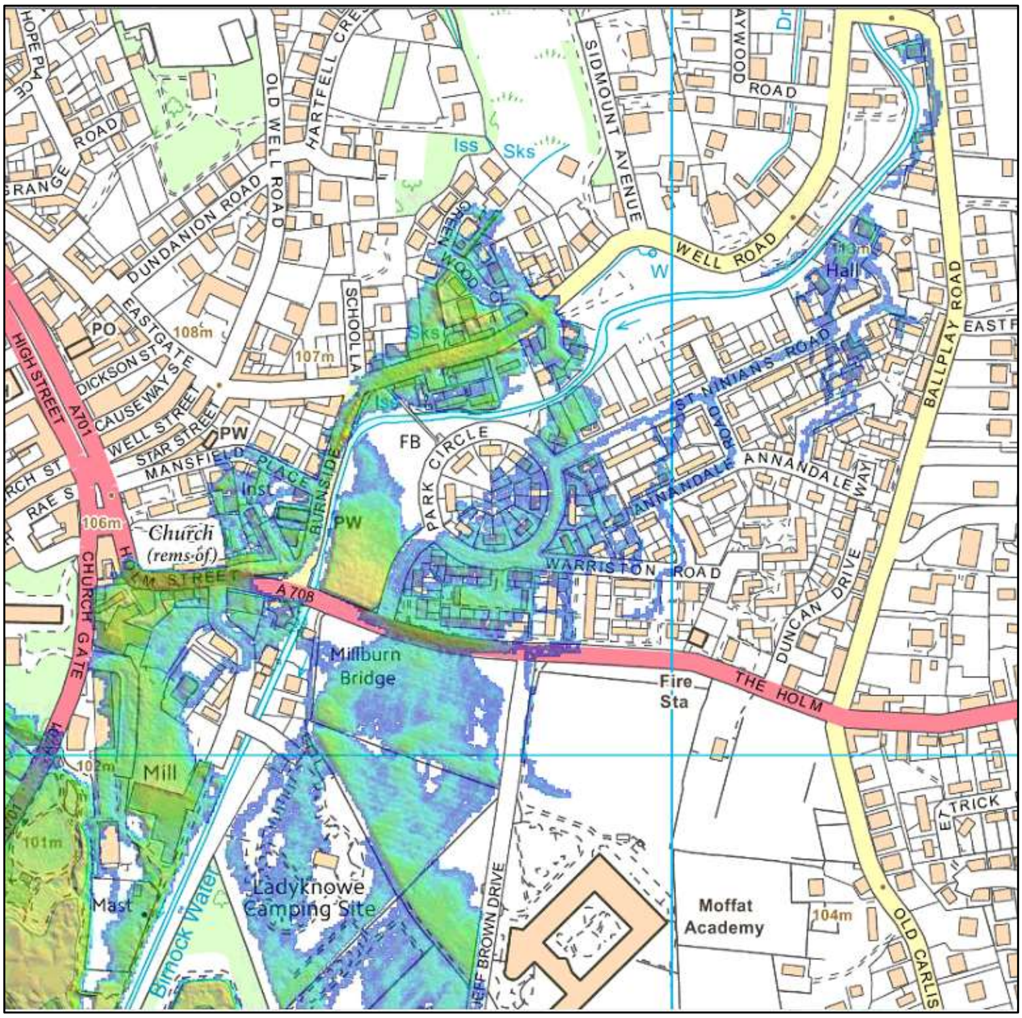


Figure 34: Two-stage Birnock Water channel, 200 year flood extent



6.3.4 Direct Defences to Mitigate Fluvial Flooding

Based on a high-level review of the potential flood mitigation options outlined above, it appears that direct defences offer the most effective and sustainable flood mitigation for Moffat. This may be in the form of flood walls and earth embankments where there is sufficient space. Direct defence options can be augmented by conveyance improvements (as in the case of increasing conveyance at Annan Bridge South and along Birnock Water).

A key consideration for direct defences will be the possibility of under seepage (i.e. water seeping through porous soil under the defences and causing flooding).

Initial modelling has shown that direct defences along the floodplains of River Annan and along both banks of Birnock Water would be required. Direct defences along River Annan have been considered in combination with increased conveyance on the right hand bank in the vicinity if Annan Bridge South, while direct defences for Birnock Water were considered with and without increased conveyance. The following options were considered:

1) River Annan (Figure 35)
    a. Earth embankment at the southern edge of Hope Johnstone Park to prevent water overtopping onto the A701;
    b. Lowering of left hand bank downstream of Annan Bridge North;
    c. Earth embankment on the north side of Annanside;
    d. Flood gate at the western end of Annanside;
    e. Earth embankment or flood wall between Annanside and the A701 (Annan Bridge South);
    f. Two-stage channel between Annanside and The Glebe;
    g. Reprofiling of land and river banks both upstream and downstream of the A701 at Annan Bridge South;
    h. Provision of a series of culverts under the A701 road embankment on the right hand bank
    i. Earth embankment at Hydro Cottage (Figure 36)

2) Birnock Water (Figure 35)
    a. Flood walls along both banks (full length); or
    b. Two-stage channel combined with flood walls in some areas

3) Crosslaw Burn and Frenchland Burn
    a. Earth embankment on the west bank of Frenchland Burn where it overtops and flows towards Crosslaw Burn, Figure 37. This will likely be up to about 1.5m high and 100m long.

With the above defences in place, the predicted 200 year flood extent is shown in Figure 38. This assumes no flooding due to seepage within the areas protected.

The predicted height of the defences (height above existing ground level) is generally up to 1.5m. However, there are two areas where the defence heights would be higher. These are at the northern edge of Annanside where defence heights in the playing field would be of the order of 2.4m at the west end towards the river, reducing to 1.8m at the east end. The other area where flood defences would be in excess of 1.5m high is in Hope Johnstone Park adjacent to the A701. Along the banks of Birnock Water defence heights would generally be 1m.

It should be noted that although no overtopping of the left hand bank between Annanside and the A701 is predicted with the proposed defences in place, a low wall/embankment may still be required along this bank to provide the same level of protection as the areas upstream. This is included in the current proposals.

It is possible that direct defences may not be effective in some areas, such as Annanside, due to seepage under defences. A ground investigation carried out by Ian Farmer Associates in 2014 found that the ground at Annanside is made up of sandy gravel for depths down to 5-6m below ground level. No information is given for the ground conditions below this level. This indicates that when water ponds on the field north of Annanside to depths of 2m or higher, it is very likely that seepage would occur under any direct defences, causing flooding of the properties, even with defences in place. At this stage a seepage analysis has not been carried out to determine the rate of seepage and its effect on the properties. Such an assessment will need to be undertaken at the next stage to determine if direct defences in this area would be feasible.

There is no information available on ground conditions at The Glebe. It is likely that similar conditions to those at Annanside may exist in this area. Therefore, the risk of seepage may also be a significant issue for The Glebe. This will need to be investigated further at the next stage of the assessment.

Figure 35: Indicative location of direct defences

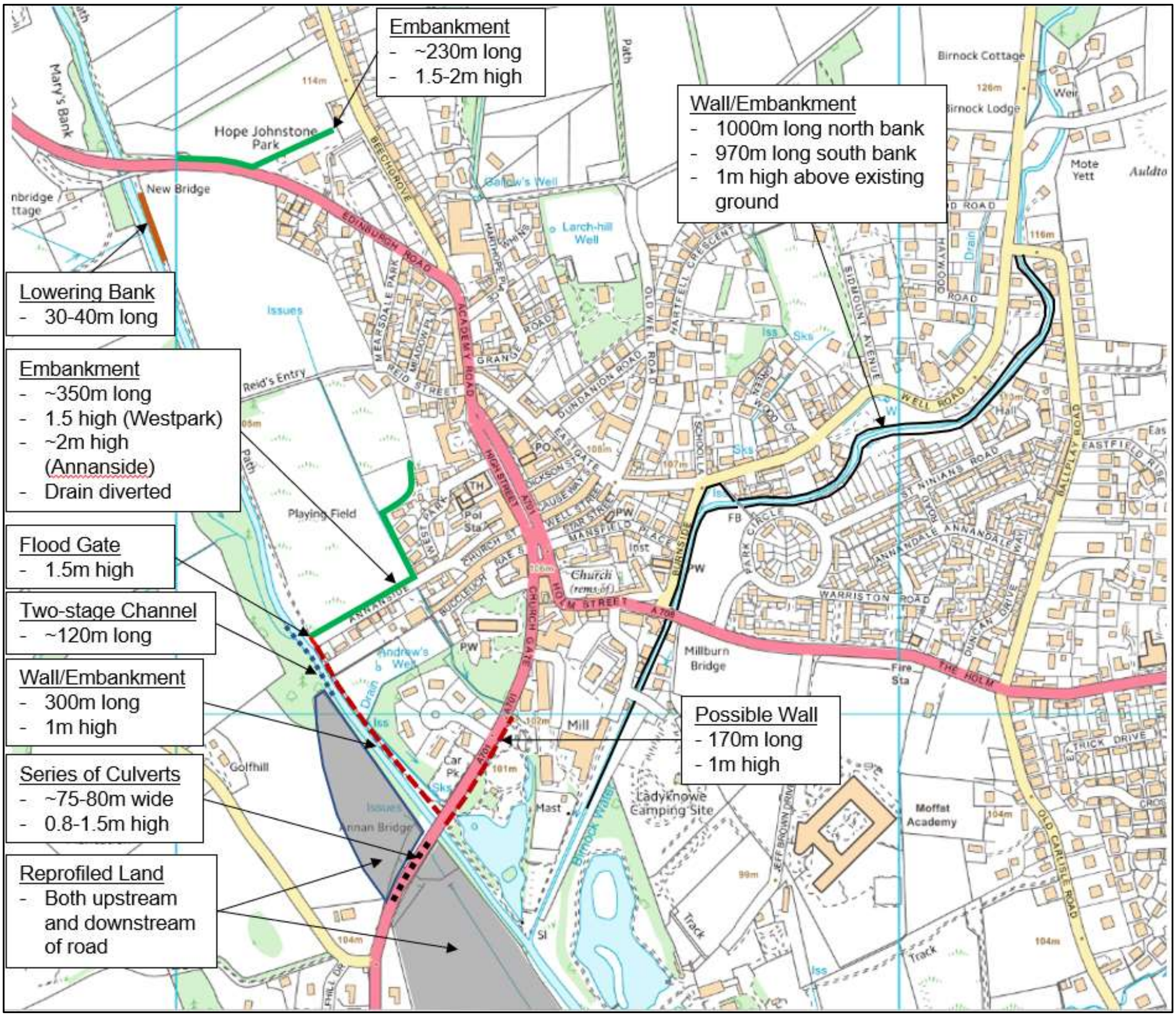


Figure 36: Possible direct defences at Hydro Cottage

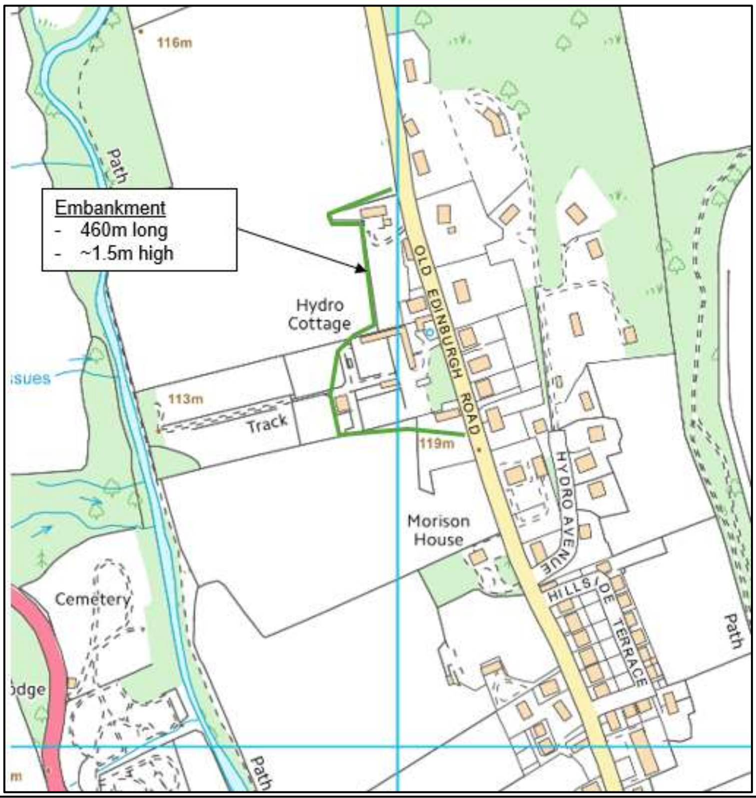


Figure 37: Embankment at Frenchland Burn

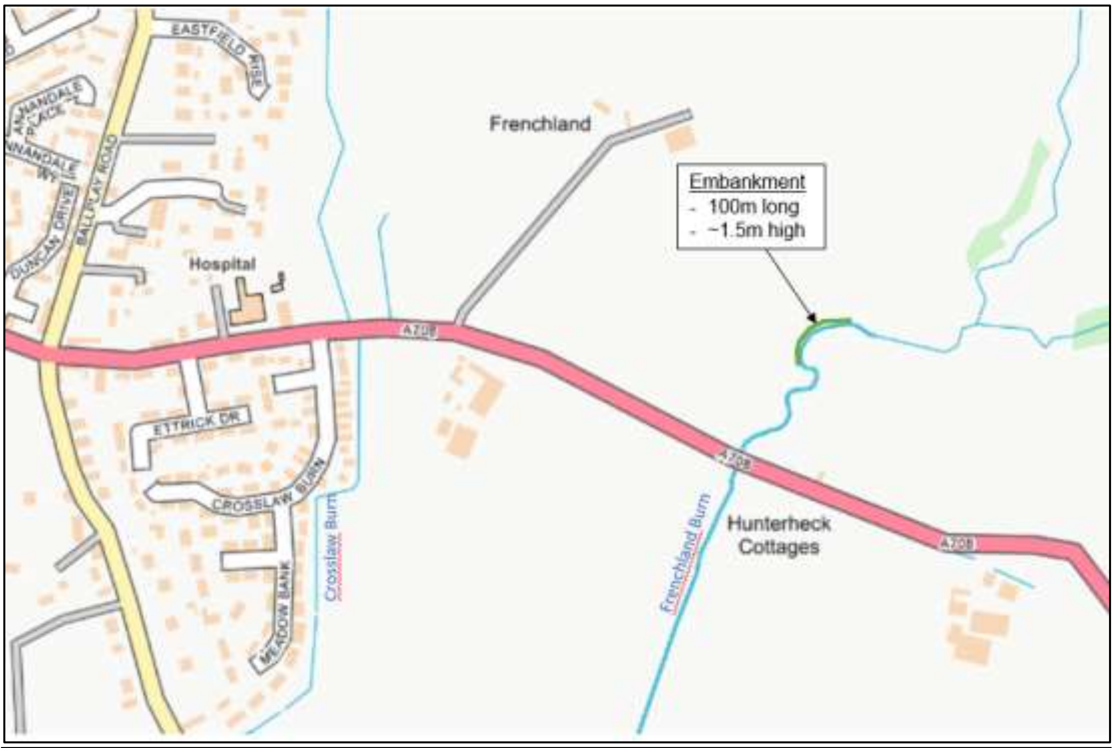
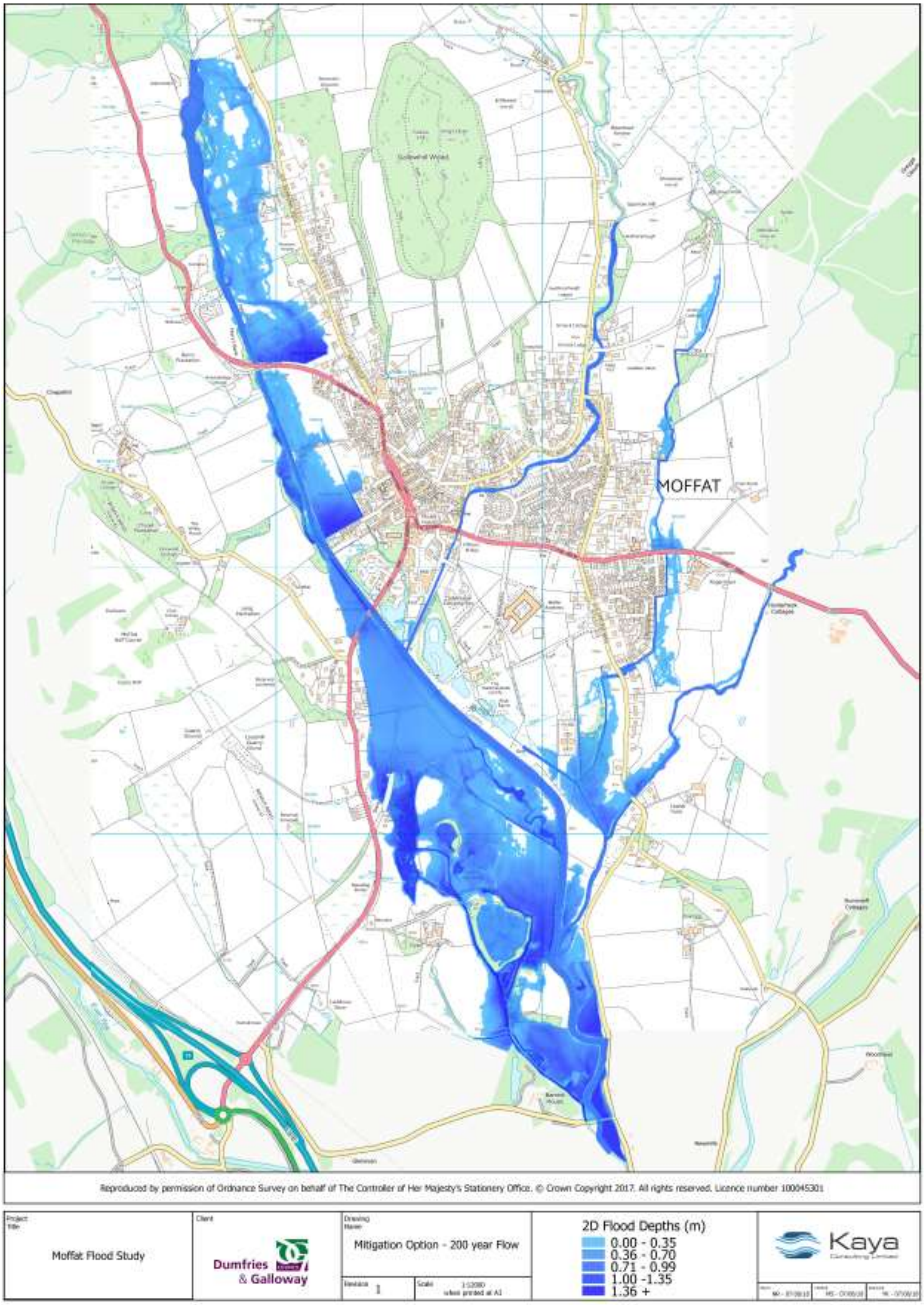


Figure 38: Predicted 200 year flood extent with proposed direct defences in place (see Figure 35)



6.4 Mitigation of Pluvial Flood Risk from Gallow Hill

It was shown in Section 5 that there are three outflow paths through which surface water runoff from Gallow Hill is routed through urban areas to the River Annan. These are the Hydro Avenue culvert, Harthope Place culvert and Greenwood Close culvert. It was shown that all three culverts are under capacity in sections or along their whole length, even without any blockage. As the drainage channels and culverts are relatively small (i.e. up to 1m), there is a high risk of blockage of drainage channels and culvert entrances.

6.4.1 Hydro Avenue Culvert

The top part of the Hydro Avenue culvert was replaced by the council in 2014. This section of the culvert is predicted to be able to convey the estimated 200 year flow (assuming no blockage). However, the section of the culvert through Hydro Avenue, Old Edinburgh Road and downstream is under capacity. This section of the culvert could possibly be upgraded along the line shown in Figure 39. The size of the new culvert would be 600mm or 750mm depending on its gradient.

Figure 39: Indicative line of upgraded Hydro Avenue culvert

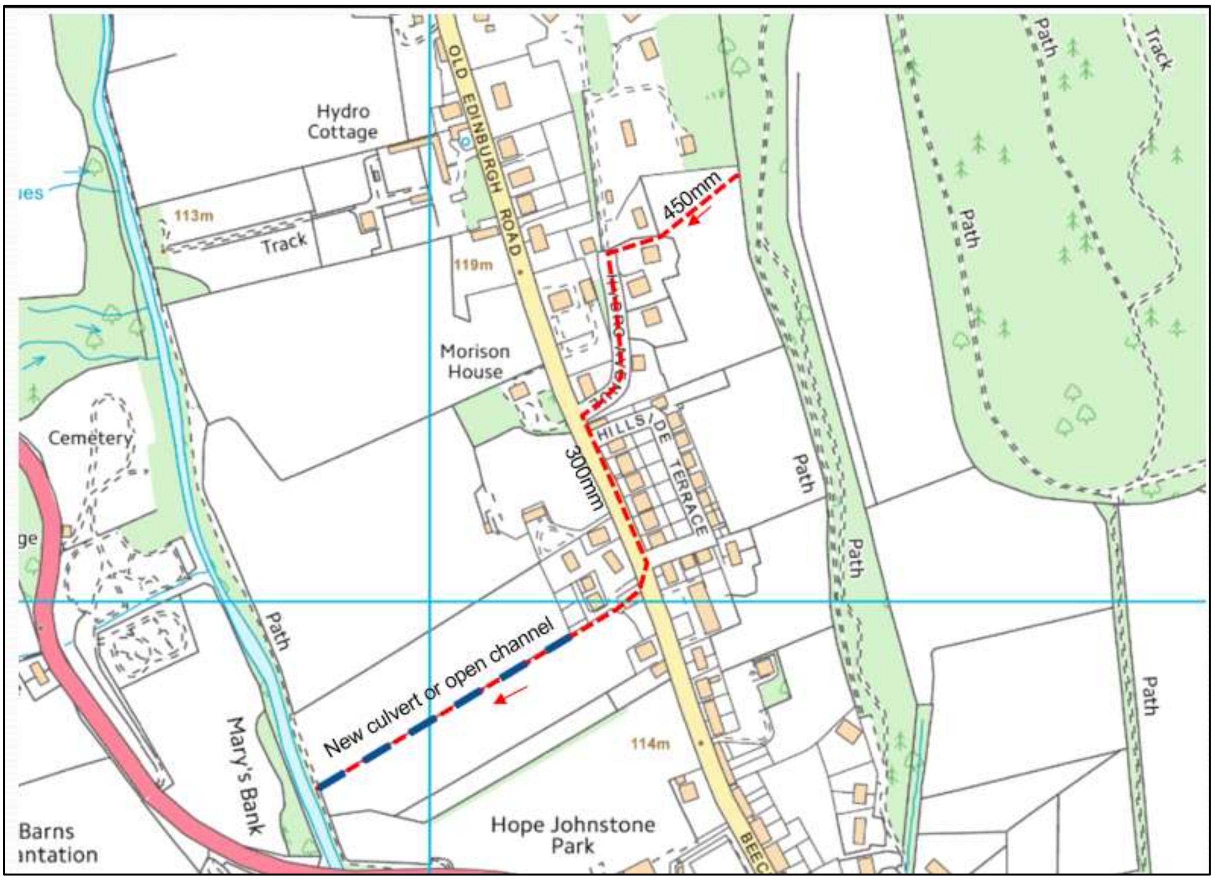
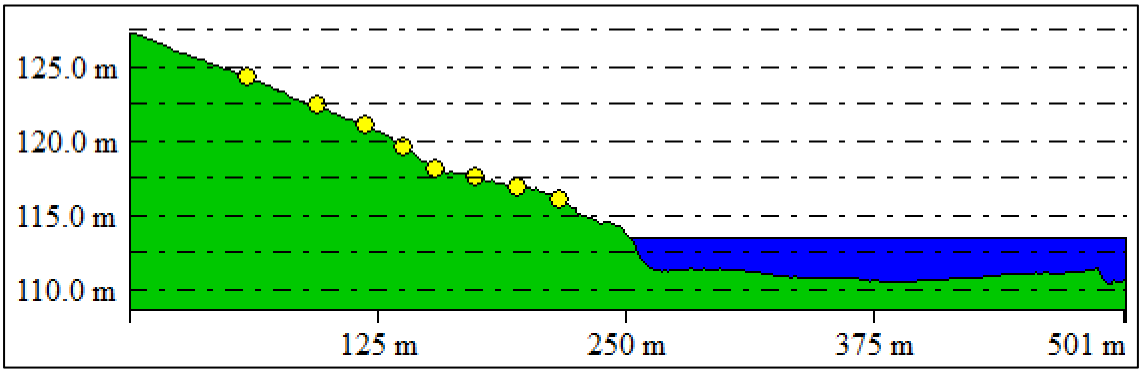


Figure 40 shows existing ground elevations along the line of the proposed upgraded culvert shown in Figure 39. This indicates that the lower section of the culvert through the fields would surcharge during a 200 year flood in the River Annan. This section could also be an open channel. However, this would only flood the fields.

Figure 40: Existing ground elevation along the line of upgraded culvert shown in Figure 32



It should be noted that the indicative line shown in Figure 39 is provided to indicated that such an option is feasible. Should this option be taken forward, the line of the culvert will be refined based on local topography, ground conditions, land ownership, etc.

6.4.2 Harthope Place Culvert

As indicated in Section 5.1, the existing culvert which runs through Harthope Place receives a substantial amount of surface water runoff from Gallow Hill, estimated to be approximately 1.3m^3/s for a 200 year event. Culvert capacity varies between 0.2m^3/s and 0.5m^3/s.

Possible mitigation options are shown in Figure 41. These are:

1) Replacing existing culvert with a larger culvert or laying a new culvert alongside the existing;
2) Retaining existing culvert and laying a new culvert from the hillside through Hope Johnstone Park and discharging into the Annan on the upstream side of New Bridge (A701 Edinburgh Road); and
3) Retaining existing culvert and laying a new culvert from the hillside through Hillside Terrace and discharging into the Annan a short distance upstream of New Bridge (A701 Edinburgh Road).

Option 1 may be difficult to implement due to constraints along Harthope Place and Edinburgh Road caused by existing utility services. The size of the pipe required to convey the total flow of 1.3m^3/s plus climate change would make laying such pipe along these roads less practical. Therefore, using the existing culvert combined with Option 2 or 3 (or both) would likely be a more practical option.

Options 2 and 3 would be able to drain 60% of the total catchment reporting to the culvert. This would equate to a 200 year flow of 0.78m^3/s. The remaining flow of 0.53m^3/s will need to be conveyed through the existing culvert. It was estimated that the section of the existing culvert along Harthope Place could pass approximately 0.5m^3/s, reducing to 0.45m^3/s through the former academy site and Edinburgh Road. Therefore, some improvements to these lengths of the culvert may still be required. It may also be possible to convey more than 60% of the catchment draining to Harthope Place through Options 2 or 3 or both, in which case no significant upgrading work to the existing culvert may be required.

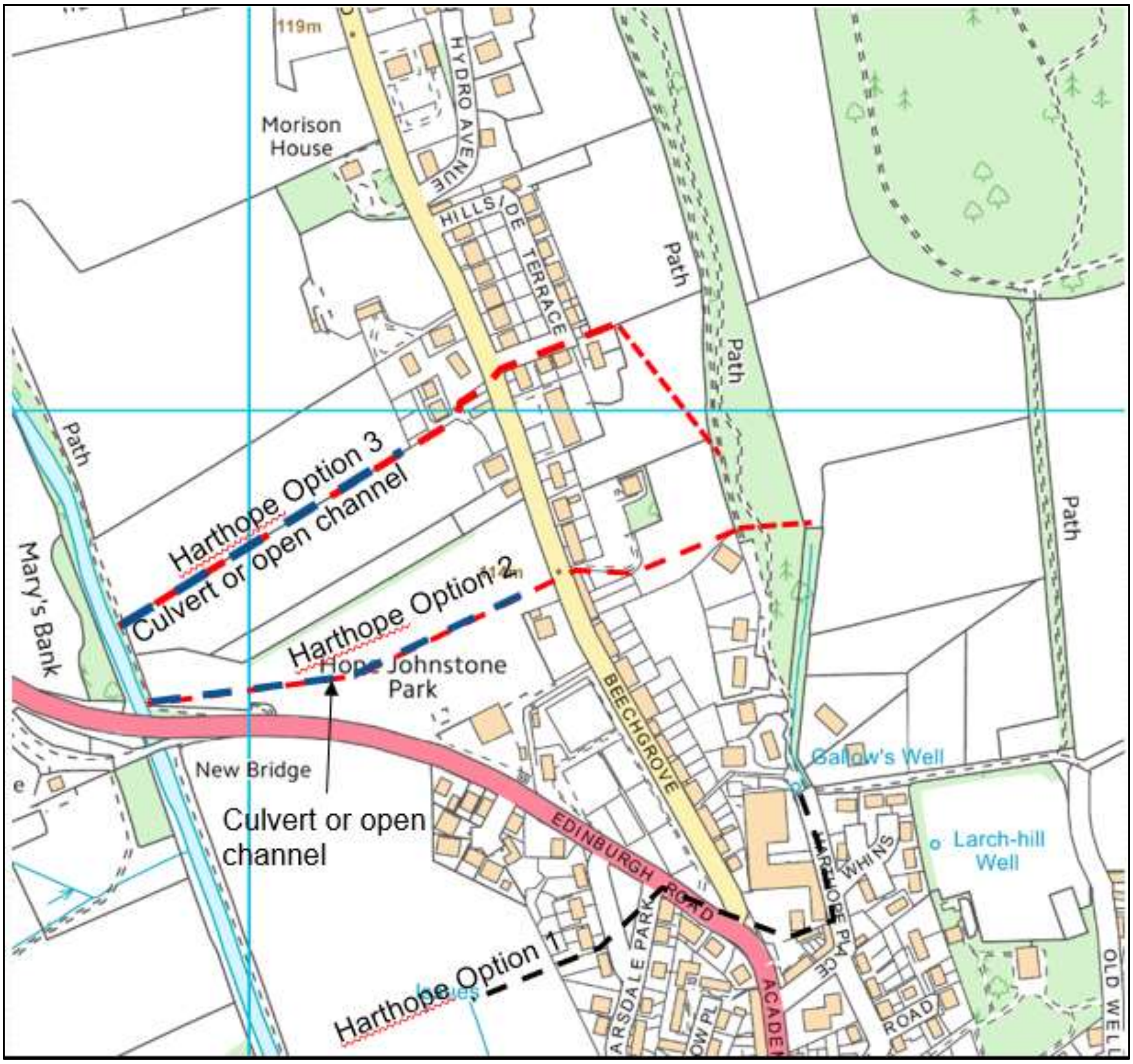
If only one of the Options 2 and 3 is implemented, the size of the culvert would likely be of the order of 900mm. If both options are implemented each culvert will unlikely be more than 600mm diameter.

The estimated lengths of the three options are:

a) Option 1: 450m
b) Option 2: 570m
c) Option 3: 600m

It should be noted that the indicative lines of Options 2 and 3 shown in Figure 41 are provided to indicate that such options are feasible. Should these options be taken forward, the line of the culverts will be refined based on local topography, ground conditions, land ownership, etc.

Figure 41: Possible options for Harthope Place culvert improvement

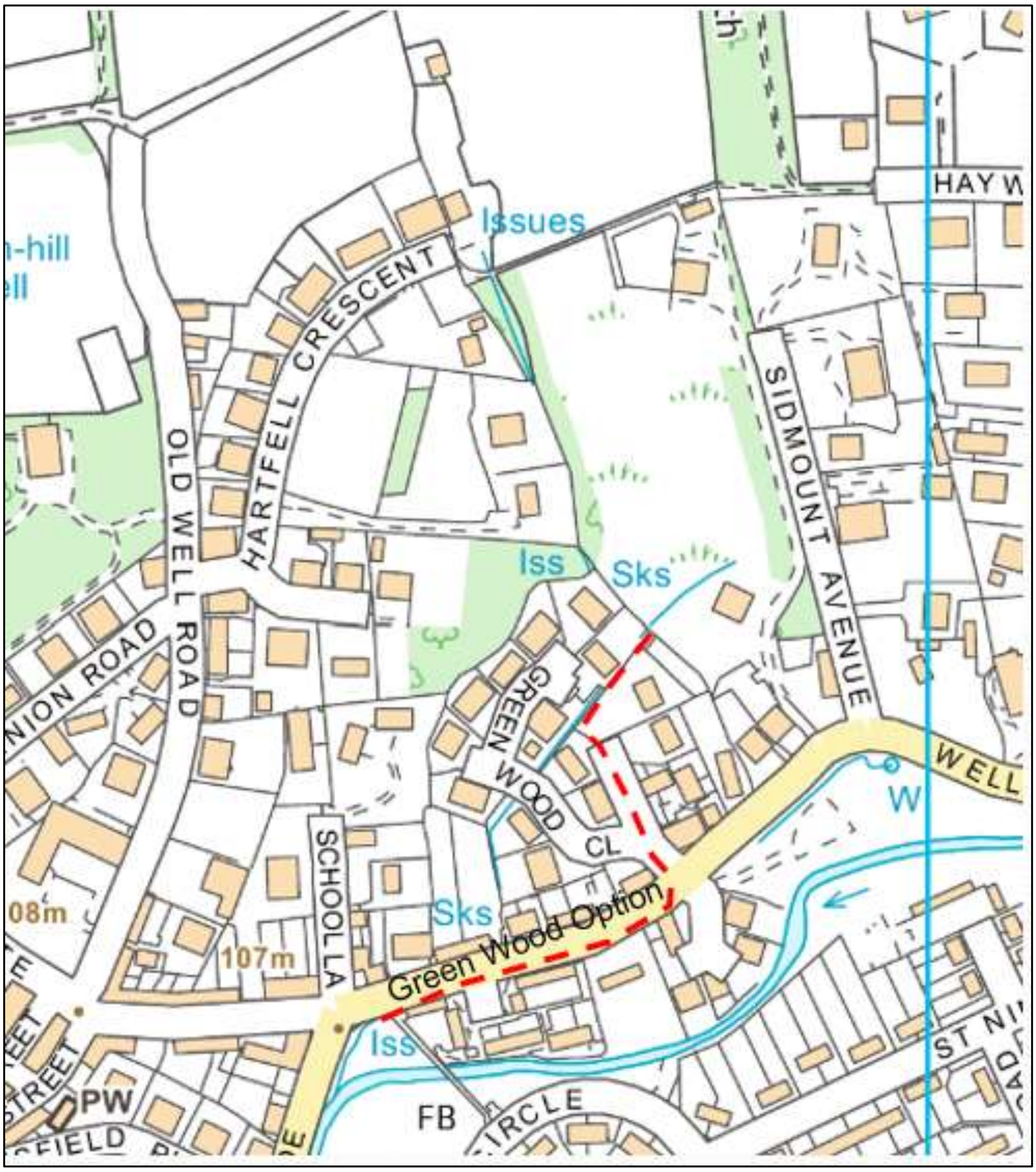


6.4.3 Greenwood Close Culvert

It was estimated that total flow arriving at this culvert during a 200 year event could be of the order of 1.36m^3/s. The existing culvert is under capacity and flooding would be expected to occur when flows reach a 1 in 4 to 1 in 5 years return period.

It may be possible to lay a new culvert along the line shown in Figure 42, which combined with the existing culvert, would be able to convey the estimated design flow. The length of the upgraded culvert shown in Figure 42 is approximately 300m. The size of the new culvert would likely be of the order of 750-900mm diameter. It should be noted that the indicative line shown in Figure 42 is provided to indicate that such an option is feasible. Should this option be taken forward, the line of the culvert will be refined based on local topography, ground conditions, land ownership, etc.

Figure 42: Indicative line of suggested Greenwood Close culvert



6.5 Summary of Flood Mitigation Measures

The hydrological and hydraulic assessment outlined in the preceding sections indicated that a large number of properties are at risk of flooding from fluvial and pluvial sources. A total of 102 properties are predicted to be affected during a 200 year fluvial event, increasing to 161 properties for the 1,000 year event. In addition, over 50 properties would be flooded from pluvial sources.

Although the predicted number of properties affected from flooding is high, due to local topography most properties would be flooded to a shallow depth. This is especially the case for properties affected by flooding from the Birnock Water.

An appraisal of potential flood mitigation options indicated that direct defences are likely to be the most effective and sustainable flood mitigation option for fluvial flooding. Increased conveyance (i.e. additional culverts) is the most effective and sustainable option for pluvial flooding (i.e. flooding from Gallow Hill).

Modelling work carried out indicated that direct flood defences in the form of flood walls and earth embankments would be able to mitigate flooding risk to those properties predicted to be at risk of fluvial flooding. The predicted defences would mostly be less than 1.5m high, except in two places (Annanside and Hope Johnstone Park).

Limited ground investigation work carried out in 2014 indicates that ground conditions in the Annanside area show permeable soils and sub-soils. Therefore, the effectiveness of direct defences in this area (and potentially at The Glebe) could be significantly reduced by under seepage. This aspect will need to be investigated in detail at the next stage.

The work outlined above indicated all three drainage outlets from Gallow Hill are under capacity. It is possible to reduce the risk of flooding from these culverts by augmenting their capacities. Potential mitigation options for all three outlets have been identified.

A summary of flood mitigation measures is given in Table 24. A floodgate at Annanside may be required to allow access to the river through the 2.4m high defence. Alternatively, access could be provided along the top of the embankment, however, this would likely reduce privacy for the existing properties.

Table 24: Summary of mitigation measures

Location	Type of defence	Length (m)	Height (m) or Culvert Diameter
Hydro Cottage area	Embankment	460	1.5
Hope Johnstone Park	Embankment	230	1.5-2.0
Annanside	Embankment	350	1.5-2.4
Two Stage Channel	Conveyance	120	
The Glebe	Wall/Embankment	300	1
Annan Bridge South	Culvert	30 (each)	0.8m-1.5m
Land Reprofiling	Conveyance		
Birnock North Bank	Wall	1000	1
Birnock South Bank	Wall	970	1
Birnock Two-Stage Channel	Conveyance	650	

Frenchland	Embankment	100	1.5
Annanside	Flood Gate	~2	1.5
Hydro Avenue	Culvert	500	900mm diameter
Harthope Place	Culvert	570	900mm diameter
Harthope Place	Culvert	600	900mm diameter
Greenwood Close	Culvert	300	900mm diameter

7 Economic Appraisal

The cost benefit analysis has been undertaken using the UK standard methodology based on;

- 'Flood and Coastal Erosion Risk Management – Handbook and Data for Economic Appraisal', 2018 published by Flood Hazard Research Centre, Middlesex University. This report is also known as the Multi-Coloured Manual 2018.

The cost-benefit analysis 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. However, flood damage calculations are based on detailed mathematical modelling and surveyed 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 7.2.4.

7.1 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, input from a qualified Quantity Surveyor with experience of construction works, and national guidance. 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 relevant information becomes available.

7.2 Outline Cost Benefit Analysis

7.2.1 Properties at Risk of Flooding

A list of address point data for all properties in Moffat was provided by Dumfries and Galloway Council. This provided geo-referenced property information including property type, location, etc. These were ground truthed in the field. Based on the modelled flood extents for each return period flood event, a list of all properties lying within various return period flood extents were compiled. A summary of the number of residential and non-residential properties affected is given in Table 22.

7.2.2 Depth of Flooding

A door-to-door survey was carried out as part of this study to obtain floor levels of all properties considered at risk of flooding.

Within the damage calculations the depth of flooding for each property was obtained by subtracting the surveyed floor level of the property from the predicted water level at the property. Water level predictions were extracted from the 2D model.

7.2.3 Flood Damage Data

Flood damage data for each property was extracted from the Multi-Coloured Manual 2018 excel spreadsheets using modules provided in the FloodModeller software package.

Flood damage data extracted from the Multi-Coloured Manual is given per square metres of property. These values were then multiplied by plan area of each property to obtain the total damage for each property for the given depth of flood.

7.2.4 Assumptions

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

a) Plan area of each property was obtained from 1: 1250 OS maps.
b) Age of each property was estimated based on visual appearance of the property. As the property bands within the Multi-Coloured Manual 2018 are quite broad it is likely that reasonably robust estimates of property age have been made. However, within the Multi-Coloured Manual 2018 methodology there are assumptions related to the damage costs associated with properties of different value and there is likely to be a high degree of uncertainty associated with these estimates.
c) Property values were estimated based on type and size of property. 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. A sensitivity analysis was carried out to determine the effect of property values on the final results. However, more information would be required if the assessment is taken forward.

It should be noted that value of properties is important when the estimated flood damage cost for the property exceeds its value. For those cases flood damage cost was set to property value. Hence, most properties for which flood damage estimates are lower than value of the property this information is not relevant. Property values are also important in estimating write-off value of properties. Therefore, property values can have a significant impact on the 'Do Nothing' scenario to which other options are compared.

It is suggested that more reliable estimates of property values are made for the detailed cost-benefit analysis, particularly those properties with large estimated flood damage (i.e. those at Annanside).

7.2.5 Outline Costing of Flood Management Measures

For the type of defence 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 <u>not</u> 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 costing has been prepared for the direct defence option.

Direct defences would largely be in the form of earth embankments for the River Annan and flood walls for Birnock Water (due to limited space available between properties at risk and the main channel of the river). A detailed structural survey of existing flood defences has not been carried out, although a visual inspection has been carried out of defences within the urban area. Without knowledge of the conditions of the existing defences, particularly below normal water level, it was assumed that all flood defence walls required will be sheet piled (i.e. extending some 5-6m below river bank). Assumptions have been made of sheet piled cut-off walls under earth embankments to reduce seepage, without detailed knowledge of ground conditions.

The estimated indicative cost of flood defences to provide 200 year level of protection is given in Table 25.

Table 25: Estimated indicative flood defence construction costs only

Flood Mitigation Measure	Type	Approximate Length (m)	Approximate Average Height (m)[a] or Culvert Diameter	Estimated Indicative Cost (£M)
Hydro Cottage	Embankment	460	1.5	1.06
Hope Johnstone Park	Embankment	230	1.5-2.0	0.52
Annanside	Embankment	350	1.5-2.4	0.87
Two-Stage Channel	Conveyance	120		0.25
The Glebe	Wall	300	1.0	0.84
Annan Bridge South	Culverts	30 (each)	0.8-1.5	0.60
Land Reprofiling	Conveyance			0.10
Birnock North Bank	Wall	1000	1.0	3.00
Birnock South bank	Wall	970	1.0	2.91
Birnock Two-Stage Channel	Conveyance	650		0.48
Frenchland Burn	Embankment	100	1.5	0.06
Hydro Avenue	Culvert	500	Ø900mm	0.75
Harthope Place	Culvert	570	Ø900mm	0.85
Harthope Place	Culvert	600	Ø900mm	0.90
Greenwood Close	Culvert	300	Ø900mm	0.45
			Total	£13.64M

[a] *Sheet piled wall assumed to extend at least 5-6m below river bed.*

The above indicated costs do not include the cost of temporary works, preliminaries, contingencies, service diversion costs, design and supervision costs, and land acquisition costs. However, the estimated indicative total cost of the scheme is presented in Table 26.

A Bias Adjustment Factor is applied to the costs. This is to account for the fact that initial cost estimates can often be optimistic (low). 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 maintenance.

Table 26: Estimated total scheme cost

Defence Option	Construction Cost (£M)	Preliminaries (15%)	Contingencies (15%)	Utility Diversion (5%)	Design & Supervision (15%)	Total
Direct Defences	13.64	2.05	2.05	0.89	2.79	21.42*

** Does not include the standard optimism bias of 60%. With 60% optimism bias, total cost of Direct Defence option becomes **£34.3M**. This is automatically added in the cost-benefit analysis.*

It should be noted that it may be possible to reduce the estimated capital cost significantly by the provision of two-stage channel along Birnock Water which would reduce the length of the walls required.

7.2.6 Outline Cost-Benefit Analysis

The method provides a standardised economic appraisal spreadsheet which can be applied to examine various scenarios. Three scenarios or options were examined in the cost-benefit analysis.

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

The standard 100 year analysis period was assumed.

Option 1 - Do Nothing

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

- Once a flood event occurs, no repairs are made to the damaged properties (i.e. they are written off).
- 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.

The average annual flood damage of £140,400 was calculated from the likely damages for a range of floods. The total damage in the analysis period is equal to and cannot exceed the total property value at risk of flooding (i.e. £20M), which is the estimated write off value of all properties within the 1 in 200 year floodplain. The benefit-cost ratio increases with increasing write off value.

This scenario is unrealistic as the Council have duties in accordance with Section 18 and Section 59 of the Flood Risk Management (Scotland) Act 2009, to maintain watercourses. However this option is used as a baseline for comparison purposes only.

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.

An annual maintenance cost of £0.12M was assumed (incurred by all responsible for maintaining existing defences, i.e. Council and private owners), see Table 27. Over the 100 year analysis period this is equivalent to £3.58M at present day value (i.e. if this sum was invested today it would provide funding for maintenance for the full analysis period of 100 years). This cost was assumed to maintain the current risk of flooding for existing defences without any improvements. This option is presented here for comparison as it is considered to be a more realistic scenario than Option 1 "Do Nothing".

Table 27: Estimated annual maintenance cost

Maintenance Item	Approximate Length (m)	Estimated Indicative Cost (£)
Flood Walls	2,270	20,000
Flood Embankments	1,140	25,000
Culverts	2,000+	25,000
Channel Clearance		10,000
General Maintenance		20,000
Contingencies and Emergencies		20,000
Total		120,000

(Estimated annual maintenance cost incurred by all those responsible for maintaining existing defences, i.e. Council and private owners)

Option 3 - Full Flood Mitigation Scheme (200 Year Level of Protection)

Option 3 has the following general assumptions:

- Damages to properties are assumed to be repaired. The total damage cost can therefore be higher than the present value of the properties.
- 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.

- A capital investment for the construction of the flood management scheme is made in the first three analysis years followed by an annual maintenance each year. The risk of flooding is greatly reduced by the flood management scheme and hence 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 is implemented as summarised in Table 25. Results of the analysis is summarised in Table 28.

A time varying annual maintenance cost is considered. It is assumed that for the first ten years maintenance of the new flood alleviation scheme should be small (assumed to be £0.025M per year), with maintenance increasing over time to a value of £0.05M after 20 years, and to £0.1M after 50 years after the construction of the scheme. Over the 100 year analysis period this is equivalent to £1.23M at present day value.

A Bias Adjustment Factor is applied to the costs. This is to account for the fact that initial cost estimates can often be optimistic (low). 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.

7.2.6.1 Summary Cost-benefit Analysis

Summary results for the cost-benefit analysis are shown in Table 28.

Table 28: 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	20.7
Total Maintenance Cost	0	3.6	1.2
Bias Adjustment (60%)	0	2.1	13.2
Total Cost	0	5.7	35.1
Benefit			
Total Flood Damages	27.3	9.1	2.2
Total Flood Damages Avoided	-	18.2	25.1
Average Benefit/Cost Ratio	-	3.18	**0.72**
Incremental Benefit/Cost Ratio	-	-	0.2

Total flood damage over the 100 year analysis period was estimated to be £27.1M. In simple terms this would indicate that a scheme costing more than £27.1M would not give a positive benefit-cost ratio. The benefit cost ratio could be increased to approximately 0.8 if capital cost could be reduced by £2.5M by providing a two-stage channel and shorter walls along the Birnock Water.

It should be noted that flood damage costs include direct damages as well as intangibles, emergency evacuation costs and vehicle damages. Other factors such as environmental and social impacts will be included at detailed design stage. This may slightly increase the benefit cost ratio.

Based on the analysis summarised above, it appears that 200 year level of protection is unlikely to be economically viable as it would not (even with environmental and social benefits included) produce a benefit-cost ratio sufficiently above unity (1). This is due to (i) the shallow depth of flooding of a number of at-risk properties, limiting damage costs and (ii) the cost of estimated flood defences including an allowance of sheet pile cut-off. These sheet pile works are necessary due to the expected permeable ground conditions to cut-off seepage. Detailed ground investigation work would be required along the lines of the defences to confirm these assumptions. This work would allow:

- seepage analysis to the undertaken;
- determining if cut-off pile would be required, and if so,
    - the depth it should extend to below ground level;
    - effectiveness of cut-off pile on flood risk; and
    - effect of cut-off pile on groundwater flow.

It is possible that in some places where rock head and/or impermeable soil layer is shallow, a cut-off pile wall below the defences may not be required. As a sensitivity, if we assume no cut-off pile wall would be required for defences along Birnock Water, this would reduce the construction cost and the resulting benefit-cost ratio could be in excess of 0.9. In addition, if no cut-off piles would be required for defences (embankments) at Hydro Cottage, then this would reduce the construction cost further and the resulting benefit-cost ratio could be increased above unity. A benefit-cost ratio above unity would be required to have any chance of attracting grant aid from Scottish Government.

In addition to refining the cost of flood defences, it is also possible to decide to provide no protection to some areas in order to reduce the cost of flood defences. Property level protection could possibly be used for some of these otherwise unprotected areas to reduce the scheme cost, although the effectiveness of such measures would largely be dependent on residents acting when a warning is received and the depth of flood waters at each property. Such measures may not provide the same level of protection afforded elsewhere by direct defences and may not result in a cost-benefit ratio in excess of unity. This option was not identified by SEPA 2011 study as a feasible option and has not been assessed in detail at this stage.

An alternative option might be to provide less than 200 year level of protection. However, if sheet-pile cut-off walls would be required, the effect of reduced level of protection on the final cost of the scheme may not be significant (as the cost of sheet-pile walls would be the same regardless of level of protection). Therefore, this may not necessarily lead to a higher benefit-cost ratio and could results in lower values.

Based on information available to date, it would appear that protecting the properties at Annanside and The Glebe could be extremely challenging. It is recommended that the next stage should involve an investigation to assess seepage and refine the cost of the scheme before the scheme progressed further. In particular, the efficacy of flood defences at Annanside and The Glebe should be assessed. Given the type and extent of defences involved, it may also be beneficial to involve a contactor to identify possible savings which could be made to reduce the cost of the scheme. Whether the construction material required would be locally available or not could have a significant impact on the cost of the scheme. This could be investigated, although even if such material is currently available locally, this could not be guaranteed at the time of construction.

The standard 60% optimism bias applied to cost of the scheme have a significant impact on the benefit-cost ration. This percentage increase covers uncertainties in the outline design. A key uncertainty for Moffat is ground conditions. Obtaining further information on ground conditions along the line of defences would reduce this factor and possibly the cost of defences.

8 Conclusions and Recommendations

This report presents the results of a detailed flood study undertaken for Moffat considering flooding risk from fluvial sources such as the River Annan, Birnock Water, Crosslaw Burn and Frenchland Burn, as well as pluvial sources, in particular surface water runoff from Gallow Hill.

SEPA in their National Flood Risk Assessment, 2011, identified Moffat as a Potentially Vulnerable Area (PVA) with 370 residential properties and 50 non-residential properties identified at risk of flooding, with an estimated Annual Average Damages (AAD) of £680,000. As part of the study, SEPA has identified a number of actions to mitigate flooding risk. These include a Flood Protection Study, for which the current study is the first step.

There are records of historical flooding in Moffat, both from fluvial and pluvial sources. The most severe fluvial flooding in recent years occurred in December 2015 when a number of properties were flooded and main roads in and out of Moffat were affected.

This flood study undertook a detailed hydrological assessment for the four watercourses, developed a linked 1D/2D flood model of these watercourses through the town, 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 alleviation option.

The 1D/2D mathematical model of the four watercourses were calibrated against recorded flood information from the December 2015 event.

The calibrated model was used to simulate flood events with a range of return periods (2, 5, 10, 25, 30, 50, 75, 100, 200, 500, and 1000 years). Flood maps were prepared for each event.

The model results predicted that 102 properties would be affected during a 200 year fluvial flood, 45 residential and 57 non-residential. For a 1000 year event, the total number of properties flooded increases to 161. The properties were flooded due to overtopping of the River Annan and Birnock Water. The number of properties predicted to flood is significantly smaller than indicated by SEPA in their 2011 study. Differences are expected due to the improved methods and datasets used in the current assessment.

Flooding of around 50 properties is predicted from surface water flooding from Gallow Hill.

A number of flood mitigation options were considered, including; flood storage upstream of Moffat; direct defences where flood risk areas could be protected by flood walls and embankments; increasing the flow passing capacity of the A701 Annan Bridge, and lowering of the river bed.

An initial appraisal of the potential options indicated that the most effective and sustainable flood mitigation option is direct defences (i.e. protecting the affected areas by flood walls and embankments) combined with increased conveyance and increasing capacity of culverts receiving runoff from Gallow Hill.

An initial cost-benefit analysis was undertaken, based on the model results and a high-level (conceptual) design of 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 a direct defences scheme providing 200 year level of protection is less than unity (1). This indicates that the scheme would not be economically viable. However, this is based on an estimated scheme cost involving sheet-pile cut-off walls below proposed flood walls and embankments to prevent seepage. Sheet piling is considered necessary due to expected ground conditions along the line of the defences (i.e. permeable material leading to the risk of seepage of defences). Sensitivity checks indicated that it may be possible to increase the benefit-cost ratio above unity if there was no or little requirement for sheet-pile cut-off walls below flood defences. However, limited ground investigation data available for the Annanside area suggests that ground conditions at least in this area are permeable at least down to 6m below ground and sheet-pile cut-off walls would likely be required (although this would depend on the rate and volume of seepage).

Based on the above, it is recommended that the next stage of the project involves an investigation to assess seepage and refine the cost of the scheme before the scheme progressed further. In addition, the efficacy of flood defences should be assessed for all areas, and in particular in the Annanside and The Glebe area. Given the type and extent of defences involved, it may also be beneficial to involve a contactor to identify possible savings which could be made to reduce the cost of the scheme. Should the cost of defences be able to be reduced below £14M, this would result in a benefit-cost ratio above unity and would indicate that such a scheme would be economically feasible and may be suitable to attract grant aid from Scottish Government.

Appendix A – Some Photographs from Historical Flood Events

Dumfries and Galloway! Whats Going on ?
30 December 2015 ·

FLOOD NEWS

Police state that Moffat appears to be surrounded by water with no routes in or out. Please avoid the area.

Photo A1: Historical Flood event Ref F2 (http://www.dng24.co.uk/flood-action-snub-for-moffat/)

Photo A2: Historical Flood events Ref F3 (https://bordersforesttrust.org/rain-rain-and-more-rain/)

Photo A3: Historical Flood events Ref F4 (https://www.dailyrecord.co.uk/news/local-news/storm-frank-annandale-eskdale-rallies-7119093)

Photo A4: Historical Flood events Ref F5 (https://www.dailyrecord.co.uk/news/local-news/storm-frank-annandale-eskdale-rallies-7119093)

Photo A5: Historical Flood events Ref F6 (https://www.dng24.co.uk/rescue-operation-as-storm-frank-hits/)

Photo A6: Historical Flood event ref F7 (Youtube screen shot)

Photo A7: Historical Flood event ref F8 (Youtube screen shot)

Photo A8: Historical Flood event F9 (youtube screen shot)

Photo A9: Historical Flood event F10 (youtube screen shot)

Photo A10: Historical Flood event F11 (youtube screen shot)

Photo A11: Historical Flood event F12 (youtube screen shot)

Photo A12: Historical Flood event ref P1 (https://bordersforesttrust.org/rain-rain-and-more-rain/)

Photo A13: Historical Flood event ref P2

(http://www.itv.com/news/border/topic/flooding/?page=59)

Photo A14: Historical Flood event F14 (public consultation)

Photo A15: Historical Flood event F15 (public consultation)

Appendix B – SEPA Historical Flood Database

Flooding Identified	Source of Flooding	Date
Pluvial flows through the beech wood, down through the garden of Springvale and onto Hydro Avenue. Water onto public and flooding to garden.	Pluvial	2015
Heavy rainfall combined with pluvial flows resulted in flooding at this location. Culvert entrance screen was blinded with silt and leaves. Re-occuring problem due to screen design, culvert capacity and leaf droppage. No reported property flooding, no reported road closure/flooding, low risk, no health hazard. Screen cleared 8pm 14.12.13 and again 6pm 15.12.13. Screen inspection planned for 16.12.13.	Pluvial	2015
Region wide rainfall event combined with surface water flows and high river water levels resulted in flooding at Northfield Bungalow, Moffat. Flood water inundation to one residential property.	Pluvial	2006
Flood screen blocked. Public road only flooded.	Pluvial	2006
Water running off road into garage of Beehive Cottage. Flooding limited to garage. understood that gullies in road cleared imporved situation.	Pluvial	2006
Heavy Rain. Region Wide Reports of surface water flooding to properties and roads at 34 Frenchlands Drive. Reports of surface water flooding to properties and roads.	River Annan	2000
Region wide rainfall event resulted in flooding of the road (A708) and properties at Frenchland access road. Residential property flooding. Reported property flooding to two dwellings. No reported road closure (passable with care).	Pluvial	2015
Flooding of agricultural land. Flooding in field.		2015
Flood water in garden to a depth of 450mm. House not flooded. Garden flooded.	Pluvial	2011
Heavy rainfall and surface water flows combined with capacity restrictions of roads drainage system resulted in flooding of the road (A701) outside the Black Bull Hotel. No reported property flooding, no reported road closure.	Pluvial	2013
Small burn at side of house. Side of house flooded and onto road but didn't enter the house. No major damage.	River Annan	2015
Report of flooding to the road (A701) between motorway and Moffat. No reported property flooding. No reported road closure.	River Annan	2011
Heavy rainfall and surface water flows combined at this location causing flooding of the road. Re-occurring problem. Dangerous road conditions, no reported property flooding, road closure results in long detour.	Pluvial	2011
Heavy rainfall combined with surface water flows resulted in flooding of the road(A701) at Hidden Corner, Moffat. Signage required, reports of vehicles stuck.	Pluvial	2015
blocked drainage system combined with heavy rainfall and surface water flows resulted in flooding of the road (A701) at Hidden Corner, Moffat. No	Pluvial	2015

reported road closure. **No property flooding.** **Unsafe conditions for motorists and pedestrians.** **Main access/egress route from Moffat.**		
The A701 Dumfries to Moffat road was closed approx ? of a mile south of Moffat (locally Hidden Corner), due to the amount of surface water lying on the road. High Impact - Road Closed.	Birnock Water	2010
Heavy rainfall and surface water flows from surrounding farmland caused flooding of the road at this location. **Re-occuring problem. No road closure, no reported property flooding, low risk, no health hazard.**	River Annan	2009
Police called OOH to report that the road was barely passable.		2014
Flooding on A701 at the old railway line. Flooding on Road.	River Annan	2009
Flooding on A701 at the 30mph signs. Flooding on road.		2016
Flooding on the A701 as you enter Moffat. Flooding on road.	Pluvial	2013
Flooding on A701 south of Moffat at Langshaw Bush. Flooding on Road.		2015
River Annan burst its banks and water is approaching properties very quickly - is currently inches away.		2015
General Flooding - No attendance by Fire and Rescue service. Reported in record of all flooding incidents received in West Scotland Fire and Rescue Service control room for event of 4th -7th December. Precise location unknown	Pluvial	2013
Flooding of road, Ballplay Road - precise location not known.	Pluvial	2013
River Annan rose submerging houses below Moffat town, flooded roads along its course. Amount of evacuees not stated, Amount of properties affected not stated.. Scotsman Archive.		2013
Heavy rainfall in Moffat over whole district. A 20 min spell flooded the pavements and roads in some parts of the town. Scotsman Archive.	Pluvial	2011
Moffat - Harthope Place - water running into garden. Garden flooded. Biennial Report. No further details.	Pluvial	2010
Moffat - Black Bull Pub - water in pub. Water in pub. Biennial Report. Pub Flooded.		2011
Town/Village. Annadale and Eskdale - Moffat - A701 - Flooding in 2 places in / near Moffat. Biennial Report. A701 flooded.		2011
Specific Location. Property level. The Glebe Moffat. Underfloor flooding to within inches of floor joists. One property affected.	River Annan	2015
Specific Location. Street level. Annandale & Eskdale - Moffat - Millburn Road, Callochill Rise, Sporkwells Way & Jackies Loaning. Biennial Report. Area mentioned - no further details.		2015
Specific Location. Street level. Annandale & Eskdale - South side of Moffat - A701 - Road Flooded. Biennial Report. Major/Trunk road flooded.		2015
Specific Location. Property level. Annandale & Eskdale - Moffat - Well Road - U307a - Property flooding. Biennial Report. Property flooded.	River Annan	1897

Specific Location. Street level. Annandale & Eskdale - Moffat - Academy Road, opposite St Marys Church - Flooding due to a blocked drain. Biennial Report. Road flooded.	Pluvial	1897
Specific Location. Street level. Nithsdale - Moffat - A701 - Road flooded at old (demolished) bridge. Biennial Report. Road flooded.	Pluvial	2006
Specific Location. Street level. Annandale & Eskdale - Moffat - Annanside - U846a - Burn blocked and reaching bursting point. Biennial Report. Burn blocked - no further details.		2006
Specific Location. Street level. Annandale & Eskdale - Moffat - Millburn Road, Callochill Rise, Sporkwells Way & Jackies Loaning. Biennial Report. Street mentioned - no details.	Pluvial	2006
Specific Location. Street level. Nithsdale - Clarencefield - B724 - Culvert unable to cope with volume of water from torrential downpour. Local Office returns. Culvert blocked.		2000
Specific Location. Property level. Annandale & Eskdale - Moffat - Northfield - A701 - choked gullys causing flood in garden and shed. Local Office returns. Garden flooded.	Birnock Water	1999
Specific Location. Annandale & Eskdale - Moffat - 5 Beechgrove - B7068 - Choked headwalls and screens. Local Office returns. Choked headworks and screen - no impacts mentioned.	Pluvial	2009
Specific Location. Property level. Annandale & Eskdale - Moffat - Ballplay Road - U802a - DGHP Garages inundated. Local Office returns. Garages flooded.	Pluvial	2008
Specific Location. Property level. The Glebe Moffat. Underfloor flooding to within inches of floor joists. Area mentioned - no further details.	Pluvial	2008
Specific Location. Property level. Annandale and Eskdale - Moffat - Harthope Place - water running into garden. Garden flooded. Biennial Report. Garden flooded.	River Annan	2009
Specific Location. Annandale and Eskdale - Moffat - Well Rd - Blocked drain. Biennial Report. Blocked drain. No other impacts mentioned.	River Annan	2008
Specific Location. Property level. Annadale and Eskdale - Moffat - Mersedale Park(Opp MoffatAcademy) - blocked drian overflowing. Biennial Report. Flooding of road.	Birnock Water	1999
Specific Location. Street level. Annandale and Eskdale - Moffat - Academy rd. Biennial Report. Area mentioned - no further details.	River Annan	2005
Specific Location. Annadale and Eskdale - Moffat - A701 - Flooding in 2 places in / near Moffat. Biennial Report. Flood in town - no specific details.	Pluvial	2004
Specific Location. Property level. Annandale and Eskadale - Moffat - Black Bull Pub - water in pub. Water in pub. Biennial Report. Water in pub.	Birnock Water	2003
Town/Village. Town level. Moffat: Annan rose "with amazing rapidity, the volume at Moffat being increased with great suddenness by a couple of feet in a short time. Sudden rise in river, but no reports of damage by flooding. Annan rose "with amazing rapidity, the v. Scotsman Archive. Note of flood - no damage reported.	Pluvial	2003
Town/Village. Regional level. Moffat: "Heaviest flood experienced in Upper Annandale for some years Holm road under water for 40 yards. Streams down in tremendous volume and Annan overleapt its confines and did		2000

considerable damage to crops in stook. Considerable da. Scotsman Archive. Crops damaged.		
Town/Village. Town level. Moffat: Public park under water. Large stretch of holmland south of town flooded. Roadway between station and bridge impassable. Serious disruption of railway traffic caused by flooding near Wamphray station. Public park under water. Large s. Scotsman Archive. Roads impassable.	Pluvial	2006
Town/Village. Town level. Moffat: Fields and meadows completely submerged, acres of land under water. Public road flooded from town to Holmend. Fields and highways flooded. Scotsman Archive. Roads flooded.	Pluvial	2006
Town/Village. Town level. Moffat: Well burn and Annan overflowed their banks, flooding turnpike roads on south side of town up to several feetThis is the highest flood experienced for about 20 years". Well burn and Annan overflowed their banks, flooding turnpike r. Scotsman Archive. Roads impassable.	Pluvial	2006
Town/Village. Town level. Moffat: Millburn in great volume, overflowing in several places. At Tillbury Lodge stable torrent swept away a strong caul(?) with piles 3 feet into the bed of the stream and many cartloads of boulders behind the wood, and filled the 6 fe. Scotsman Archive. Crops damaged.	Pluvial	2006
Town/Village. Regional level. Moffat: Public park flooded, meadows along rivers from Moffat to the Dyke farm also flooded. Hay , tramp coles and corn ruined by the floods. Evan , Moffat Little Annan and Wamphray also in heavy flood. Public park flooded, meadows along. Scotsman Archive. Crops lost. Car park also flooded.	Pluvial	2006
Town/Village. Town level. Moffat: Public park flooded, road between Moffat and Beattock impassable to foot passengers. Kerr holms below the town "like an inland sea". Public park flooded, road between Moffat and Beattock umpassable to foot passengers. Kerr holms b. Scotsman Archive. Roads impassable.		2006
Town/Village. Regional level. Moffat: "Annan…. overleapt its bounds at every few yards". Whole of low-lying holms south of town flooded to several feet. Small bridge 250 yards from Moffat Station, collapsed; train service stopped. Public road at Moffat Station flo. Scotsman Archive. Max flood depth-Public road at Moffat Station flooded for 80 yards to 2and half feet. Estimated serverity-Reccurence and comment-Bridges collapsed. Roads impassable. Properties flooded.	Birnock Water	1906
Town/Village. Regional level. Moffat: Annan "came down in tremendous volume, and owing to the bed of the rive being much silted up, the weight of water was too much for the depth of the channel and at several points overleaped the banks". Acres of land submerged. On. Scotsman Archive. Disruption to road traffic.	Birnock Water	1907
Town/Village. Regional level. Moffat: roads under water around the town due to the "choking of conduits and the overflowing of streams". On Beattock rd, water knee-deep across the highway. Acres of land south of the town submerged. Holms resembled lakes in Moffatdale. Scotsman Archive. Rail traffic suspended.	Birnock Water	1909
Town/Village. Regional level. Moffat: Annan overflowed quickly due to silting up of the channel over last several years. Meadows flooded, highway	Birnock Water	1911

below the bridge of the Beattock road flooded for 100 yards and over 2 feet deep. The Millburn overflowed at 2 points bet. Scotsman Archive. Max flood depth-Meadows flooded, highway below the bridge of the Beattock road flooded for 100 yards and over 2 feet deep. The Millburn overflowed at 2 points between the Infant School and the Burgh Slaughterhouse up to 18 inches. Estimated serverity-Reccurence and comment-Road flooded.		
Town/Village. Town level. Moffat: serious flooding. No report of damage. No report of damage. Scotsman Archive. Note of flood - no specific details.	Birnock Water	1883
Town/Village. Regional level. Moffat: Streams and hill tribs swollen with melted snow, low-lying holmes submergedLand under water, no other damage reported. Not much damage reported. Scotsman Archive. Note of flood - no specific details.	Birnock Water	1884
Town/Village. Town level. Moffat: Public park invaded by flood and Beattock Rd impassable. Slaughterhouse and sawmill badly flooded. Railway embankment in jeopardy. Highway adjoining the bridge and the new culvert cut up by water. Public park invaded by flood and Be. Scotsman Archive. Businesses flooded. Roads impassable.	Birnock Water	1893
Town/Village. Regional level. Moffat: Acres of holm land submerged. 9 inches of water on Beattock road, traffic completely stopped. Acres of holm land submerged. 9 inches of water on Beattock road, traffic completely stopped. Traffic disrupted. Scotsman Archive. Roads impassable.	Birnock Water	1894
Town/Village. Regional level. Moffat: Large tracts of holms adjacent to the Annan inundated, acres of grass submerged. Roads flooded and impassable to pedestrians. Large tracts of holms adjacent to the Annan inundated, acres of grass submerged. Roads flooded and imp. Scotsman Archive. Road flooded.	Birnock Water	1898
Town/Village. Regional level. Moffat: large tract of holms south of town flooded, Beattock road impassable. Crops washed away. Crops immersed and washed away, many acres inundated. Roads impassable. Scotsman Archive. Max flood depth-"Great volume of water found its way through the cattle bridge on the Moffat railway, a few yards from the girder bridge which spans the Beattock road about a mile distant from the town. Estimated serverity-Reccurence and comment-Crops lost.	Birnock Water	1899
Town/Village. Regional level. Moffat: Considerable extent of haugh lands submerged south of the town. Beattock road also under water and pedestrian traffic interrupted. Considerable extent of haugh lands submerged south of the town. Roads affected. Pedestrian traffi. Scotsman Archive. Road flooded.	Birnock Water	1899
Town/Village. Regional level. Moffat: Haughlands inundated. Beattock road flooded. Water within top of the embankment of the Moffat and Beattock Railway. Haughlands inundated. Beattock road flooded. Water within top of the embankment of the Moffat and Beattock Railw. Scotsman Archive. Road flooded.	Birnock Water	1900
Town/Village. Regional level. Moffat: Fingland Court area flooded, Moffat Weavers showroom flooded, Station Park flooded. Holmside, Berryscaur (Dryfe Water): flooded workshop. Express Dairy factory, Priestdykes, Lockerbie cut off by River Annan. Raging Moffat Water. Annan. Photograph collection. Several roads closed. Factory blocked off.	Birnock Water	1900

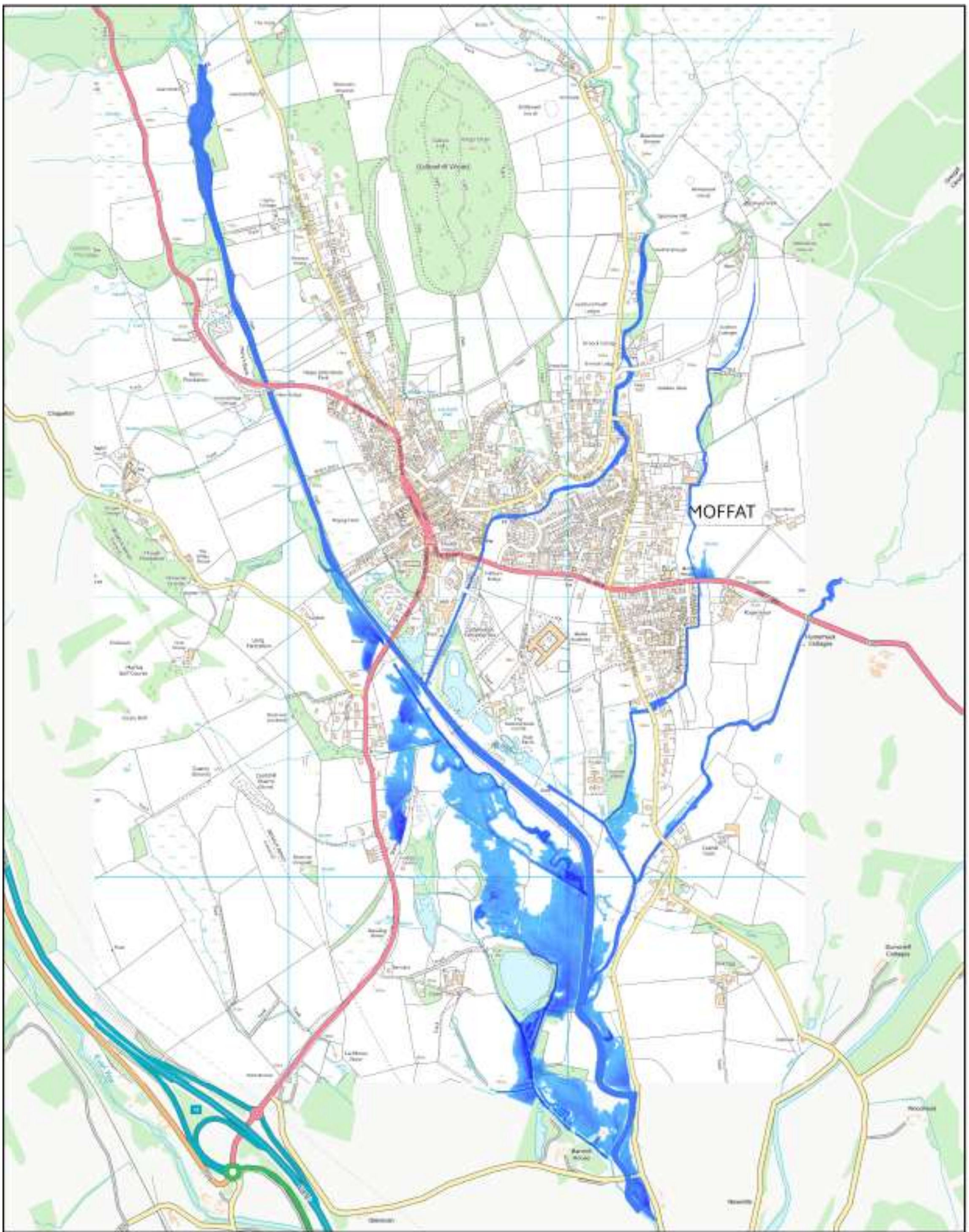
Town/Village. Subcatchment/river reach. Localised flooding along M74. Moffat affected by floodwater, in particular Well St and area around Callow Hill. Article didn't report a lot of damage and the flooding on the M74 didn't close the road. Annandale Herald. Major/Trunk road flooded.	Birnock Water	1901
Specific location. Street levelAt the bridge near Moffat, on the Moffat and Beattock road, the River Anna so greatly overflowed the road as to render it impassable on foot". Road blocked. Road blocked. Scotsman Archive. Note of flood - no specific details.	Birnock Water	1902
Town/village. Neighbourhood level. Flooding at Moffat - assumed from Annan "In the neighbourhood of Moffat the rivers have overflowed all the holm-lands, and greatly destroyed the outlying hay and some cut crops, besides thinning the visiting population". Agirulcutral. Scotsman Archive. Agricultural land / fields flooded.	Birnock Water	1902
Town/Village. Neighbourhood level. No specific date given - mid December - flooding around Moffat - several embankments breached. rmation given on impacts. Scotsman Archive. Note of flood - no specific details.	Birnock Water	1903
Town/Village. Town levelAbnormal rain fell incessantly overnight at Moffat, culminating in a cloudburst at eight o'clock yesterday morning. Many houses were flooded, and extensive damage was done. The public park was submerged, bridges were endangered, roads were i. Scotsman Archive. Properties flooded, road blocked and bridges damaged.	Birnock Water	1903
Specific location. water flowing on road exacerbated by flow from surcharged manholes. Public. Road flooding and flooding of garage - 9 Meadow Bank.	Birnock Water	1903
Specific location. Station Park Moffat. DGC staff. Expensive repairs required.	Birnock Water	1903
Specific location. Prolonged heavy rainfall combined with high water levels and saturated ground resulted in flooding of roads properties and public space. DGC staff. Risk of drowning, Properties flooded, roads flooded, public space flooded, Town cut off due to flood water. Scour damage, sediment deposits, possible water contamination.	Birnock Water	1977
Specific location. Build up of debris and sedament at trash screen combined with heavy rainfall and pluvial flows from the Gallow Hill resulted in flood water bypassing the culvert entrance and flooding roads. DGC staff. Prolonged problem, risk of flooding to residential properties, dangerous driving conditions on Hydro Avenue and Old Edinburgh Road.	Birnock Water	1996
Specific location. Pipe colapse in Hydro Avenue culvert combined with heavy rainfall and surface water flows from the Gallow Hill resulted in flooding of roads and risk of flooding to residential properties at Hydro Avenue. DGC staff. Damage to culvert, risk of flooding to properties, flooding to gardens and driveways, flooding of the road.	River Annan	1877
Specific location. Water running off road into garage of Beehive Cottage. Public. Max flood depth- unknown but no evidence property was affected so not deep. Estimated serverity-Reccurence and comment-Flooding limited to garage.	Birnock Water	1873
Specific location. Flooding of agricultural land. DGC staff. Flooding in field.	Birnock Water	1852

Specific location. Heavy rainfall and surface water flows combined at this location causing flooding of the road. Re-occurring problem. DGC staff. Dangerous road conditions, no reported property flooding, road closure results in long detour.	Pluvial	1931
Specific location. The A701 Dumfries to Moffat road was closed approx ¾ of a mile south of Moffat (locally Hidden Corner), due to the amount of surface water lying on the road. Other. High Impact - Road Closed.	Pluvial	2011
Specific location. Heavy rainfall and surface water flows from surrounding farmland caused flooding of the road at this location. Re-occuring problem. DGC staff. No road closure, no reported property flooding, low risk, no health hazard.	River Annan	2011
Specific location. Police called OOH to report that the road was barely passable. Other. Barely passable.	River Annan	2013
Specific location. Flooding on A701 at the old railway line. Public. Flooding on Road.	Birnock Water	2013
Specific location. Flooding on A701 at the 30mph signs. Other. Flooding on road.	Birnock Water	2014
Specific location. Flooding on the A701 as you enter Moffat. Other. Flooding on road.	Pluvial	2011
Specific location. Flooding on A701 south of Moffat at Langshaw Bush. Other. Flooding on Road.		2010
Specific location. Flood screen blocked. Public. Public road only flooded.		2013
Specific location. Pluvial flows through the beech wood, down through the garden of Springvale and onto Hydro Avenue. Public. Water onto public and flooding to garden.	Pluvial	2013
Specific location. Heavy rainfall combined with pluvial flows resulted in flooding at this location. Culvert entrance screen was blinded with silt and leaves. Re-occuring problem due to screen design, culvert capacity and leaf droppage. DGC staff. No reported property flooding, no reported road closure/flooding, low risk, no health hazard.	Pluvial	2013
High water level in Birnock Water, Moffat. Banks bursting through gabion baskets behind St Ninian's road, Moffat. Further rainfall could lead to flooding on Park Circle.	Pluvial	2013

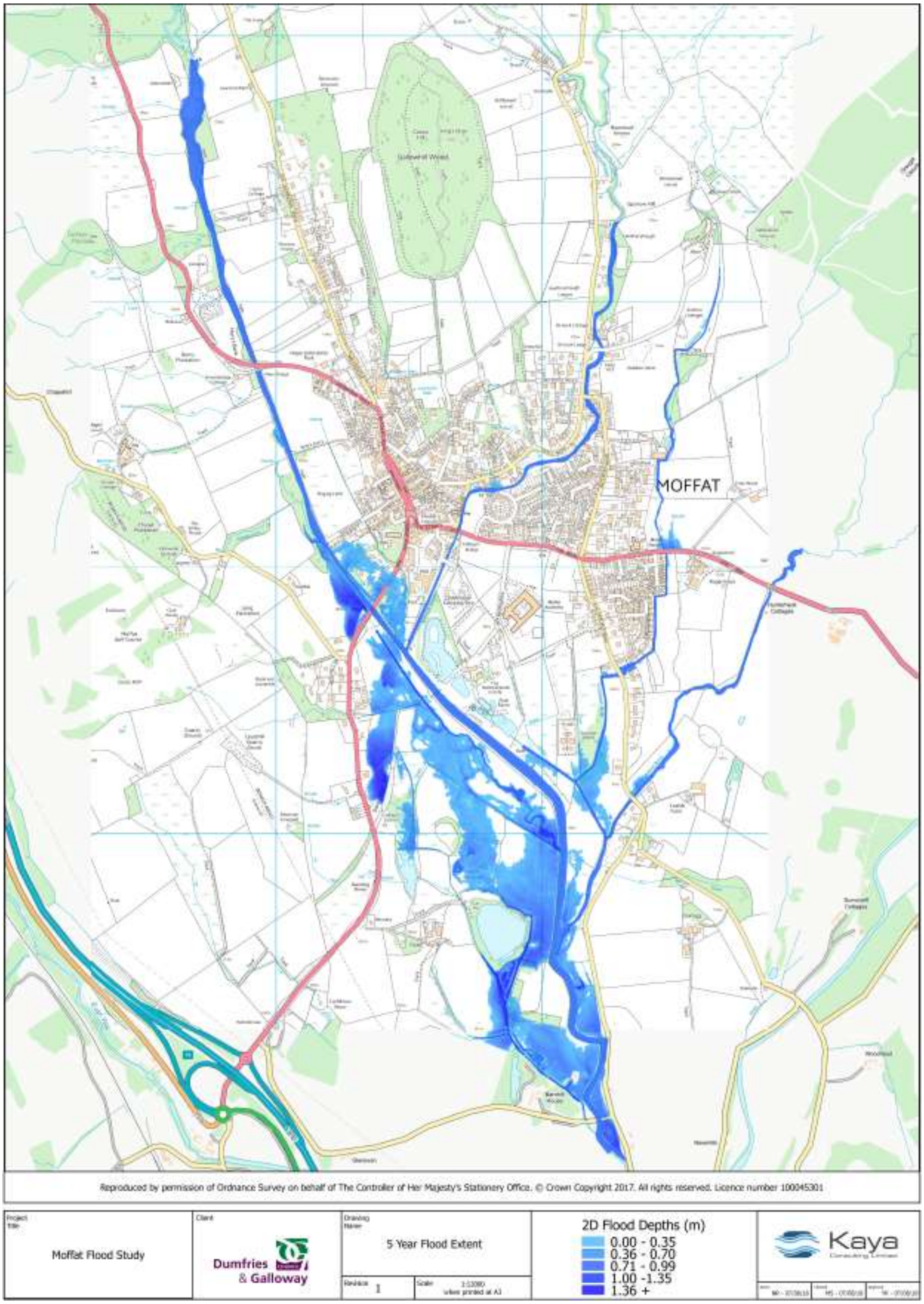
Appendix C – Flood Maps

Figure 43:

Predicted 2 year flood map



Project Title	Client	Drawing Name	2D Flood Depths (m)	
Moffat Flood Study	Dumfries & Galloway	2 Year Flood Extent Revision 1 Scale 1:12000 when printed at A1	0.00 - 0.35 0.36 - 0.70 0.71 - 0.99 1.00 -1.35 1.36 +	Kaya Consulting Limited


MOFFAT
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Project Title
Moffat Flood Study
Client
Dumfries & Galloway
Drawing Name
5 Year Flood Extent
Revision 1
Scale 1:13000 when printed at A3
2D Flood Depths (m)
0.00 - 0.35
0.36 - 0.70
0.71 - 0.99
1.00 -1.35
1.36 +
Kaya

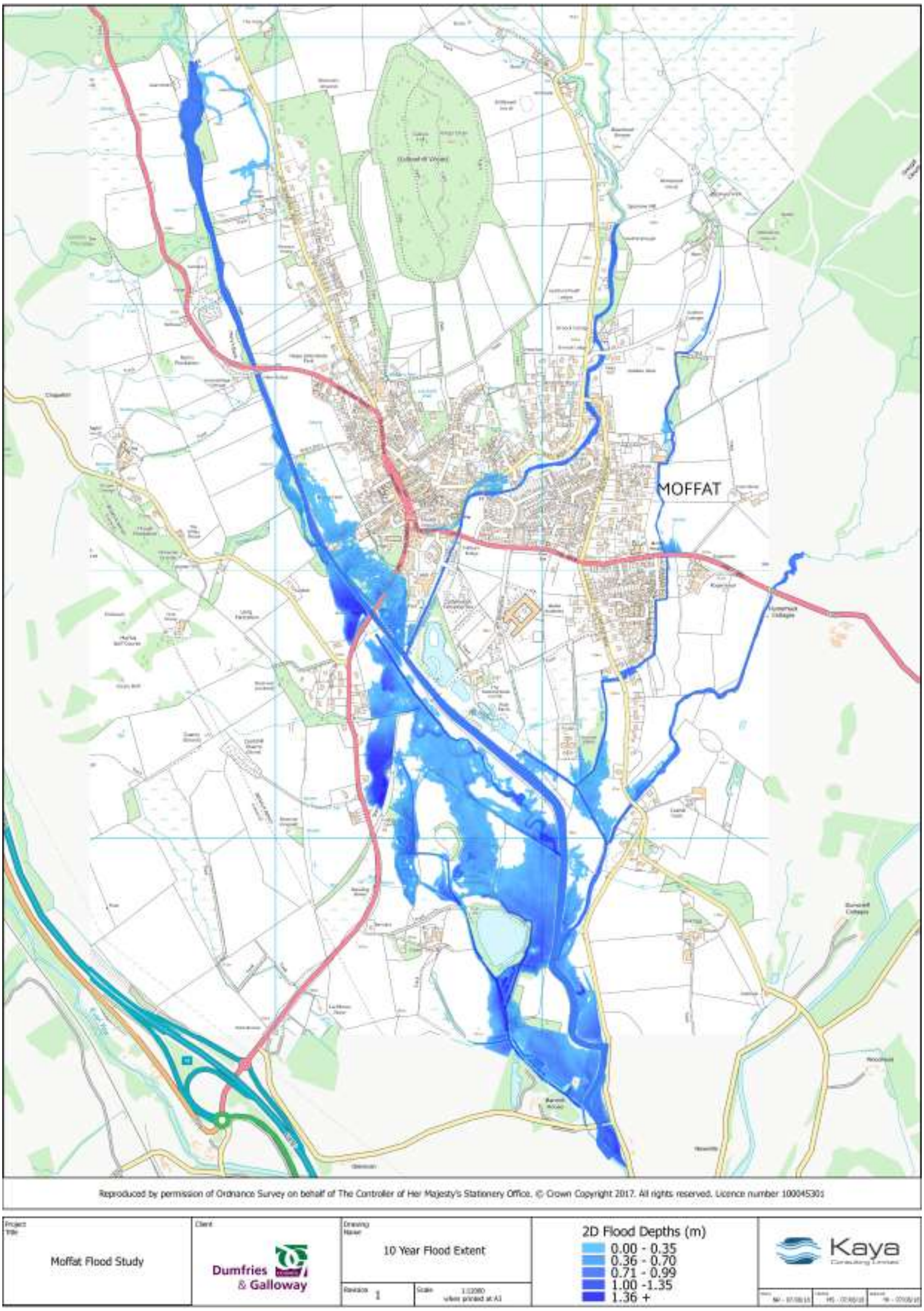

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Figure 46: Predicted 25 year flood map

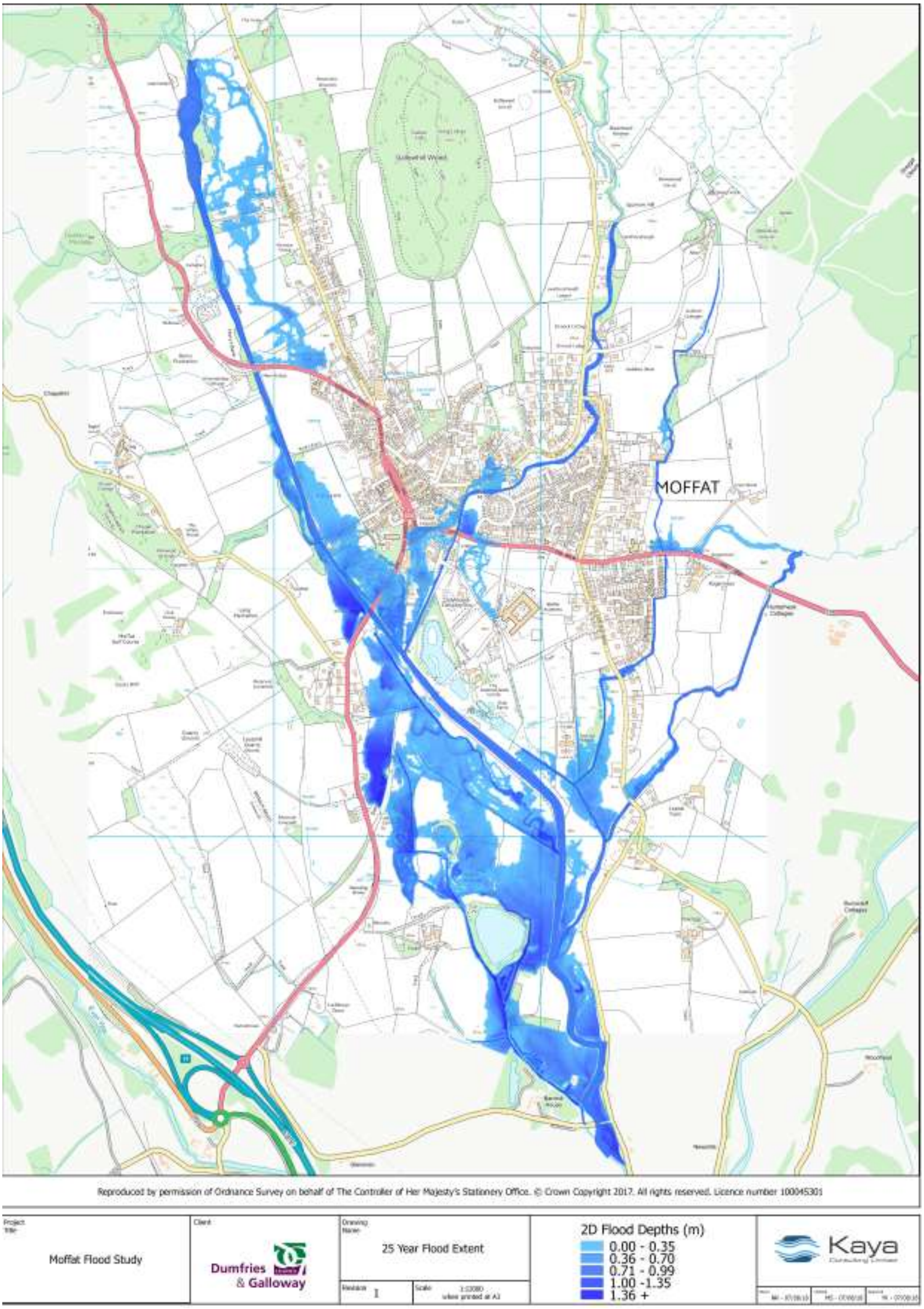


Figure 47: Predicted 30 year flood map

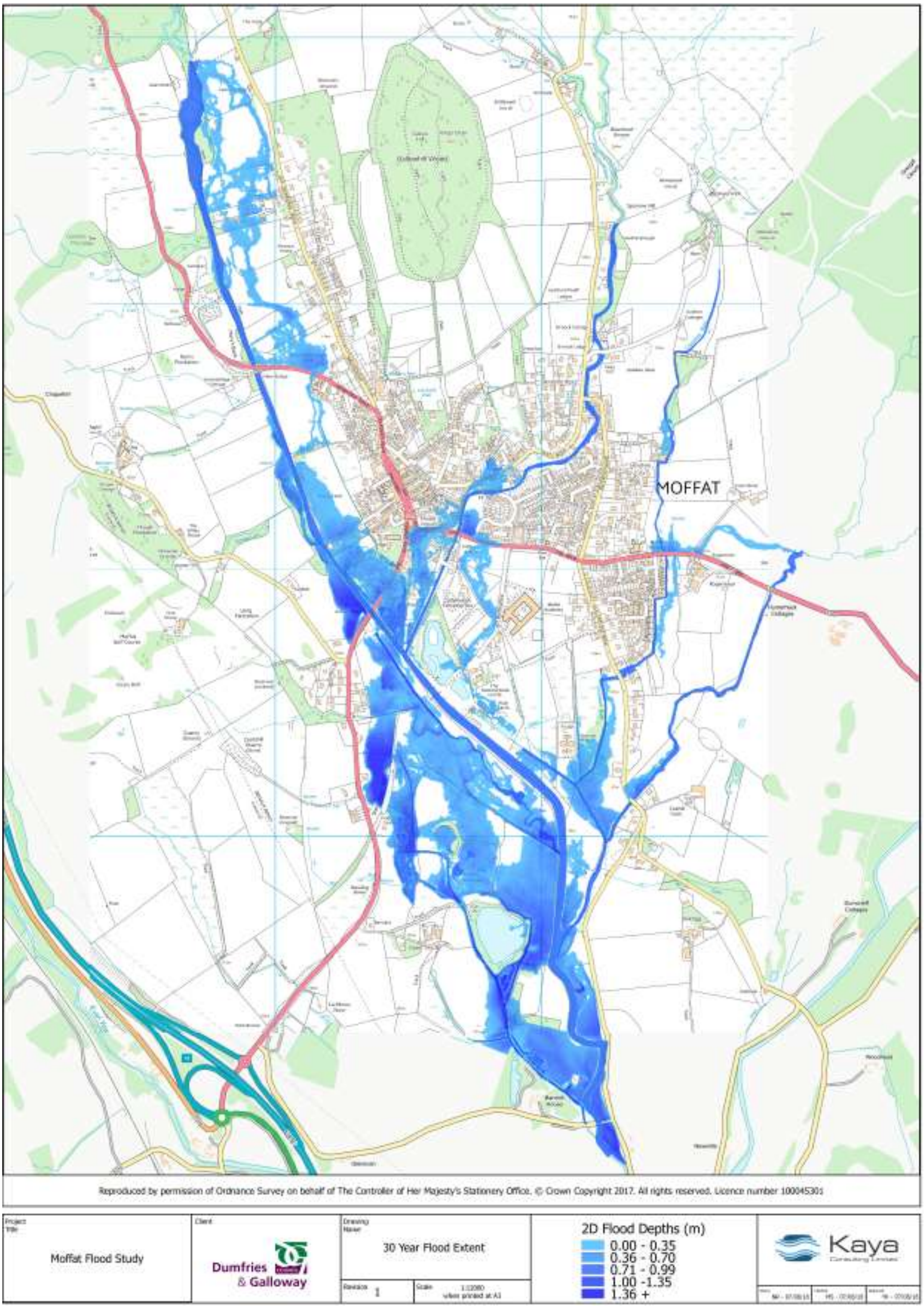


Figure 48: Predicted 50 year flood map

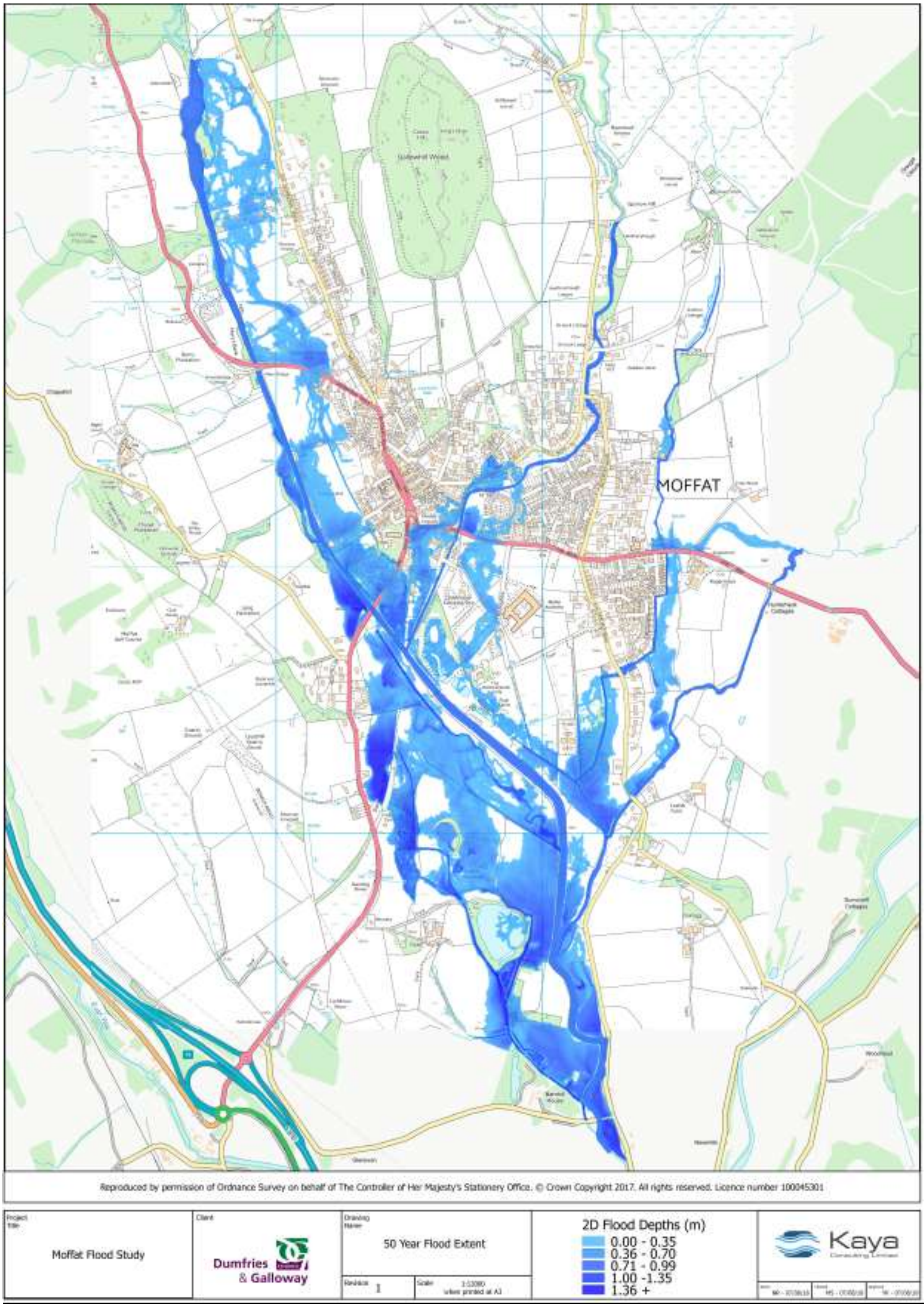


Figure 49: Predicted 75 year flood map

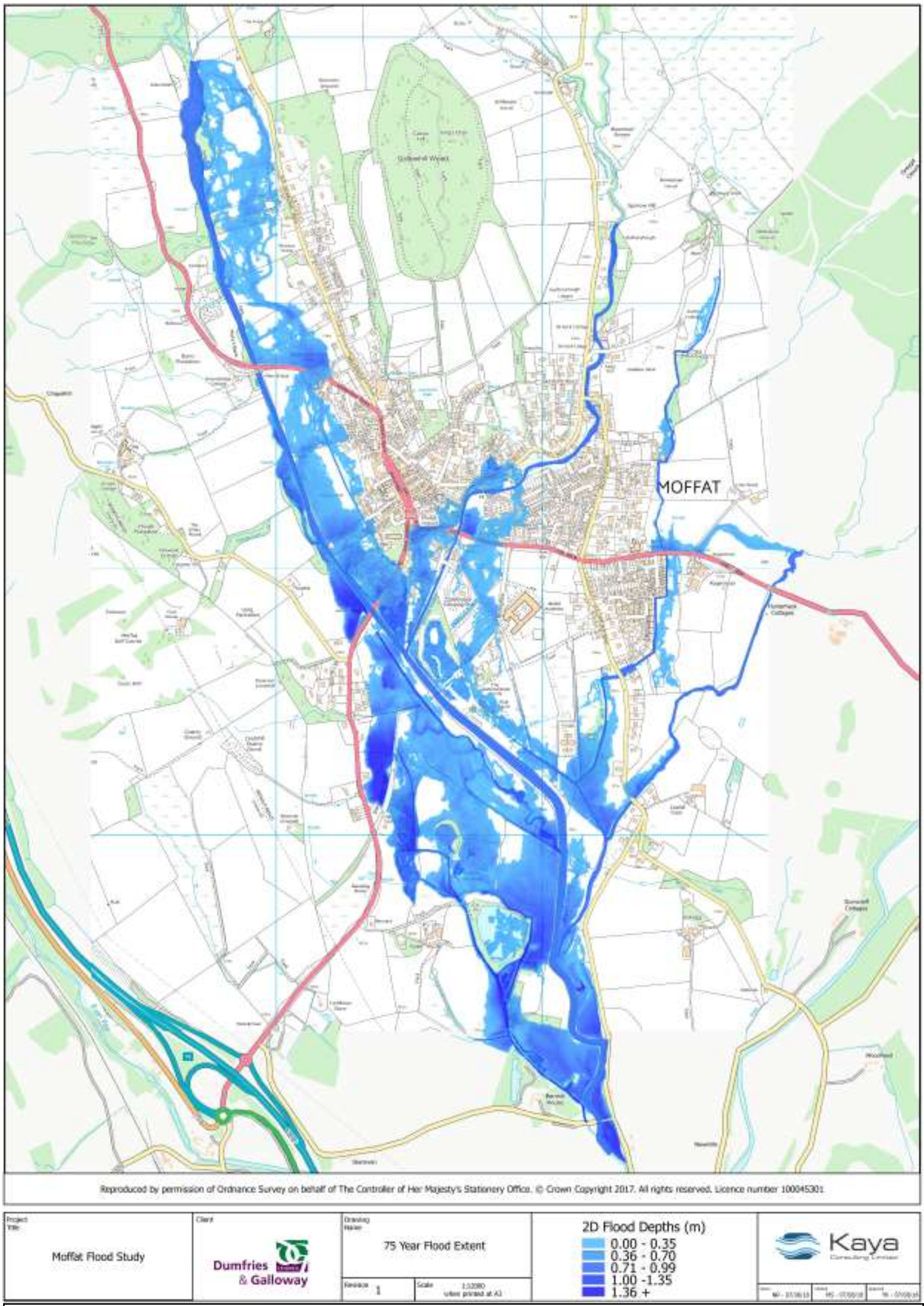


Figure 50: Predicted 100 year flood map

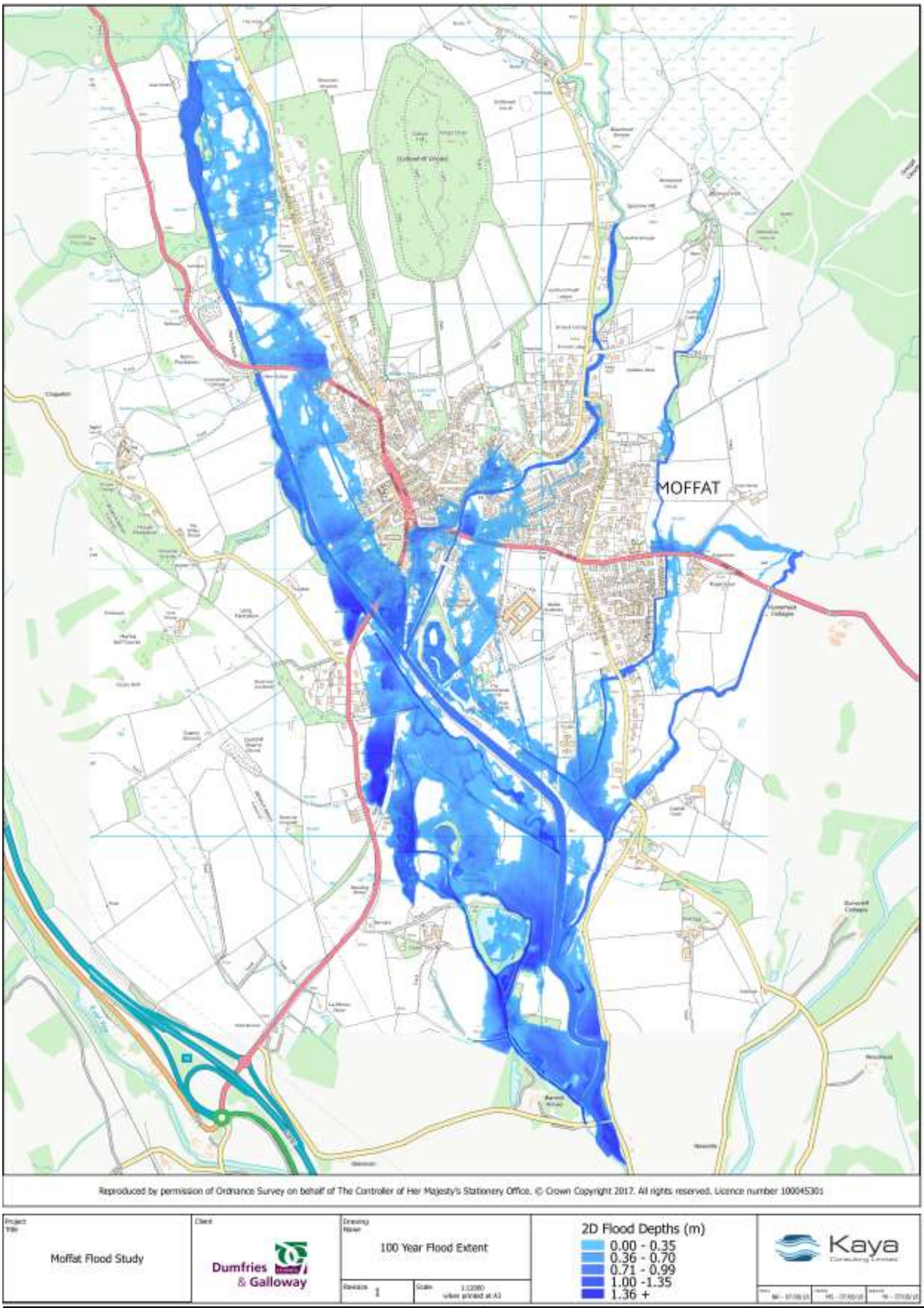


Figure 51: Predicted 200 year flood map

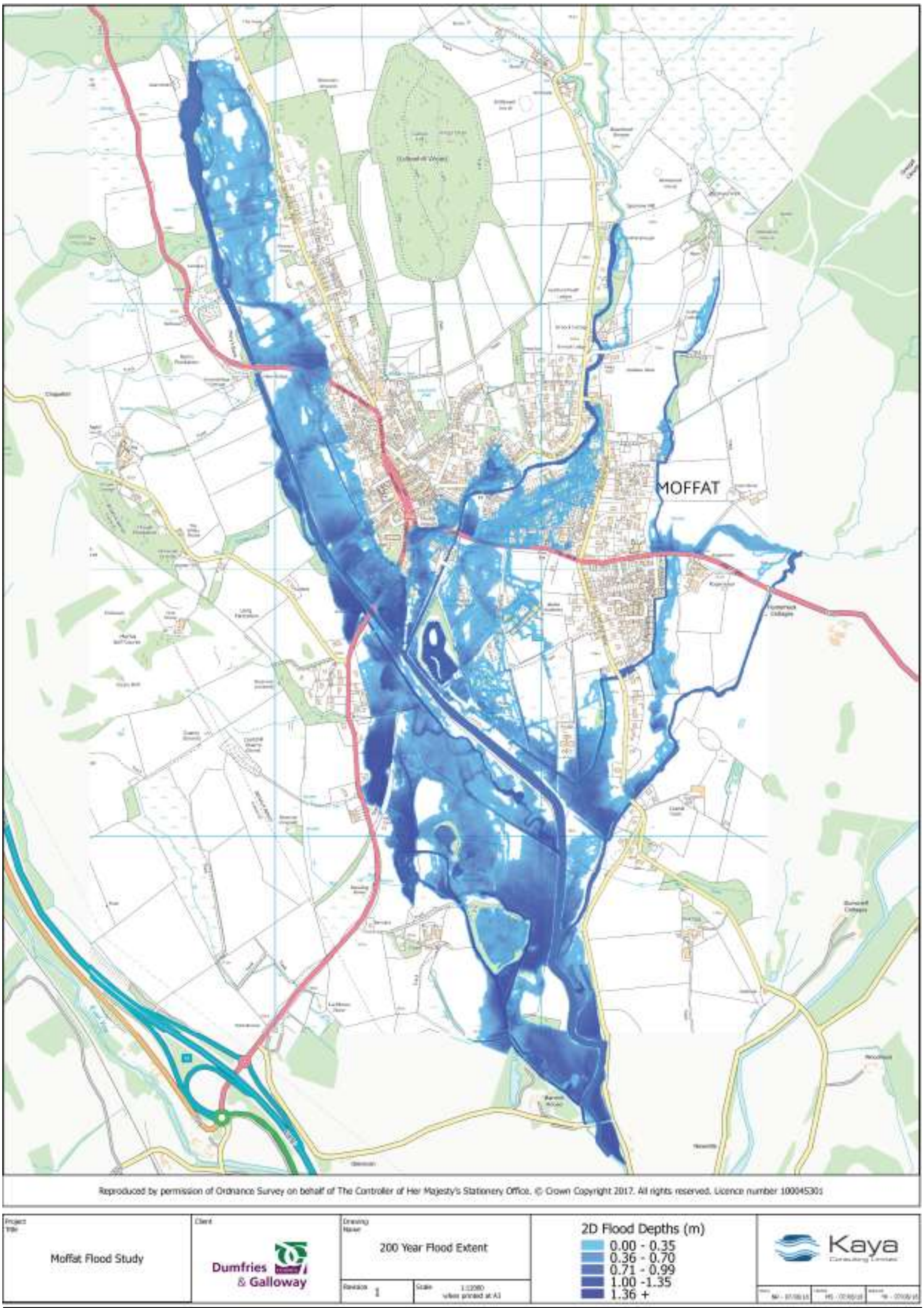


Figure 52: Predicted 500 year flood map

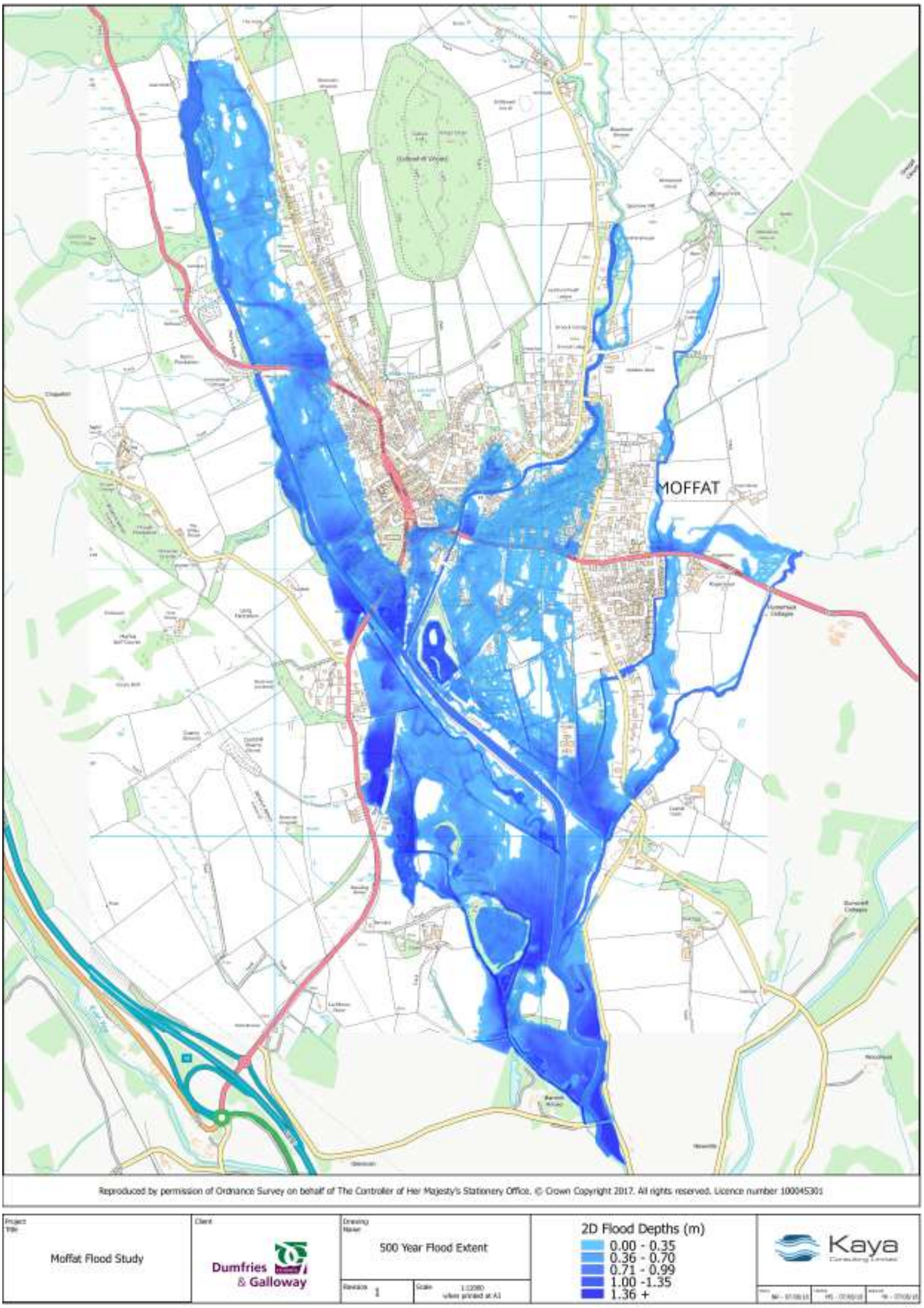
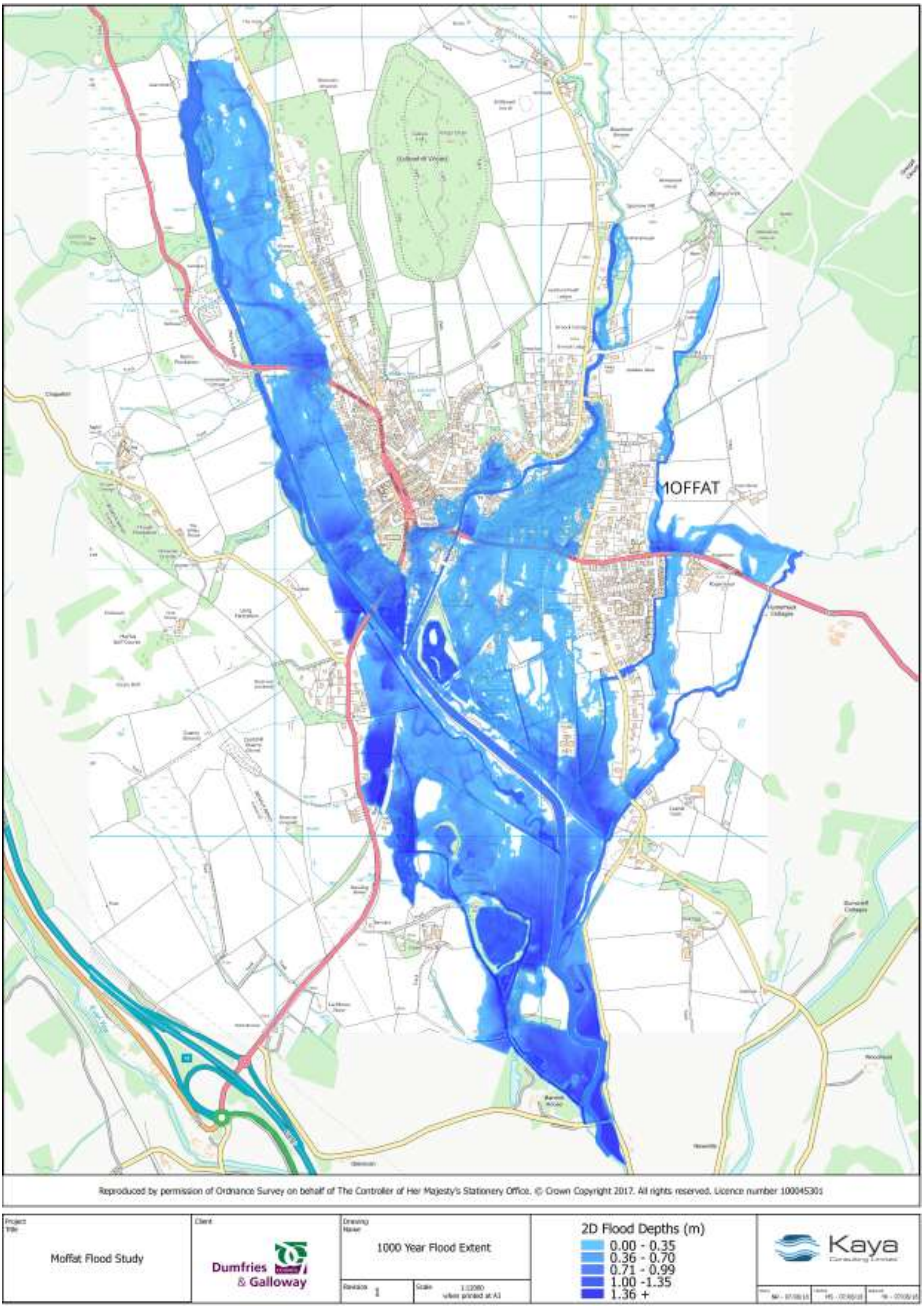


Figure 53: Predicted 1000 year flood map



Appendix D - Predicted Peak Water Levels

Table 29: Predicted water levels at each model node (m AOD)

Cross-Section	2	5	10	25	30	50	75	100	200	500	1000
B86	131.56	131.75	131.86	132.03	132.05	132.15	132.21	132.27	132.45	132.66	132.78
B85B_U	130.75	131.03	131.15	131.38	131.38	131.49	131.53	131.59	132.06	132.11	132.11
B85B_Crest	130.66	131.07	131.21	131.43	131.43	131.55	131.60	131.67	132.31	132.45	132.46
B85A_UP_C	130.58	131.00	131.13	131.34	131.34	131.44	131.48	131.53	132.29	132.43	132.44
B85A_UP	128.53	128.88	129.10	129.36	129.44	129.59	129.67	129.74	129.95	130.92	131.41
B85A_DS	127.80	128.19	128.41	128.75	128.81	129.01	129.15	129.25	129.47	129.87	130.04
B85_U	127.02	127.28	127.45	127.67	127.70	127.82	127.90	127.97	128.14	128.43	128.60
B85_D	126.95	127.21	127.37	127.58	127.61	127.72	127.78	127.84	127.98	128.22	128.35
B84	124.11	124.31	124.42	124.60	124.63	124.73	124.81	124.86	124.99	125.21	125.36
B83A	122.95	123.11	123.21	123.37	123.40	123.49	123.55	123.60	123.71	123.89	124.00
B83	122.47	122.62	122.72	122.86	122.88	122.97	123.02	123.07	123.17	123.32	123.39
B82	121.22	121.34	121.41	121.53	121.56	121.63	121.68	121.72	121.82	121.97	122.08
B81	119.08	119.28	119.39	119.56	119.60	119.70	119.77	119.83	119.97	120.20	120.44
BR80_U	117.95	118.14	118.25	118.43	118.46	118.57	118.64	118.70	118.84	119.07	119.26
B80	117.88	118.06	118.17	118.34	118.38	118.48	118.55	118.60	118.73	118.95	119.12
B79	117.55	117.73	117.84	118.01	118.05	118.15	118.21	118.27	118.39	118.60	118.77
B78	115.67	115.86	115.98	116.17	116.20	116.30	116.37	116.42	116.55	116.79	117.20
B77U	114.52	114.74	114.87	115.08	115.12	115.22	115.30	115.35	115.42	115.42	115.42
B77	114.46	114.66	114.78	114.98	115.02	115.12	115.20	115.26	115.38	115.56	115.67
B76	113.78	113.99	114.11	114.30	114.33	114.43	114.49	114.55	114.68	114.91	115.11
B75	112.79	112.97	113.08	113.23	113.26	113.36	113.43	113.48	113.59	113.71	113.80
B74	111.60	111.85	112.00	112.20	112.24	112.37	112.46	112.52	112.60	112.69	112.75

B73	110.84	111.10	111.26	111.51	111.56	111.71	111.82	111.88	111.99	112.09	112.14
B72	109.93	110.09	110.19	110.34	110.37	110.46	110.51	110.56	110.64	110.72	110.78
B71	109.26	109.42	109.51	109.64	109.66	109.74	109.78	109.82	109.89	109.96	110.01
B70	108.37	108.59	108.70	108.84	108.87	108.92	108.95	108.98	109.03	109.07	109.09
B69	107.86	108.09	108.22	108.41	108.44	108.53	108.57	108.59	108.64	108.68	108.71
B68	107.10	107.30	107.40	107.53	107.54	107.59	107.62	107.63	107.67	107.70	107.72
B67A	106.13	106.33	106.45	106.61	106.62	106.68	106.72	106.74	106.79	106.83	106.87
B67	106.09	106.29	106.41	106.57	106.58	106.64	106.67	106.70	106.74	106.78	106.79
B66	105.05	105.29	105.44	105.58	105.61	105.65	105.69	105.71	105.78	105.80	105.84
B65	104.46	104.66	104.78	104.88	104.90	104.93	104.94	104.95	104.96	104.98	104.99
B64	103.90	104.11	104.22	104.34	104.36	104.41	104.44	104.46	104.50	104.52	104.54
B64A	103.81	104.02	104.16	104.31	104.34	104.39	104.42	104.43	104.47	104.48	104.50
B63	102.88	103.11	103.25	103.36	103.37	103.39	103.40	103.40	103.39	103.41	103.41
B63A	102.78	103.00	103.13	103.26	103.28	103.32	103.34	103.34	103.36	103.37	103.38
B62	101.64	101.89	102.04	102.16	102.17	102.18	102.18	102.18	102.19	102.19	102.19
B61	100.28	100.47	100.56	100.70	100.73	100.85	100.94	101.00	101.08	101.18	101.24
B60	100.20	100.38	100.44	100.53	100.55	100.58	100.62	100.65	100.71	100.77	100.82
B60_x	100.21	100.41	100.48	100.58	100.60	100.65	100.70	100.73	100.80	100.87	100.92
C0	132.19	132.28	132.31	132.38	132.39	132.42	132.44	132.44	132.47	132.51	132.54
C1	131.33	131.41	131.47	131.57	131.59	131.67	131.73	131.76	131.81	131.87	131.90
C2	131.02	131.11	131.16	131.23	131.24	131.28	131.31	131.32	131.35	131.39	131.41
C3	128.11	128.14	128.17	128.21	128.22	128.24	128.26	128.27	128.31	128.35	128.38
C4	122.38	122.43	122.47	122.53	122.54	122.57	122.60	122.62	122.68	122.77	122.86
C5	120.08	120.15	120.19	120.27	120.28	120.32	120.36	120.40	120.48	120.66	120.75
C5a	119.94	119.98	120.02	120.09	120.11	120.16	120.22	120.28	120.41	120.63	120.73
C6a	119.58	119.64	119.68	119.76	119.77	119.81	119.84	119.87	119.95	120.06	120.08
C6	119.58	119.64	119.68	119.76	119.77	119.80	119.84	119.86	119.93	120.02	120.05
C7	118.65	118.74	118.78	118.84	118.85	118.89	118.93	118.95	119.01	119.11	119.17

C8	116.48	116.56	116.61	116.70	116.71	116.76	116.80	116.82	116.89	116.99	117.07
C9	115.51	115.56	115.60	115.66	115.67	115.71	115.74	115.76	115.82	115.90	115.98
C10	114.14	114.21	114.26	114.33	114.35	114.39	114.43	114.46	114.53	114.67	114.81
C11	113.21	113.33	113.38	113.44	113.44	113.44	113.46	113.46	113.49	113.55	113.59
C12	113.07	113.20	113.27	113.34	113.35	113.37	113.40	113.42	113.45	113.51	113.55
C13	112.71	112.80	112.85	112.92	112.93	112.96	112.99	113.01	113.07	113.16	113.24
C14	111.22	111.33	111.39	111.50	111.52	111.56	111.61	111.64	111.73	111.85	111.97
C15	109.41	109.52	109.60	109.71	109.72	109.78	109.84	109.87	109.96	110.09	110.22
C16	109.00	109.11	109.18	109.28	109.30	109.34	109.38	109.41	109.50	109.60	109.60
C17	108.46	108.57	108.63	108.72	108.74	108.80	108.84	108.87	108.94	109.05	109.24
C18	107.52	107.63	107.69	107.80	107.81	107.86	107.91	107.95	108.03	108.12	108.20
C19	106.88	106.98	107.05	107.13	107.15	107.20	107.25	107.28	107.34	107.45	107.57
C20	105.99	106.09	106.14	106.24	106.25	106.28	106.32	106.33	106.38	106.49	106.83
C21	105.33	105.39	105.36	105.51	105.52	105.56	105.61	105.63	105.79	106.16	106.58
C21a	105.14	105.22	105.18	105.37	105.39	105.44	105.51	105.54	105.79	106.28	106.65
C22a	104.96	105.03	105.00	105.15	105.16	105.17	105.22	105.23	105.29	105.37	105.42
C22	104.84	104.92	104.88	105.04	105.05	105.04	105.10	105.10	105.16	105.21	105.23
C23	104.54	104.62	104.59	104.76	104.76	104.96	104.84	104.86	104.93	104.99	105.00
C50	103.74	103.83	103.80	104.00	104.02	104.21	104.13	104.15	104.21	104.30	104.35
C24	103.40	103.49	103.46	103.63	103.64	103.82	103.76	103.78	103.82	103.89	103.95
C49	102.99	103.07	103.04	103.22	103.24	103.51	103.35	103.38	103.49	103.58	103.62
C48	102.20	102.30	102.27	102.43	102.45	102.71	102.57	102.60	102.70	102.79	102.82
C47	101.29	101.38	101.35	101.53	101.55	101.78	101.69	101.71	101.77	101.85	101.91
C46	100.56	100.64	100.61	100.77	100.79	101.01	100.92	100.94	101.00	101.05	101.08
C45	99.15	99.20	99.18	99.29	99.30	99.44	99.39	99.41	99.45	99.48	99.50
C45D	99.13	99.18	99.16	99.27	99.28	99.42	99.37	99.39	99.42	99.45	99.47
C44	97.90	97.94	97.93	97.99	97.99	98.08	98.01	98.02	98.03	98.04	98.06
C43	96.36	96.46	96.43	96.61	96.62	96.96	96.74	96.76	96.81	96.86	96.89

C42	95.84	95.92	95.90	96.05	96.06	96.14	96.11	96.11	96.12	96.12	96.13
C41	95.33	95.40	95.39	95.48	95.49	95.64	95.55	95.57	95.74	95.94	96.08
C40	94.99	95.11	95.15	95.31	95.33	95.61	95.48	95.54	95.74	95.94	96.08
C39U	94.98	95.11	95.15	95.31	95.33	95.60	95.48	95.54	95.73	95.94	96.08
C39	94.98	95.11	95.15	95.31	95.33	95.60	95.48	95.54	95.73	95.94	96.08
C38	94.85	95.00	95.05	95.25	95.27	95.58	95.45	95.51	95.72	95.92	96.05
C38D	94.53	94.70	94.78	95.14	95.19	95.56	95.42	95.49	95.71	95.90	96.02
C37	94.40	94.59	94.68	94.99	95.03	95.37	95.24	95.29	95.51	95.69	95.76
C37_C	94.39	94.59	94.68	94.99	95.03	95.37	95.23	95.29	95.51	95.69	95.76
F1	122.84	122.91	122.95	123.04	123.05	123.10	123.13	123.16	123.21	123.31	123.42
F2	120.70	120.80	120.86	120.92	120.94	120.98	121.01	121.04	121.09	121.17	121.25
F3	118.86	118.93	118.96	118.99	118.99	119.01	119.02	119.03	119.05	119.08	119.11
F4	117.04	117.11	117.15	117.20	117.20	117.22	117.24	117.25	117.28	117.32	117.36
F5	114.71	114.79	114.84	114.90	114.91	114.95	114.97	114.99	115.03	115.08	115.13
F6	114.22	114.34	114.40	114.49	114.51	114.55	114.58	114.61	114.66	114.73	114.81
F60	114.00	114.12	114.17	114.25	114.26	114.30	114.33	114.35	114.39	114.45	114.51
F59	111.24	111.35	111.41	111.48	111.50	111.54	111.56	111.58	111.62	111.68	111.74
F8	109.88	109.97	110.02	110.10	110.11	110.14	110.16	110.18	110.22	110.28	110.34
F58	106.18	106.30	106.37	106.47	106.49	106.54	106.57	106.60	106.65	106.72	106.77
F57	101.31	101.42	101.48	101.56	101.57	101.61	101.63	101.65	101.69	101.76	101.82
F56	98.72	98.82	98.86	98.93	98.94	98.98	98.99	99.01	99.06	99.20	99.31
F55	96.52	96.67	96.76	96.88	96.89	96.94	96.97	97.00	97.04	97.22	97.30
F54	95.80	95.95	96.04	96.18	96.19	96.30	96.30	96.33	96.39	96.56	96.64
F54D	95.73	95.89	95.96	96.10	96.12	96.23	96.22	96.26	96.30	96.39	96.43
F53	94.99	95.13	95.21	95.29	95.29	95.56	95.44	95.49	95.71	95.90	96.03
F52	94.64	94.81	94.90	95.09	95.12	95.42	95.29	95.35	95.57	95.80	95.93
F36U	94.39	94.59	94.68	94.99	95.03	95.37	95.23	95.29	95.51	95.69	95.76
F36	94.39	94.59	94.68	94.99	95.03	95.37	95.23	95.29	95.51	95.69	95.76

F35	94.08	94.27	94.34	94.63	94.66	94.97	94.85	94.91	95.11	95.31	95.41
F34	93.82	93.94	94.00	94.18	94.21	94.41	94.33	94.36	94.51	94.66	94.79
F33	93.72	93.81	93.85	93.96	93.97	94.07	94.04	94.05	94.12	94.32	94.46
A5	93.64	93.71	93.74	93.80	93.80	93.85	93.85	93.86	93.88	93.96	94.04
A5_x	93.65	93.72	93.76	93.86	93.87	93.93	93.94	93.95	94.00	94.08	94.15
A32	118.70	118.86	118.95	119.05	119.06	119.12	119.15	119.17	119.23	119.32	119.40
A31	116.33	116.50	116.60	116.71	116.73	116.78	116.82	116.85	116.92	116.99	117.04
A30	114.78	114.98	115.09	115.23	115.25	115.30	115.31	115.33	115.46	115.64	115.77
A29	113.56	113.79	113.91	114.05	114.07	114.21	114.29	114.33	114.36	114.37	114.38
A28	112.37	112.63	112.78	112.99	113.03	113.13	113.22	113.28	113.45	113.65	113.76
A27	111.47	111.74	111.85	112.00	112.02	112.03	112.04	112.05	112.08	112.11	112.14
A26	110.46	110.69	110.84	111.00	111.04	111.16	111.27	111.31	111.40	111.48	111.53
A25	109.00	109.27	109.43	109.62	109.65	109.72	109.76	109.77	109.81	109.85	109.92
A24D	108.12	108.34	108.47	108.62	108.64	108.71	108.75	108.77	108.82	108.87	108.91
A24C	108.11	108.35	108.49	108.64	108.67	108.72	108.76	108.78	108.82	108.86	108.91
A24B	107.98	108.19	108.31	108.46	108.49	108.54	108.59	108.60	108.64	108.69	108.73
A24A	107.89	108.12	108.25	108.41	108.44	108.50	108.54	108.56	108.60	108.65	108.69
A23	107.25	107.48	107.63	107.78	107.81	107.87	107.90	107.91	107.94	107.98	108.01
A22	106.24	106.51	106.64	106.73	106.75	106.79	106.82	106.82	106.84	106.86	106.88
A21	105.59	105.83	105.95	106.05	106.06	106.08	106.10	106.10	106.11	106.14	106.16
A20	104.36	104.54	104.63	104.78	104.81	104.86	104.89	104.90	104.93	105.03	105.08
A19	103.60	103.75	103.84	103.86	103.86	103.86	103.89	103.90	103.92	103.94	103.93
A18	102.97	103.13	103.15	103.16	103.16	103.17	103.17	103.18	103.21	103.30	103.35
A17	102.25	102.45	102.51	102.54	102.55	102.56	102.58	102.59	102.65	102.70	102.72
A16	101.46	101.75	101.87	101.95	101.96	101.98	102.00	102.01	102.10	102.22	102.30
A16A	101.38	101.65	101.73	101.78	101.78	101.79	101.80	101.82	101.88	101.96	102.02
A15	101.28	101.52	101.60	101.63	101.64	101.64	101.66	101.68	101.76	101.88	101.97
A14	100.40	100.46	100.46	100.48	100.49	100.51	100.55	100.58	100.64	100.72	100.79

A14i	100.21	100.41	100.48	100.58	100.60	100.65	100.70	100.73	100.80	100.87	100.92
A14_x	100.21	100.41	100.48	100.58	100.60	100.65	100.70	100.73	100.80	100.87	100.92
A13	99.76	99.93	99.99	100.07	100.08	100.12	100.16	100.19	100.24	100.29	100.34
A12	99.05	99.23	99.30	99.40	99.41	99.46	99.50	99.52	99.58	99.64	99.69
A12A	99.04	99.21	99.27	99.36	99.37	99.41	99.45	99.47	99.52	99.57	99.61
A11	98.54	98.71	98.77	98.85	98.86	98.90	98.94	98.95	99.00	99.05	99.09
A10	97.68	97.84	97.89	97.97	97.98	98.01	98.04	98.06	98.10	98.15	98.18
A9	96.70	96.85	96.90	96.95	96.96	96.98	97.01	97.01	97.04	97.07	97.09
A8	95.45	95.48	95.50	95.53	95.53	95.54	95.56	95.56	95.58	95.60	95.61
A7	94.76	94.80	94.83	94.86	94.87	94.88	94.89	94.90	94.92	94.95	94.98
A6	94.08	94.14	94.18	94.23	94.24	94.27	94.30	94.31	94.35	94.44	94.50
A5C	93.68	93.76	93.79	93.89	93.90	93.96	93.96	93.98	94.02	94.11	94.17
A5C_x	93.65	93.72	93.76	93.86	93.87	93.93	93.94	93.95	94.00	94.08	94.15
A5C_2	93.65	93.72	93.76	93.86	93.87	93.93	93.94	93.95	94.00	94.08	94.15
A4	93.10	93.17	93.21	93.28	93.29	93.32	93.32	93.33	93.36	93.48	93.57
A3	92.30	92.39	92.43	92.60	92.61	92.71	92.71	92.75	92.86	93.10	93.24
A2	91.70	91.87	91.96	92.12	92.15	92.29	92.33	92.35	92.46	92.70	92.89
A1N	91.34	91.53	91.64	91.80	91.83	91.93	91.96	91.98	92.09	92.31	92.48
A1N_C	91.34	91.53	91.64	91.80	91.83	91.93	91.96	91.98	92.09	92.30	92.44
A_L1	91.23	91.46	91.58	91.75	91.78	91.89	91.92	91.94	92.05	92.27	92.40
A_L2	90.71	90.94	91.06	91.24	91.27	91.37	91.39	91.42	91.52	91.74	91.86

Appendix E – Sensitivity Analysis

Figure 54: Predicted 200 year flood map with 44% climate change increase

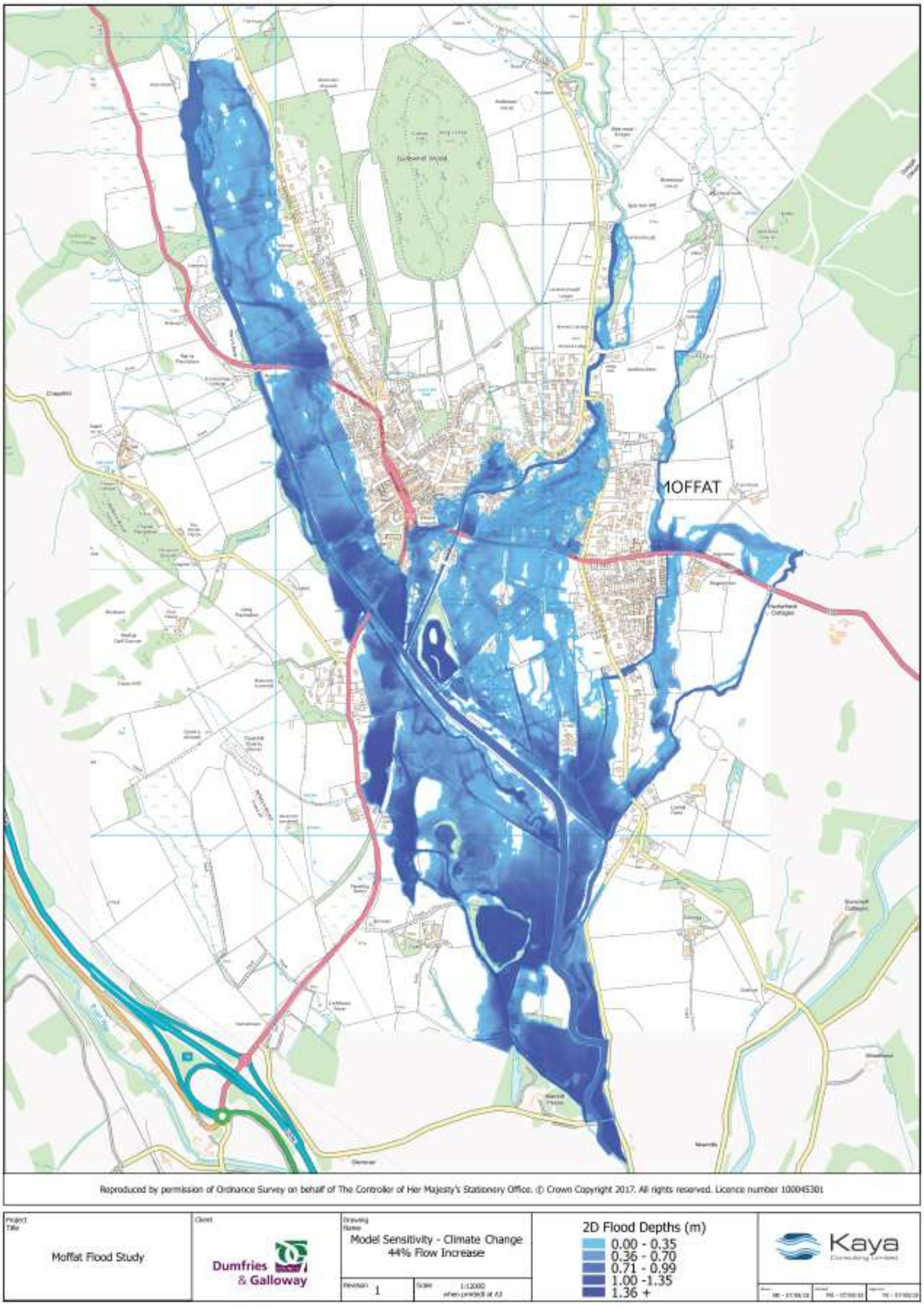


Figure 55: Predicted 200 year flood map with 20% increase in roughness

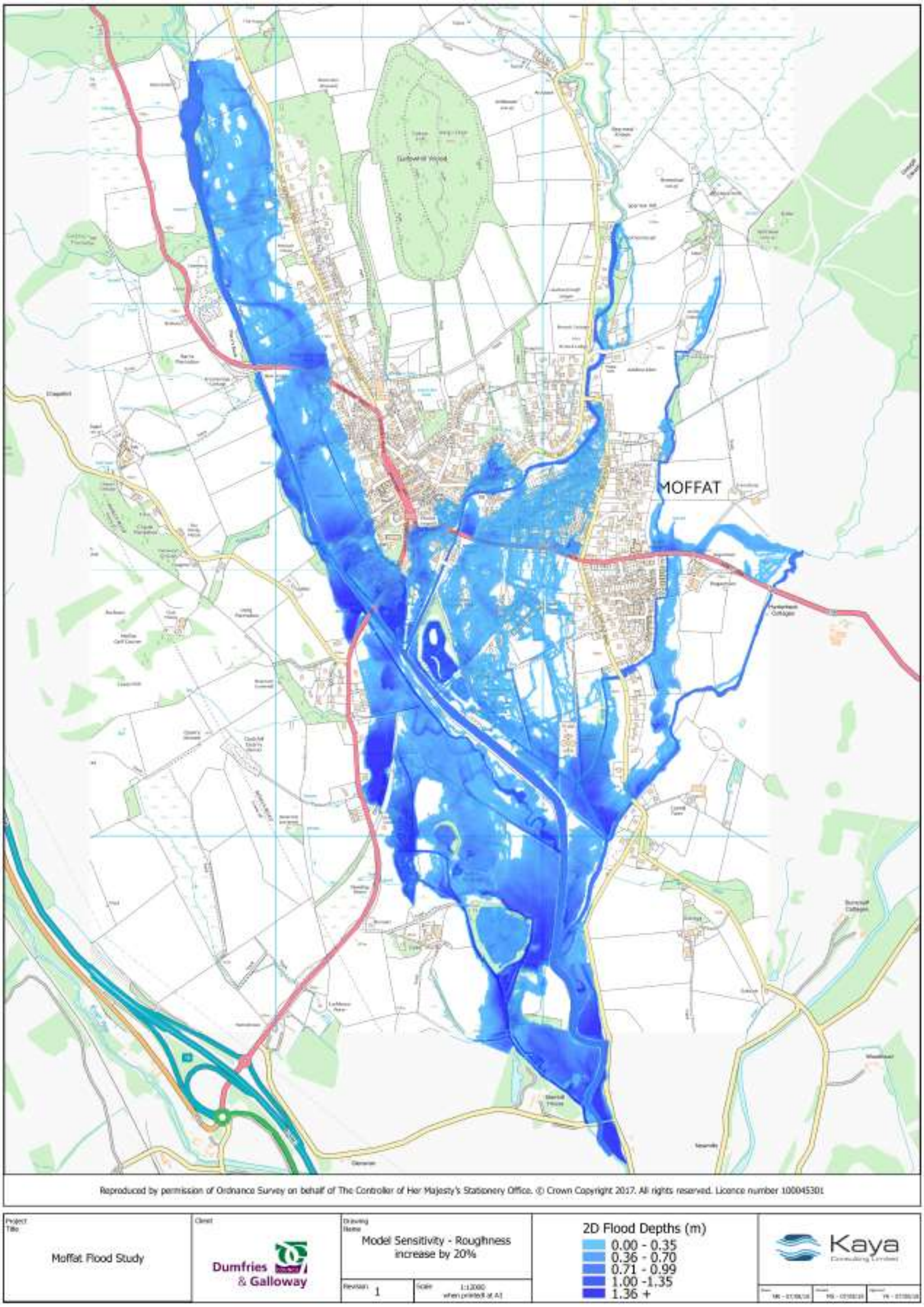


Figure 56: Predicted 200 year flood map for 20% reduction in downstream boundary slope

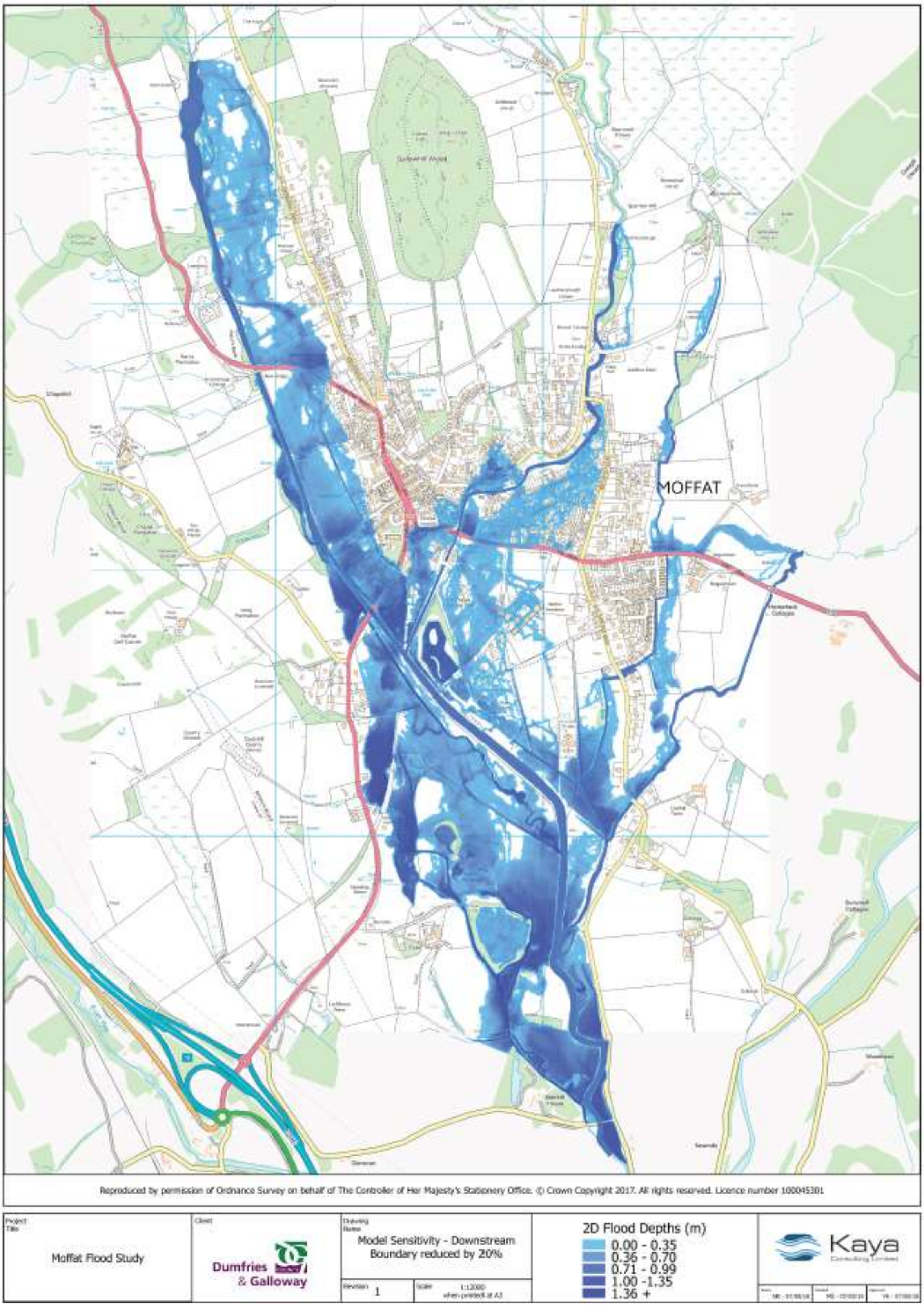


Table 30: Sensitivity Analysis Cross Section Results

Label	Change from 1 in 200 year water level (m)			
	200 year	44% increase in flows for Climate Change	20% Increase in Manning's n	20% Reduction in Downstream Boundary Slope
B86	132.45	0.30	0.11	0.00
B85B_U	132.06	0.06	-0.02	0.00
B85B_Crest	132.31	0.16	-0.04	0.00
B85A_UP_C	132.29	0.16	-0.05	0.00
B85A_UP	129.95	1.24	0.17	0.00
B85A_DS	129.47	0.53	0.23	0.00
B85_U	128.14	0.41	0.16	0.00
B85_D	127.98	0.34	0.16	0.00
B84	124.99	0.34	0.14	0.00
B83A	123.71	0.27	0.14	0.00
B83	123.17	0.20	0.12	0.00
B82	121.82	0.25	0.12	0.00
B81	119.97	0.43	0.23	0.00
BR80_U	118.84	0.39	0.16	0.00
B80	118.73	0.36	0.17	0.00
B79	118.39	0.34	0.16	0.00
B78	116.55	0.55	0.21	0.00
B77U	115.42	0.00	0.13	0.00
B77	115.38	0.27	0.15	0.00
B76	114.68	0.40	0.16	0.00
B75	113.59	0.20	0.10	0.00
B74	112.60	0.13	0.09	0.00
B73	111.99	0.14	0.08	0.00
B72	110.64	0.13	0.06	0.00
B71	109.89	0.11	0.07	0.00
B70	109.03	0.06	0.16	0.00
B69	108.64	0.06	0.05	0.00
B68	107.67	0.05	0.05	0.00
B67A	106.79	0.08	0.04	0.00
B67	106.74	0.05	0.03	0.00
B66	105.78	0.04	0.01	-0.02
B65	104.96	0.03	0.04	0.00
B64	104.50	0.04	-0.06	0.00
B64A	104.47	0.03	0.00	0.00
B63	103.39	0.02	0.00	0.00
B63A	103.36	0.03	0.00	0.00
B62	102.19	0.01	0.01	0.00
B61	101.08	0.17	0.01	0.01
B60	100.71	0.13	0.07	0.00
B60_x	100.80	0.13	0.03	0.00
C0	132.47	0.06	0.07	0.00
C1	131.81	0.09	0.01	0.00

C2	131.35	0.06	0.04	0.00
C3	128.31	0.06	0.03	0.00
C4	122.68	0.16	0.05	0.00
C5	120.48	0.25	0.04	0.00
C5a	120.41	0.30	0.00	-0.01
C6a	119.95	0.15	0.08	0.00
C6	119.93	0.12	0.07	0.00
C7	119.01	0.14	0.05	0.00
C8	116.89	0.17	0.07	0.00
C9	115.82	0.15	0.05	0.00
C10	114.53	0.25	0.09	0.00
C11	113.49	0.10	0.05	0.00
C12	113.45	0.09	0.02	0.00
C13	113.07	0.15	0.05	0.00
C14	111.73	0.22	0.11	0.00
C15	109.96	0.22	0.11	0.00
C16	109.50	0.10	0.05	0.00
C17	108.94	0.25	0.10	0.00
C18	108.03	0.16	0.06	0.00
C19	107.34	0.14	0.06	0.00
C20	106.38	0.37	0.05	0.01
C21	105.79	0.75	0.19	0.00
C21a	105.79	0.84	0.20	-0.01
C22a	105.29	0.13	0.11	0.00
C22	105.16	0.08	0.06	0.00
C23	104.93	0.08	0.05	0.00
C50	104.21	0.13	0.07	0.00
C24	103.82	0.11	0.06	0.00
C49	103.49	0.12	0.08	0.00
C48	102.70	0.11	0.09	0.00
C47	101.77	0.11	0.05	0.00
C46	101.00	0.07	0.00	0.00
C45	99.45	0.05	0.00	0.00
C45D	99.42	0.05	0.00	0.00
C44	98.03	0.02	0.00	0.00
C43	96.81	0.06	0.01	0.00
C42	96.12	0.00	0.00	0.00
C41	95.74	0.32	0.15	0.00
C40	95.74	0.32	0.15	0.00
C39U	95.73	0.33	0.15	0.00
C39	95.73	0.33	0.15	0.00
C38	95.72	0.31	0.16	0.00
C38D	95.71	0.30	0.18	0.00
C37	95.51	0.25	0.20	0.00
C37_C	95.51	0.25	0.20	0.00
F1	123.21	0.18	0.08	0.00
F2	121.09	0.15	0.07	0.00

F3	119.05	0.05	0.02	0.00
F4	117.28	0.07	0.02	0.00
F5	115.03	0.10	0.02	0.00
F6	114.66	0.14	0.02	0.00
F60	114.39	0.11	0.04	0.00
F59	111.62	0.11	0.04	0.00
F8	110.22	0.11	0.04	0.00
F58	106.65	0.11	0.03	0.00
F57	101.69	0.12	0.05	0.00
F56	99.06	0.23	0.11	0.00
F55	97.04	0.24	0.17	0.00
F54	96.39	0.29	0.10	0.00
F54D	96.30	0.12	0.08	0.00
F53	95.71	0.31	0.16	0.00
F52	95.57	0.35	0.25	0.00
F36U	95.51	0.25	0.20	0.00
F36	95.51	0.25	0.20	0.00
F35	95.11	0.29	0.18	0.00
F34	94.51	0.26	0.17	0.00
F33	94.12	0.33	0.17	0.00
A5	93.88	0.16	0.13	0.00
A5_x	94.00	0.15	0.05	0.00
A32	119.23	0.18	0.11	0.00
A31	116.92	0.14	0.05	0.00
A30	115.46	0.34	0.05	0.00
A29	114.36	0.03	0.06	0.00
A28	113.45	0.34	0.05	0.00
A27	112.08	0.06	0.09	0.00
A26	111.40	0.14	0.03	0.00
A25	109.81	0.13	0.05	0.00
A24D	108.82	0.11	0.06	0.00
A24C	108.82	0.11	0.03	0.00
A24B	108.64	0.11	0.04	0.00
A24A	108.60	0.11	0.04	0.00
A23	107.94	0.07	0.05	0.00
A22	106.84	0.04	0.03	0.00
A21	106.11	0.06	0.03	0.00
A20	104.93	0.16	0.03	0.00
A19	103.92	0.03	0.09	0.00
A18	103.21	0.16	0.10	0.00
A17	102.65	0.08	0.02	0.00
A16	102.10	0.23	0.05	0.00
A16A	101.88	0.16	0.06	0.00
A15	101.76	0.23	0.09	0.00
A14	100.64	0.17	0.18	0.00
A14i	100.80	0.13	0.03	0.00
A14_x	100.80	0.13	0.03	0.00

A13	100.24	0.11	0.09	0.00
A12	99.58	0.12	0.11	0.00
A12A	99.52	0.10	0.11	0.00
A11	99.00	0.10	0.11	0.00
A10	98.10	0.09	0.08	0.00
A9	97.04	0.06	0.04	0.00
A8	95.58	0.03	-0.02	0.00
A7	94.92	0.08	0.02	0.00
A6	94.35	0.16	0.03	0.00
A5C	94.02	0.15	0.06	0.00
A5C_x	94.00	0.15	0.05	0.00
A5C_2	94.00	0.15	0.05	0.00
A4	93.36	0.21	0.13	0.00
A3	92.86	0.38	0.20	0.00
A2	92.46	0.43	0.10	0.01
A1N	92.09	0.39	0.11	0.04
A1N_C	92.09	0.35	0.11	0.04
A_L1	92.05	0.35	0.10	0.04
A_L2	91.52	0.34	0.13	0.13