JBA consulting

Eddleston Water Hydrologic and Hydraulic Modelling of NFM: Phase 2

Report

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Tweed Forum

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Revision History

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Contract

This report describes work commissioned by Luke Comins, on behalf of the Tweed Forum, by an email dated December 2019. The Tweed Forum's representative for the contract was Luke Comins. Barry Hankin, Angus Petit, Jack Dudman, Rozy Shepherd, David Cameron and Iain Craigen of JBA Consulting carried out this work.

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Purpose

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We are grateful for the support received from the different partners in terms of data, models and advice on catchment hydrometry. We are especially grateful to the steering group panel including Luke Comins, Prof Chris Spray, Dr Andrew Black, Prof Andy Young, Fiona McLay and Debi Garft.

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Executive summary

The Tweed Forum have secured European Interreg funding to develop a whole-catchment model of Eddleston Water, one of the foremost instrumented catchments in Scotland investigating the effectiveness of nature-based measures, often referred to as Natural Flood Management (NFM). A hydrometric monitoring network of fourteen stream gauges and four recording rain gauges has been operated continuously since 2011, with two years of baseline monitoring before the main phase of NFM measures was delivered between 2013 and 2015, involving engineered-log-jams, on-line ponds, riparian planting, transverse infiltrations strips, and more, in a highly focused catchment-wide programme of measures.

The Phase 1 investigation reviewed a range of catchment information, reports and previous relevant studies and literature, combining data and modelling sufficiently accurate to take forward into the construction of a new whole catchment model for the 70km^2 catchment capable of representing the whole-system response to changes resulting from NFM. The first phase reviewed different conceptualisations and suitable software for such a model that would make best use of emerging datasets that are likely to become available for other catchments. It concluded that whilst a range of modelling packages are capable of representing NFM in the whole catchment, HEC-RAS 2D made best use of new high-resolution LiDAR data, has a flexible mesh allowing refinement where necessary, and can be exchanged between partners without licensing restrictions. It was acknowledged that whilst the current version of the software (5.07) did not include distributed hydrological losses, the next planned release (5.10) includes this functionality.

Phase 2 has taken forward the recommendations and constructed the whole catchment model with a view to providing knowledge transfer to other studies intending to incorporate NFM into risk appraisal. The integrated modelling approach helps with an understanding of the "whole system response" to a mixture of distributed NFM measures and traditional risk reduction measures, that is otherwise more difficult to understand. Representing NFM in models continues to be the subject of much on-going research, especially in terms of its effectiveness at larger scales greater than ten square kilometres, for example, there are three on-gong UKRI NERC projects[1]. In the current study, alternative representations of engineered log jams were investigated in finer detail in one of the smaller sub-catchments to support the approach used in the whole catchment model. It was found there are trade-offs between representing hydraulic structures more precisely, requiring detailed data to calibrate loss coefficients and long model run-times to ensure stability, or more simply using increased roughness which could risk overlooking more subtle changes to response. These findings have been built into a decision-tree and accompanying user-guide developed as part of this study to help others intending to represent NFM in scheme appraisal.

New hydrological approaches were used (DAYMOD / ReFH2.2 Calibration Utility) in order to estimate antecedent soil moisture conditions and estimate a realistic net-rainfall for six real high-flow events. These were used as inputs into the new whole catchment model, using the Tweed Forum data to calibrate the friction loss coefficients across the catchment. A pre-NFM (2012) and post-NFM (2015) terrain model and roughness grid were constructed that represented the changes over the period of NFM installation. The new model was compared against a range of data including the measured hydrographs at small, intermediate and whole-catchment scales, analysis of peak flow time delay along the system, and a trash line survey.

[1] https://nerc.ukri.org/research/funded/programmes/nfm/

Overall the performance was considered to be reasonable for a catchment of this size, and it has been possible to model its response to many distributed changes on the basis of the multi-scale monitoring data. A limited uncertainty analysis was also undertaken to understand the influence of distributed roughness parameter uncertainty on model predictions, which could be expanded in future research, but helps to contextualise estimates of risk-reduction using the model. Further improvements to calibration could be made in the future using distributed rainfall runoff modelling capable of continuous simulations such as ReFH 2.3 calibration utility, or models such as Dynamic Topmodel.

Nine design events were computed using ReFH2, and the pre-NFM and post-NFM scenarios were simulated with a broad-scale representation of the NFM in terms of storage, changes to bathymetry with re-meandering work, and friction based on published ranges and considering the fine-scale model results. Whilst the ReFH2 and FEH statistical method with local adjustment using Tweed Forum data gave very similar estimates of the average annual flood, there were significant differences in the growth curves. This uncertainty should be reduced as more high flow events are gauged in the catchment, and the investigation has primarily focussed on the change in response with and without NFM to different magnitude flood events. The average annual damages and damages avoided were computed following Multi-Coloured-Manual approaches leading to estimates of Present Value benefits of the NFM risk reduction that encompass fluvial and surface water risk.

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Abbreviations

AEP	Annual Exceedance Probability
API	Application Programming Interface
CEH	Centre of Ecology and Hydrology
DEM	Digital Elevation Model
DTM	Digital Terrain Model
ELJ	Engineered Log-Jam
FEH	Flood Estimation Handbook
GIS	Geographic Information Systems
GPU	Graphics Processing Unit
HEC	Hydrologic Engineering Centre (as in HEC-RAS)
HRU	Hydrological Response Unit
HYPE	Hydrological Predictions for the Environment
JBA	Jeremy Benn Associates

LiDAR	Light Detection And Ranging
LEM	Landscape Evolution Model
MCA	Multi Criteria Analysis
NERC	National Environment Research Council
NFM	Natural Flood Management
NRFA	National River Flow Archive
QMED	Median Annual Maximum Flood
RAS	River Analysis System (as in HEC-RAS)
ReFH	Revitalised Flood Hydrograph
SAC	Special Area of Conservation
SBC	Scottish Borders Council
SCS	Soil Conservation Service
SEPA	Scottish Environment Protection Agency
SRH	Sedimentation and River Hydraulics (as in SRH-2D)
SWAT	Soil and Water Assessment Tool
TBR	Tipping Bucket Raingauge
WFD	Water Framework Directive
WWF	World Wide Fund

1 Model build

1.1 Overview

The project has been a two-phased approach to provide a modelling strategy capable of testing the effectiveness of different NFM measures Eddleston Water (Figure 1-1). This report pertains to Phase 2.

- Phase 1 reviewed available data and existing models and has evaluated the most appropriate 'whole-catchment' approach to modelling the effectiveness of the NFM measures deployed and to determine the most appropriate method of assessing wider land use and tree planting schemes.
- Phase 2 aims to develop a combined hydrologic and hydraulic model of the Eddleston Water catchment before (2012) and after NFM (2015), used in conjunction with the monitoring data, to test the effectiveness of the model to represent NFM measures and develop scenario analysis for evaluating the potential effectiveness of future measures which could be used in other catchments.

The ultimate aim has been to develop a whole-catchment combined hydrological and hydraulic model can help answer the research questions for Eddleston Water, Figure 1-1, and offer advice to other studies wishing to incorporate NFM in integrated flood risk management schemes.

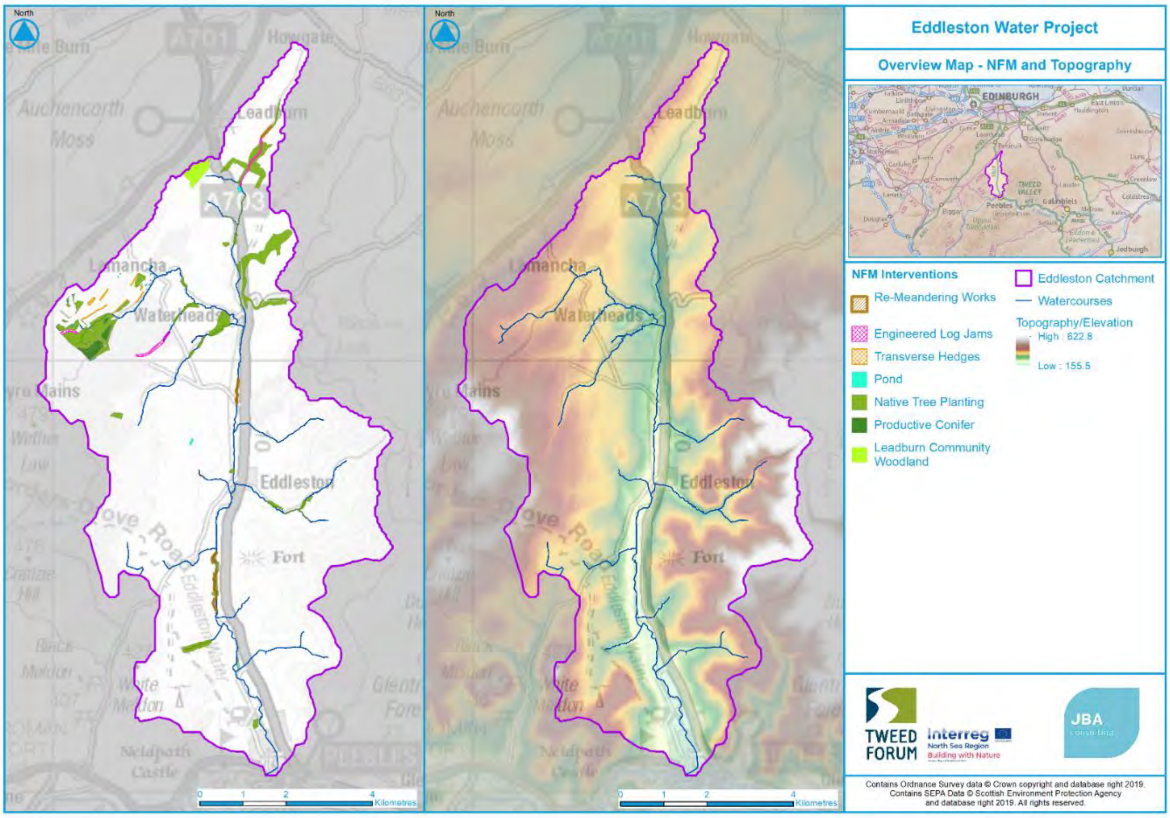

Figure 1-1 Overview of Eddleston Catchment

1.2 Summary of Phase 1 findings

Phase 1 of this study first reviewed catchment information, reports and previous studies relevant to the new model, including identifying the key models where accurate information was available for use in the new whole catchment model to be constructed in Phase 2. It included a review of the hydrometric data, which is updated here, and identified events and data to use in the calibration of the new model. A literature review was undertaken of representation of NFM in modelling, although this is rapidly changing and there have been some key new publications, including in Scotland, such as the review by Addy and Wilkinson (2019).

The Phase 1 study also reviewed the data, objectives and a range of criteria agreed by the steering group by which to decide which modelling package and conceptualisation should be used in Phase 2. Whilst many packages are capable of undertaking similar types of modelling, HEC-RAS 2D benefits from not requiring a license fee, being able to represent sub-grid topography and make the most of the detailed 0.5m DTM, which is characteristic of the emerging datasets that will make this type of approach more accurate in other catchments in the future. The overall concept for the whole catchment model has been to use a 2D-only approach (capable of mesh refinement and internal hydraulic structures), driven by net rainfall (and baseflow contributions in-channel) with hydrological losses computed using ReFH2. For comparisons with real events, initial soil moisture calibration was proposed using the DAYMOD facility and used to estimate the initial soil moisture (Cini) in the ReFH losses model. An initial basic model was setup and the flexibility of the approach was demonstrated, by way of including more details in the flexible mesh where needed or representing for example engineered log jams through direct hydraulic structures or through patches of increased friction. Finally Phase 1 provided a proposed scope for Phase 2, reproduced in the next sub-section.

1.3 Summary of Phase 2 scope

The Phase 1 report recommended that the scope for Phase 2 included construction of a whole catchment HEC-RAS 2D direct runoff with ReFH2 losses model of Eddleston Water. HEC-RAS 2D is freely licensable, so the model can be taken forward by multiple partners in the future. It has other advantages over other software, in that it is capable of estimating storage and conveyance using high-resolution terrain data (0.5m is used here), typical of recent improvements in catchment-data collection. Phase 1 also recommended the new model should incorporate bathymetry from earlier models as described in Phase 1 report, and build these into the best 'baseline, pre-NFM' and 'post NFM' terrain possible for the new study. It was agreed the model would use direct rainfall (net) with ReFH2 based losses and be calibrated against different events before and after NFM and using the new DAYMOD or ReFH2 Calibration Utility. The model should incorporate baseflows using along-reach internal flow boundaries where possible and allow possibility for inputs from ReFH2 or other rainfall-runoff model (e.g. Dynamic Topmodel) or groundwater model in the future. It was agreed that the focus would initially be on NFM influencing changes to hydraulics such as restoration schemes and log-jams, since the uncertainties are large in understanding changes to infiltration and wet canopy evaporation, and that large changes of area are needed before significant changes would be observable in the hydrographs. Whilst distributed losses cannot be represented in v5.07 of HEC-RAS 2D these will be available in the new version 5.1, so some broadscale changes to hydrological losses or smaller scale modelling or portions of the catchment was recommended. Phase 2 recommended using CORINE 2018 land use or OS open rivers and water open data and other open-datasets where possible to facilitate sharing.

A range of specific recommendations were made with regards to model proving and making best use of the Eddleston monitoring network, but a substantive steer was given to providing others with guidance on modelling and appraising NFM as part of other flood risk management schemes.

1.4 Structure of Report

- Section 2 of the report summarises additional data analysis that has been undertaken in Phase 2, including update of NFM measure spatial data, an update to the hydrometric data review and time of translation analysis.
- Section 3 provides a summary of the design hydrology and examines the differences between ReFH2 and FEH statistical methods.
- Section 4 provides the ReFH2 Cini calibration analysis for six events using DAYMOD.
- Section 5 describes the preparation and assumptions behind the terrain models. The offsets in the DTM, and how two terrain models for pre-NFM and post-NFM scenarios were compiled along with design meshes for the NFM restorations are covered.
- Section 6 summarises the whole catchment model build, including modifications to the DTM, the mesh refinement and how NFM can be represented with differing amounts of spatial detail.
- Section 7 covers a refined model of part of the catchment (Middle Burn), recommendations on representation of NFM in the broadscale model, calibration across multiple scales using the Tweed Forum hydrometry, and proving against monitoring data and trash-line survey where available.
- Section 8 explores risk reduction for NFM before and after installation using 8 design events and assesses peak flow reduction, increase in travel time and damages avoided.
- Section 9 introduces user-guidance and decision support developed through the whole process to help guide modelling of NFM for other studies.
- Section 10 summarises the findings and provides recommendations.
- Appendix A provides more details of representing small scale hydraulic features in the broad-scale model to support Section 7.
- Appendix B provides details of the economic damage calculations undertaken in Section 8.

2 Data Analysis and Design Hydrology

This section provides a summary of additional data analysis of the hydrometry and hydrology required for the model build in Section 4. Some of the datasets are spatio-temporal in nature, although Section 3 later separates the analysis into to provide more details, but the integrated nature of the catchment is brought back together in across scale calibration in Section 7.

2.1 Hydrometry

The different hydrometry sites are shown in Figure 2-1. The Phase 1 report summarised the 2015 hydrometric review, but there has subsequently been an additional review (WHS, 2019), although this did not result in significant modifications. The review undertook the annual rating review and preparation of time series data up until 2018, and whilst there were some offset changes these are after the core period analysed having large events for model calibration.

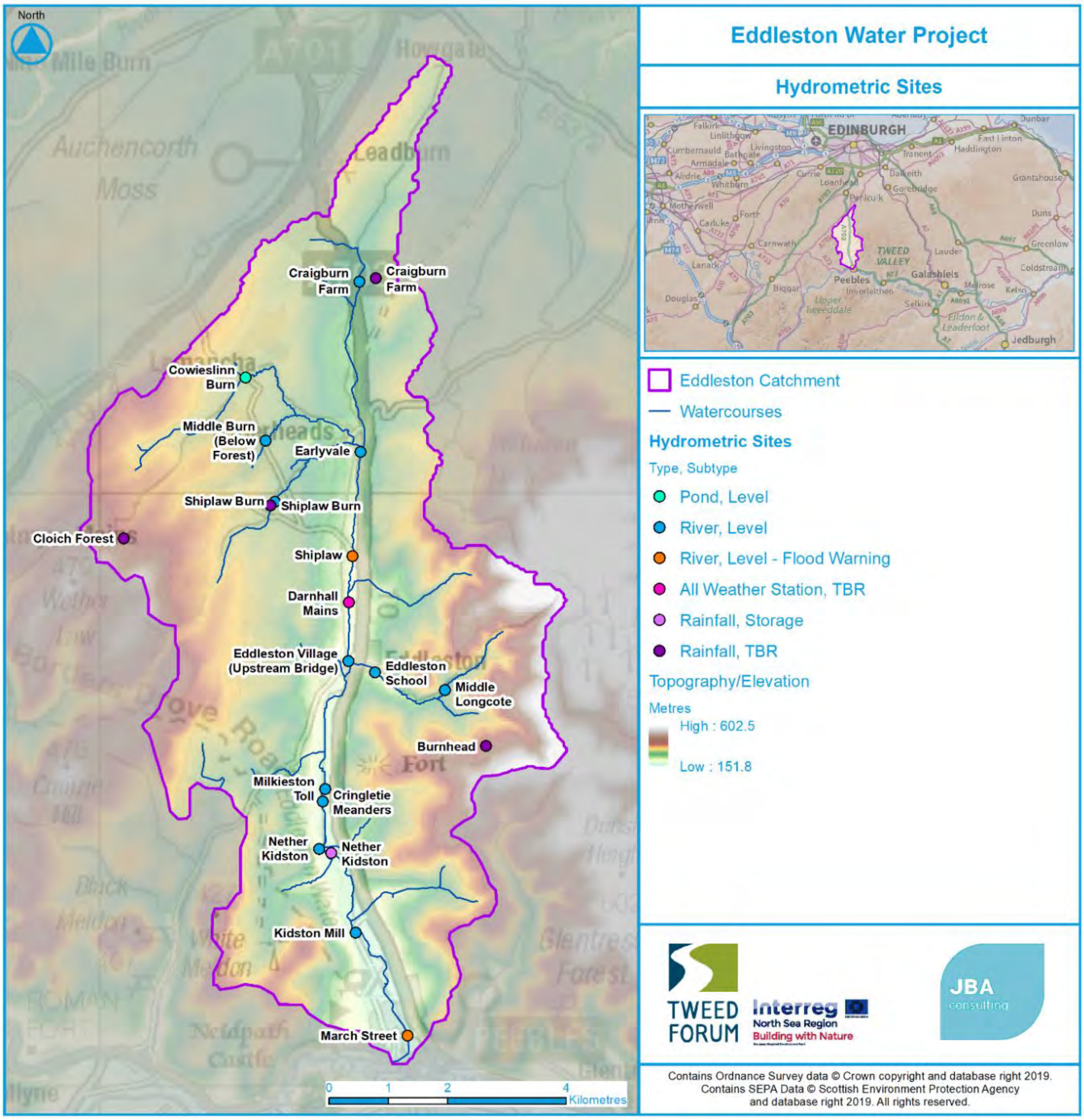

Figure 2-1 Overview of Hydrometric Network

Table 2-1 provides a summary of the recent hydrometric review. Most time series show the most significant peaks in 2012 (pre-NFM) and in 2015, for which the approximate peak flow is shown in the last column.

Table 2-1 Summary of updated hydrometric review

Gauge	Period	Data Quality	Rating	Comments	2012 peak (m3/s) 2015 peak (m3/s)
Kidston Mill	2011-date	Good, minor gaps	Pre and post- 2017 ratings required Highflows > 2m3/s estimated	Some poorly fitting gaugings not used – 2 ratings as 2017 bridgeworks	27.5 18.1
Nether Kidston	Site 1 2011-2014 Site 2 2014-date	Good, Minor gaps, but site moved 2014 due to siltation	First site/ period applied offset to correlate 2 sites		13
Eddleston Village	2011-date	Good with minor gaps. Some strange level changes at low flows	2 part rating with good fit.		9.4
Shiplaw Burn	2011-date	Good with minor gaps	High scatter potentially from control instability, many gaugings removed	Concerns over possible logger not being submerged	0.71
Middle Burn	2011-date	Good with minor gaps	High flow gauging removed – uncertainty at high flows	Large error typical of <5l/s flow range	0.59
Earlyvale	2011-date significant gaps	5months mossing from March 2017	2 part rating fits well	2012 peak slightly higher than 2015.	20 19
Craigburn	2011-date	Good with minor gaps		2012 peak slightly higher than 2015. Some diurnal oscillation at low flows	2.4 1.6

2.2 Hydrological lag and time of travel estimation

Hydrological lag and time of travel are not always straightforward, given that runoff is being delivered via surface pathways which may be more tortuous overland or by sub-surface pathways. Thus, these timings depend on the nature of the sub-catchment delivering flows to different parts of the channel network. Different rainfall events can also result in different patterns of behaviour in the response at different locations. For Eddleston Water there is known groundwater-surface water interaction on the floodplain along parts of the main river [[2]].

It should be borne in mind that it has not been possible to capture significantly high flow events, with the return period for the highest flow on record estimated between 10 and 25 years.

2.2.1 Analysis from University of Dundee

Analysis by Dr Andrew Black, University of Dundee based on 7 years of 15-minute continuous rainfall and level data, concluded the following:

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[2] http://www.bgs.ac.uk/research/groundwater/catchment/eddleston/home.html

- The NFM measures that include leaky barriers, riparian planting and on-line ponds in the headwaters and down to catchment areas of 25.6km^2 are effective in that they produce a statistically significant increase in the time of travel of up to 1 hour between pre-NFM and post-NFM situations.
- Down to a catchment area of 36.7km^2, changes of up to 1 hour are observed although with reduced precision.
- In the lower catchment, with 60-70 km^2 catchment area, the hydrological lag time post-interventions were within 10 minutes of pre-intervention values based on recent presentation at the Scottish FRM Conference [3].

These conclusions based on data are later compared with modelling outputs. The next section is based on time delay analysis of a limited number of the more significant flood peaks.

2.2.2 Analysis based on Phase 2 calculations

Table 2-2 shows the difference in timing between the peak flows for the pre-NFM (July 2012) and post-NFM (December 2015) flood events at different locations. The locations are summarised in the schematic Figure 2-2 to help visualise the network.

Table 2-2 Differences in timing pre and post NFM

Sites	2012 Time Lag (h)	2015 Time Lag (h)	Difference (h)
Craigburn Farm - Earlyvale	0.25		
Cowieslinn - Earlyvale	1	1.5	0.5
Middle Burn (Below Forest) - Earlyvale	1	2	1
Shiplaw Burn - Earlyvale	1.25		
Earlyvale - Darnhall Mains	0.5		
Darnhall Mains - Eddleston Village	0.25	0.25	0
Eddleston Village - Nether Kidston	1.25	1	-0.25
Middle Longcote - Nether Kidston	3.75	4.25	0.5
Nether Kidston - Kidston	1	3.25	2.25

[3] https://www.sniffer.org.uk/news/scotlands-flood-risk-management-conference-2020

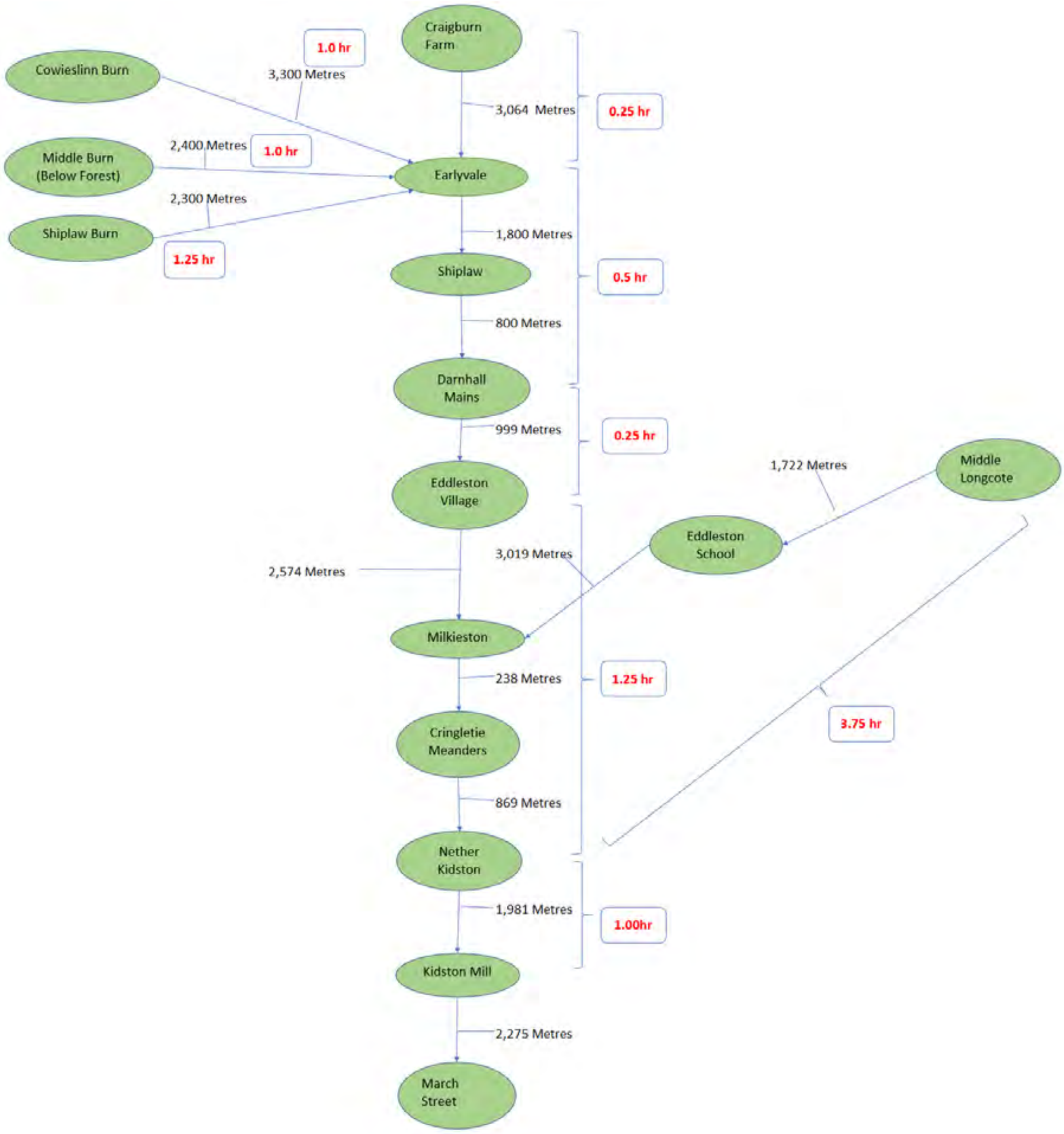

Figure 2-2 Schematic showing Network Time of Travel for July 7th 2012 (Pre-NFM travel times in red – see Table 2.2 for differences with post-NFM)

The statistical significance has been analysed by University of Dundee so further analysis has not been undertaken here, albeit to present timings for the key pre-NFM and post-NFM flood events. Analyses of this were presented by Dr Andrew Brown at the Scottish Flood risk Management Conference 2020[4], and further comparisons with modelled outputs are being considered

[4] https://www.sniffer.org.uk/floodriskmanagement2020

3 Flood Estimation Hydrology

Peebles has a long history of flooding from Eddleston Water and the Tweed, as reported in the Peebles Flood Study (MM & JBA, 2017), including specifically flooding from Eddleston Water in 1902, 1949, 1950, and 2005 with other high flow events in 2012 and 2015 and recently in March, 2019 when flood alerts [5] were issued in relation to snow melt.

This report also developed design hydrographs where the FEH Statistical approach was used for the following design events: 2, 5, 10, 25, 30, 50, 75, 100, 200 and 1000-year return periods (the same approach used in the 2017 for the Peebles Flood Study (MM & JBA, 2017)). Whilst the FEH estimates were re-evaluated here, the ReFH2 approach has been used to allow for the use for the losses model and direct calibration of antecedent soil moisture for six real events.

SEPA operate a level-only gauge on the Eddleston Water at March Street in Peebles and there is no rating, so effectively Eddleston Water has to be treated as ungauged in FEH analysis. Pooling group analysis was therefore used for the Eddleston Water just upstream of its confluence with the Tweed. A Generalised Logistic distribution was used for the growth curve and the Tweed at Peebles gauging station (station number 21003) was used as the donor for QMED (resulting in an adjusted QMED value of 18.64 m3/s). This was checked against an earlier report, for which QMED estimated as 17.05 m3/s, although this is no guarantee that the current best estimate is accurate. Additional local donor adjustment using the new data from Kidston Mill was then undertaken and strongly improves the agreement between the ReFH2 estimate of QMED as 15.08 m3/s, and FEH (local adjusted) estimate of 15.26 m3/s.

The closest downstream Tweed Forum Gauge at Kidston Mill measured the peak flow as 18.1m3/s for the 2015 event. Since there was some flooding out of bank, this suggests the peak flow was larger than QMED (using geomorphological reasoning), and that the estimates of approximately 15 m3/s are realistic. In 2012 street flooding was observed [6], but with limited property flooding, and a limited trash line survey was digitised upstream for a smaller June 2012 event that preceded the July 2012 event. The catchment descriptors for Eddleston (cd v3) are provide in Table 3-1, and the different estimates are in Table 3.2.

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5 https://www.sbalert.co.uk/da/262206/Flooding_Alert_-_Eddleston_Water.html

6 https://www.bbc.co.uk/news/uk-scotland-south-scotland-19727819

Table 3-1 Catchment Descriptors on Tweed and at base of Eddleston Water

Catchment Descriptor	Tweed at Peebles	Eddleston Water at Peebles
AREA (km^2)	696.89 adjusted (698.01 default FEH CD-ROM)	69.20
ALTBAR (m above sea level)	355	293
BFIHOST	0.517	0.535
DPLBAR (km)	25.11	10.87
FARL	0.974	0.997
FPEXT	0.0505	0.0468
FPDBAR	0.615	0.498
SAAR (mm)	1140	902
SAAR4170 (mm)	1199	938
SPRHOST (%)	37.16	34.02
URBEXT 1990	0.0019 adjusted (0.0018 default FEH CD-ROM)	0.0047 adjusted (0.0044 default FEH CD-ROM)
URBEXT 2000	0.0025 adjusted (0.0024 default FEH CD-ROM)	0.0052 adjusted (0.0050 default FEH CD-ROM)

The peak flows were determined using the FEH Statistical method as in Table 3-2, including a local adjustment using the Tweed Forum data at Kidston Mill, and compared with the ReFH2 (FEH13). There are significant differences at higher flows, so there are still uncertainties in the rarity of the events which may be reduced as further high flows data is collected.

Table 3-2 Peak flow estimates for Eddleston updated with ReFH2 (FEH13) statistical

Watercourse		Eddleston Water	Eddleston Water	Eddleston Water	Statistical Peak Flow / Rural Peak flow	**Statistical Peak Flow / "Local Adjusted" FEH**
Location		Peebles, us Tweed	Peebles, us Tweed	Peebles, us Tweed		
NGR		NT 25200 40650	NT 25200 40650	NT 25200 40650		
Method		Statistical (P)	Statistical (P)	ReFH2 (FEH13)		
Adjustments		Default (No adjustment required)	Local Adjustment using Kidston Mill 8 year record	Default (No adjustment required)		
Rainfall						
AREA (km2)		69.2	69.2	69.2		
Tp0 (h)						
Parameters		peak flow	peak flow	rural peak flow		
Units		(m^3/s)	(m^3/s)	(m^3/s)	ratio	**ratio**
AP	T (years)					
50	2	18.64	15.26	15.08	1.24	**1.01**
20	5	27.21	22.29	19.53	1.39	**1.14**
10	10	33.92	27.78	22.82	1.49	**1.22**
4	25	44.24	36.23	27.70	1.60	**1.31**
3.33	30	46.56	38.14	28.81	1.62	**1.32**
2	50	53.65	43.94	32.35	1.66	**1.36**
1.33	75	59.97	49.12	35.72	1.68	**1.38**
1	100	64.87	53.13	38.44	1.69	**1.38**
0.5	200	78.3	64.13	46.11	1.70	**1.39**
0.2	500	100.3	99.01	58.33	1.72	**1.70**
0.1	1000	120.89	120.89	68.86	1.76	**1.76**
3.33 + CC	30 + CC	61.93		38.31		
0.5 +CC	200 +CC	104.14		61.33		

In Table 3-2, although the agreement is strong between the two estimates of QMED (FEH statistical with local adjustment, and ReFH2), at higher flows the ratios of the locally adjusted FEH statistical (pink) to ReFH2 (green) are significant (shown in the last red column), increasing from 1.14 to 1.76 between the 5 year and 1000 year events, and it is considered this is in part due to the difference in growth curves for the FEH13 rainfall data that drive ReFH2 compared with the growth curves obtained from the statistical method based on flows.

The purpose of this study has been to investigate the difference in catchment response with and without NFM features for flows of different magnitudes. In time, following capture of further high flow flood events it will be possible to undertake a further local gauge correction to the FEH estimates and constrain the growth curves so that the rarity for the higher flow events is known more accurately. Ultimately there is uncertainty in the probability of the largest events on record, with FEH statistical (local adjusted) placing the peak discharge of approximately 27.5 m3/s (July 2012) at Kidston Mill with a return period of 10 years, and ReFH2 implying approximately 25 years. This uncertainty in the rarity (10-25 years) should come down as larger events are gauged with a longer record.

Understanding the absolute magnitude of the design storm was not the focus of the current study. If it is a requirement of a future study then some insights may be gained through consideration of the design hydrology estimates and flow records within neighbouring sub catchments of the River Tweed with more extensive hydrometric records.

ReFH2 (version 2.2) was used to provide the net-rainfall to drive the whole-catchment HEC-RAS 2D model, along with the introduction of an internal inflow boundary using the ReFH2 baseflow prediction – which combined with the direct runoff response gives the total runoff in the schematic in Figure 3-1.

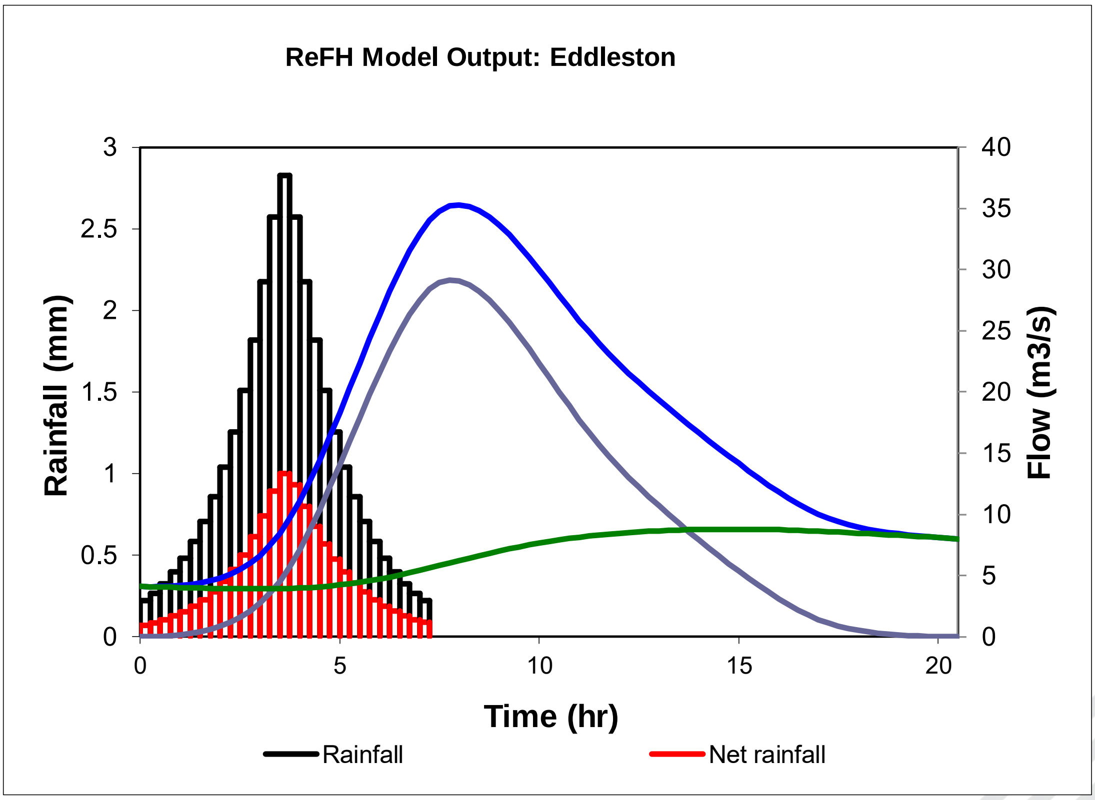

Figure 3-1 Schematic showing ReFH outputs used to drive the HEC-RAS 2D model including the net rainfall in red and the green baseflow response

The next section details how the ReFH2 Cini soil moisture calibration utility was used to estimate the initial soil moisture stores in the ReFH2 losses model and provide the net rainfall and baseflows for the event simulation.

4 Event Hydrology using DAYMOD to estimate initial soil moisture

4.1 Introduction

DAYMOD or ReFH2 calibration utility requires antecedent rainfall and evaporation data for up to two years prior to the event of interest. Since the NFM rainfall monitoring began in 2011, a few earlier years of compatible rainfall were required so the Hallmanor House daily rainfall provided by Dr Andrew Black, University of Dundee. For the period of record 2012-2015 modelled in this study, the catchment average rainfall from the Tweed Forum monitors was used, and calibration was undertaken at the furthest downstream flow gauge at Kidston Mill. There was one exception to this, for the more unusual June 2012 event, where simply very little rainfall was recorded. For this event some weighting of the Shiplaw and Craigburn TBR datasets were used to infill.

4.2 Additional Rainfall data for antecedent conditions

Antecedent rainfall was extended two years before the commencement of Eddleston monitoring in 2011, using the Hallmanor House TBR gauge. Figure 4-1 shows a double-mass plot of Hallmanor House and Tweed Forum hydrometry cumulative rainfalls, showing reasonable agreement for the period 2001-2017 (although after around 3000mm, the Kidston Mill data is 20% less than the longer record). The Hallmanor House data was used to provide the early rainfall although the difference in the later period may mean the antecedent soil moisture is over-estimated depending on which rainfall is more correct.

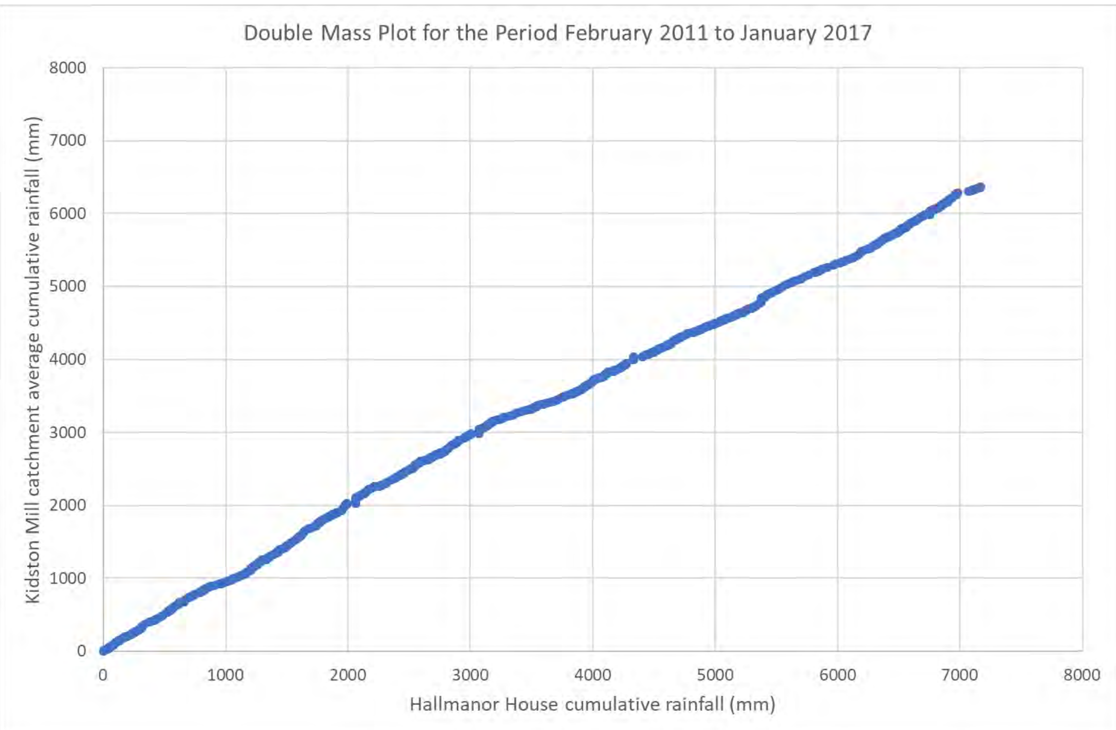

Figure 4-1 Comparing averaged rainfall for Eddleston Water with Hallmanor House TBR

The DAYMOD software also requires antecedent reference potential evaporation data and uses a sinusoid, for which the amplitude was estimated from direct measurements in the catchment [7]. The project was provided with daily estimated Evapotranspiration (ET) data (and monthly/annual summary data) from March 2011-May 2016, calculated using the Penman-Monteith method (and another actual ET method for comparison) using the R

[7] With thanks to Edinburgh University student, Leo Peskett

package Evapotranspiration. The range of annual average ET from this data was between 0.90 to 1.54 – so the default of 1.4 was used.

4.3 ReFH2 Event Calibration

DAYMOD was used to estimate the initial soil moisture stores before some key events. None of the six events studied could be classed as extreme floods and are more likely to be between 5-20% AEP (accuracy of estimation will be improved through time as more storms are captured). For each event the antecedent conditions were included for two years of data, and the baseflow model parameters BL and BR were allowed to vary.

4.3.1 June 2012 pre-NFM Calibration

The June rainfall hyetograph was estimated as a weighted average of the rainfall hyetographs observed at the Craigburn and Shiplaw gauges. Based on the measurements of rainfall it is suspected that the depth and profile of the rainfall during this event varied significantly across the event. This may not be captured in the input hyetograph and the lumped application of the ReFH model may not adequately describe the relationship between rainfall and runoff for this event. .

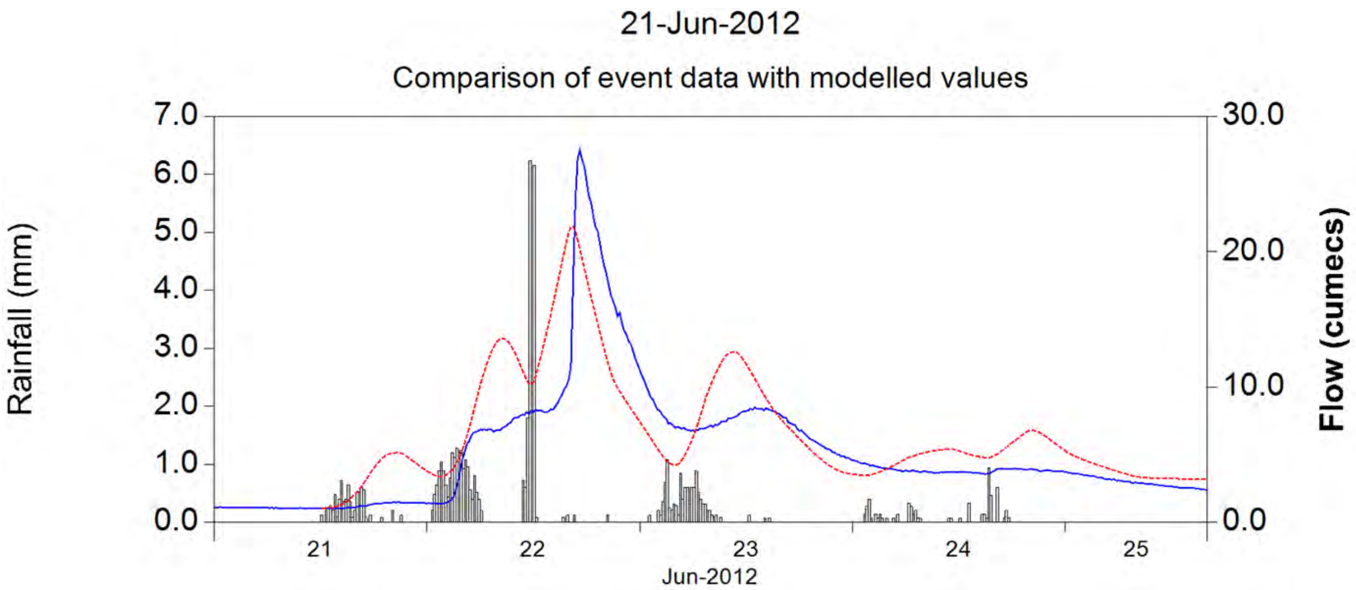

Figure 4-2 June 2012 event (pre-NFM) recorded in blue with ReFH calibration in red, with uncertain rainfall inputs (grey)

4.3.2 July 2012 pre-NFM Calibration

The hyetograph July 2012 event was better represented by the observations, and the adjustment of initial soil moisture led to a good performance (Figure 4-3).

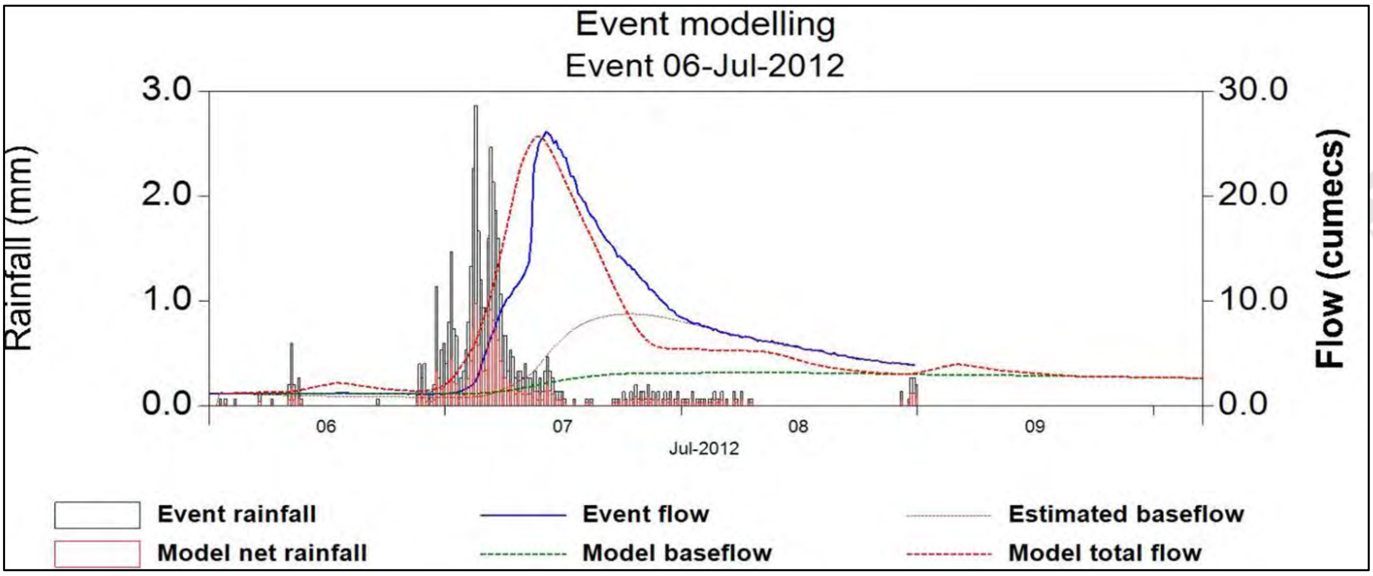

Figure 4-3 July 2012 event (pre-NFM)

4.3.3 Oct 2012 pre-NFM Calibration

For this event, the catchment has been more wetted up over a longer period of time and Figure 4-4 demonstrates a *strong pre-NFM calibration event*.

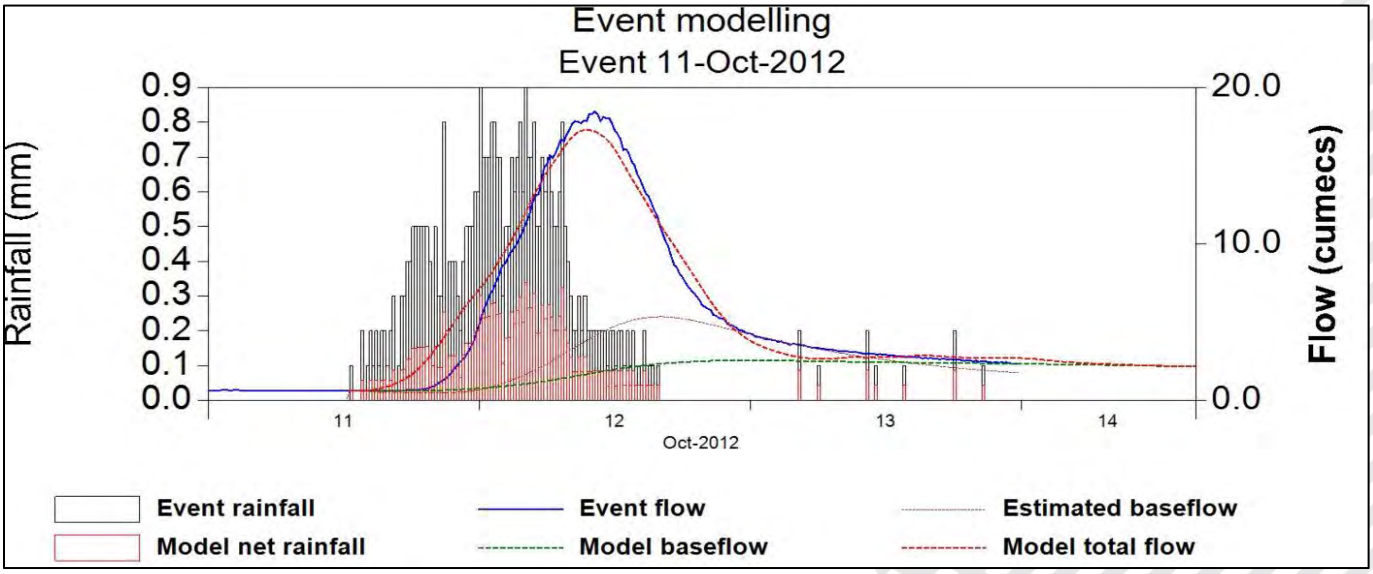

Figure 4-4 Oct 2012 event (pre-NFM) – the event chosen for pre-NFM calibration

4.3.4 Dec 2013 pre-NFM Calibration

For this event, the runoff response to the initial rainfall peak is overestimated by the model. This may be a consequence of an over estimate of Cini at the start of the event. However, as but the calibration of the peak associated with the main rainfall concentration is well matched, as shown in Figure 4-5, it is more likely that the hyetograph is an over estimate of the catchment average rainfall in the early part of the event.

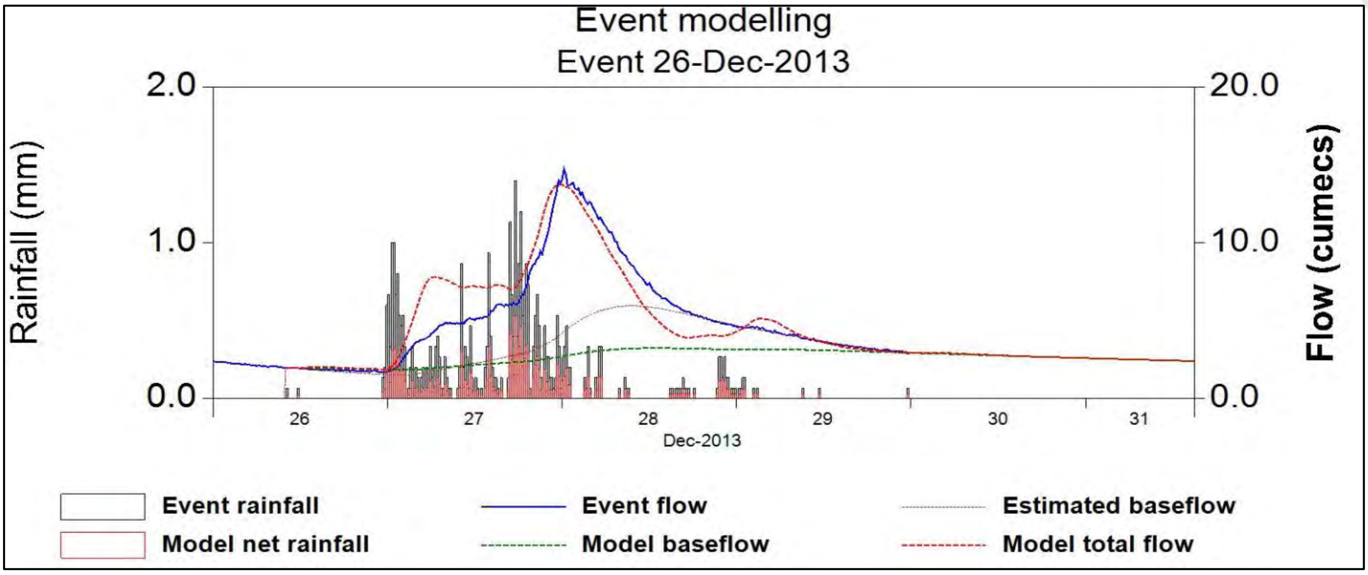

Figure 4-5 Dec 2013 event (during-NFM)

4.3.5 December 2014 event during-NFM

This event is reasonably well represented by the model (Figure 4-6), although it has not been taken forwards to model with the whole catchment model as not all the NFM was implemented at this stage.

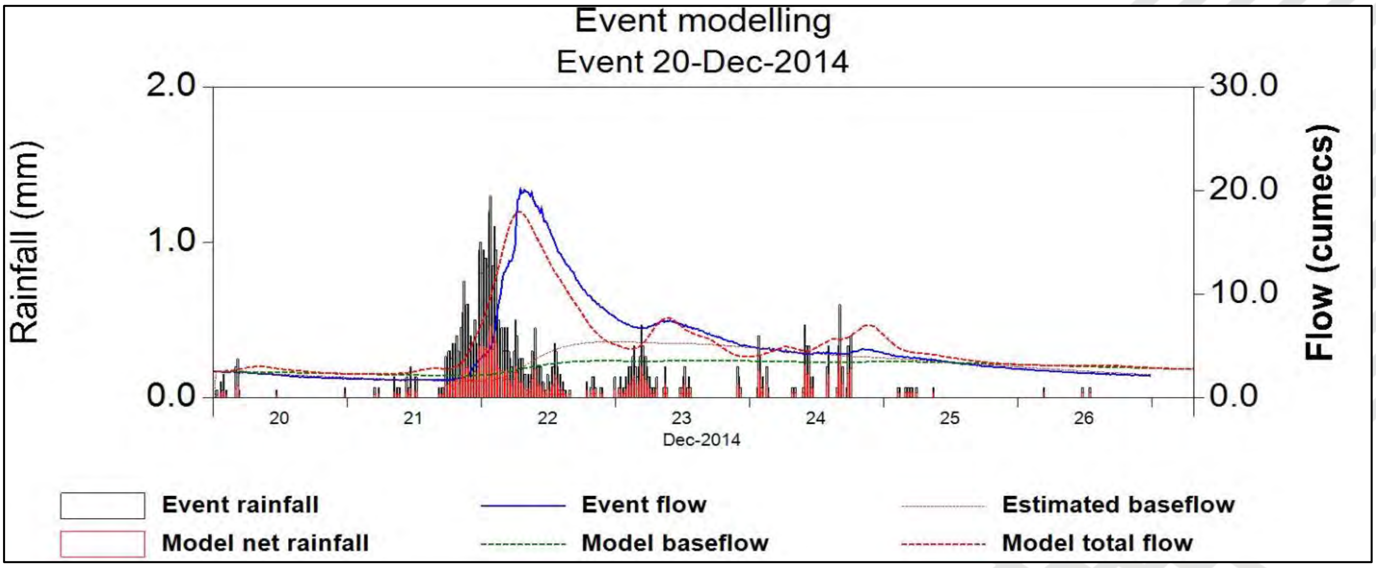

Figure 4-6 Dec 2014 event (during-NFM)

4.3.6 Dec 2015 post-NFM Calibration

The multi-peaked event is particularly challenging owing to the repeated wetting and drying, although the peaks are in reasonable agreement given the noise in the data (Figure 4-7).

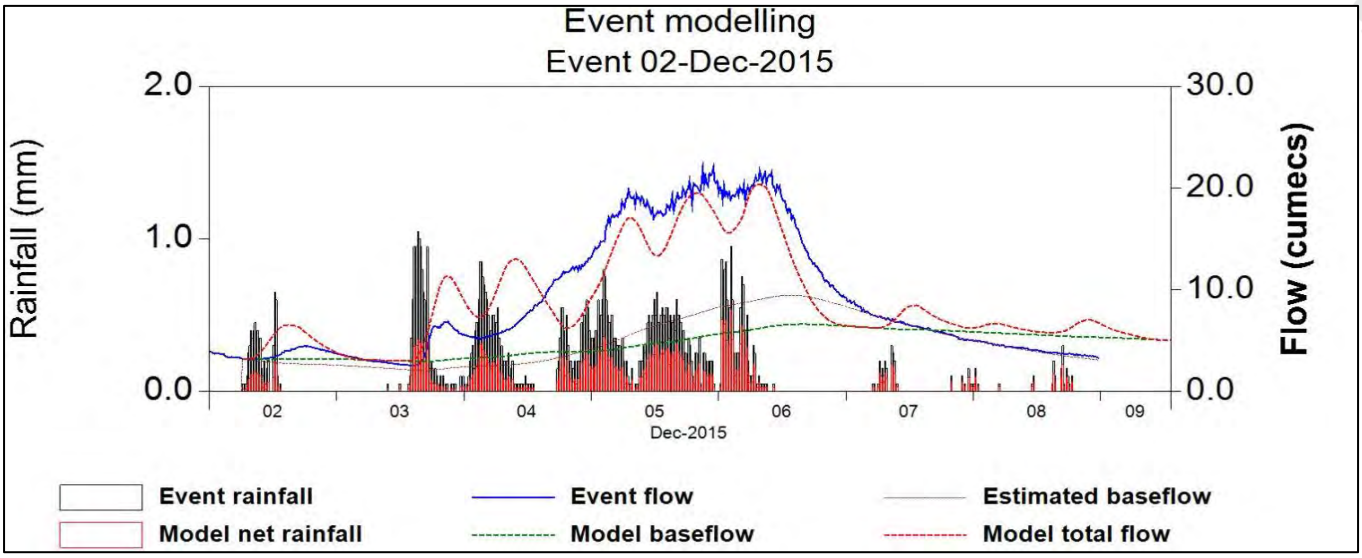

Figure 4-7 Dec 2015 Multi-peaked event – the main post-NFM event

Following analysis of the above events, some additional events were calibrated at the end of the main analysis. These included the very wet winter of 2015, the Boxing Day storm on the 26th December and Storm Ciara in February, 2020.

4.3.7 Dec 26th 2015 post-NFM Calibration

The Boxing Day storm in 2015 produced another relatively high flow event in Eddleston Water (Figure 4-8). The simulated ReFH2.2 model of fits reasonably well with the observed data, although is slightly early and overpredicted. However, since there was a lot of rainfall prior to this event, the model did not 'fit' the event data much better when trying to recalibrate the event on an individual basis.

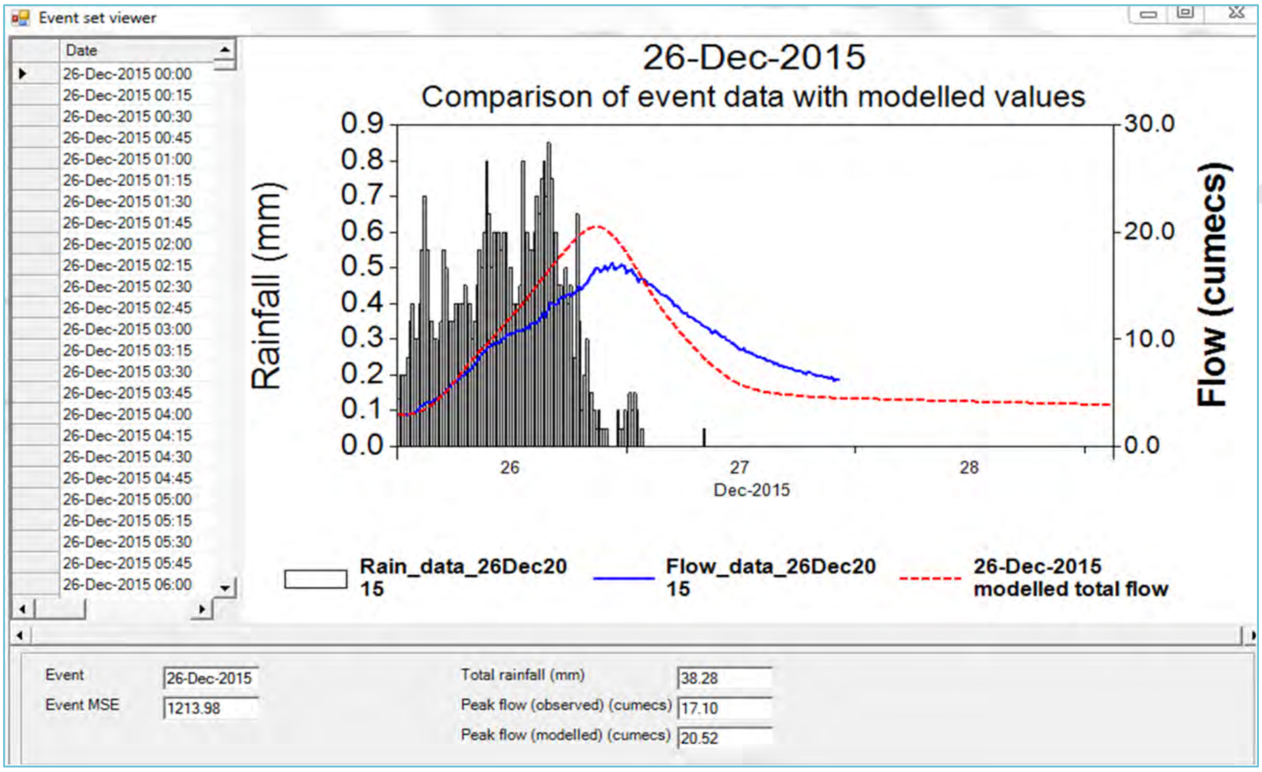

Figure 4-8 Dec 2015 Boxing Day event

4.3.8 Feb 9 2020 post-NFM Calibration

Storm Ciara in February 2020 also produced a relatively high flow event in Eddleston Water (Figure 4-9). The simulated model using the originally calibrated parameters did not fit the observed data very well, potentially due to the dry antecedent soil moisture conditions, and the recession limb being short (from the observed data). When attempting to recalibrate ReFH2.2 the parameters used for previous events had to be altered considerably, and given the trade-off against reasonable performance for the other events this original set of parameters were retained.

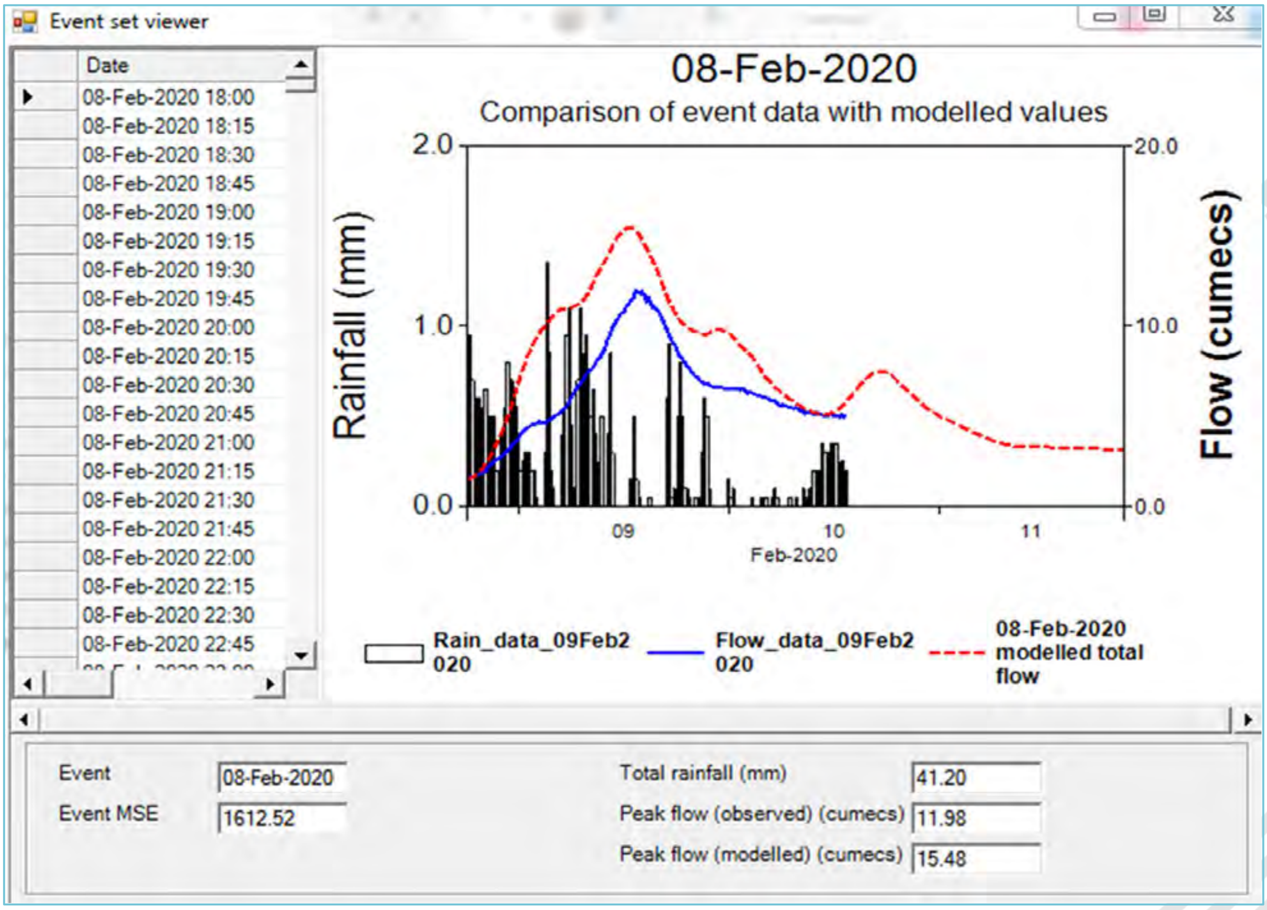

Figure 4-9 Storm Ciara - Feb 2020 Event

5 Spatial Data Analysis

5.1 Digital Terrain Models with and without NFM

The original intention here was to use the older Peebles 1m DTM (which covers from Eddleston Village to Peebles as in Figure 5-1 as a pre-NFM (2012), and the new 0.5m resolution Fugro dataset of the whole catchment for post-NFM (2015).

However, problems were encountered with the economic analysis (Section 8) as there is an offset between the Peebles DTM and higher resolution Fugro DTM. There may need to be a correction for the Fugro DTM (some LiDAR datasets have required a conic correction to the projection), shown here along the transect on Figure 5-1 in Peebles, and in Eddleston Village in Figure 5-2. These differences make absolute comparisons between models using the different DTMs unreliable, so the Fugro DTM was used for both (where there were no changes due to NFM), although it may require correcting in the future.

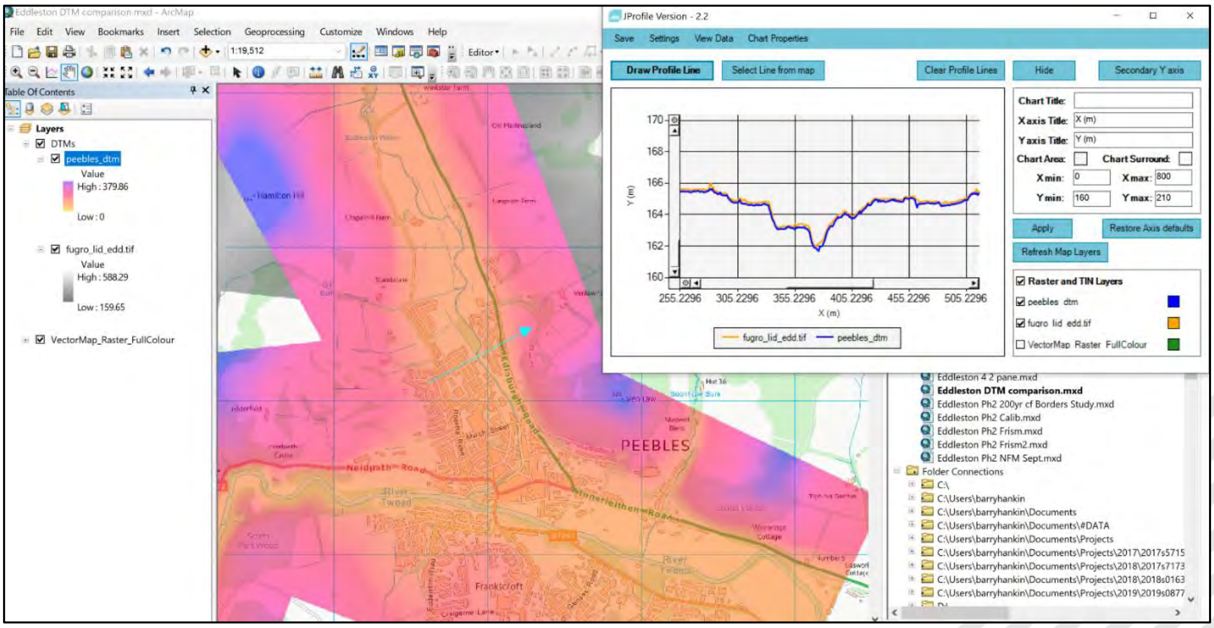

Figure 5-1. Transect through Peebles with significant differences in absolute elevation

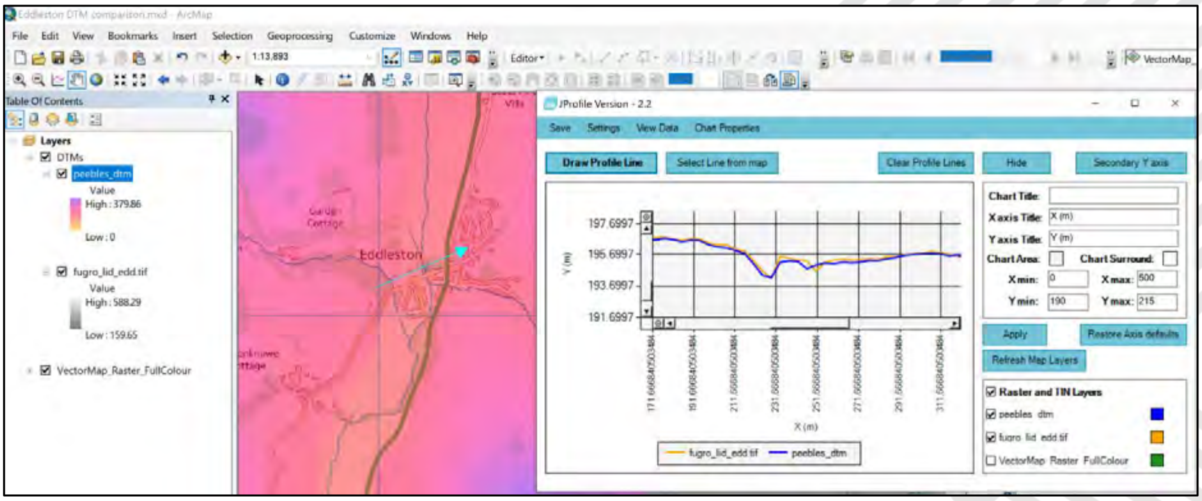

Figure 5-2. Transect through Eddleston with significant differences in absolute elevation

The Fugro DTM was flown under low flow conditions before excessive vegetation between 08/05/2016 and 14/05/2016. Figure 5-3 shows hydrographs at the Kidston Mill gauge showing low flow conditions (in the lower half of the interquartile range, by reference to neighbouring gauged catchments) good for capture of much of the channel and bathymetry.

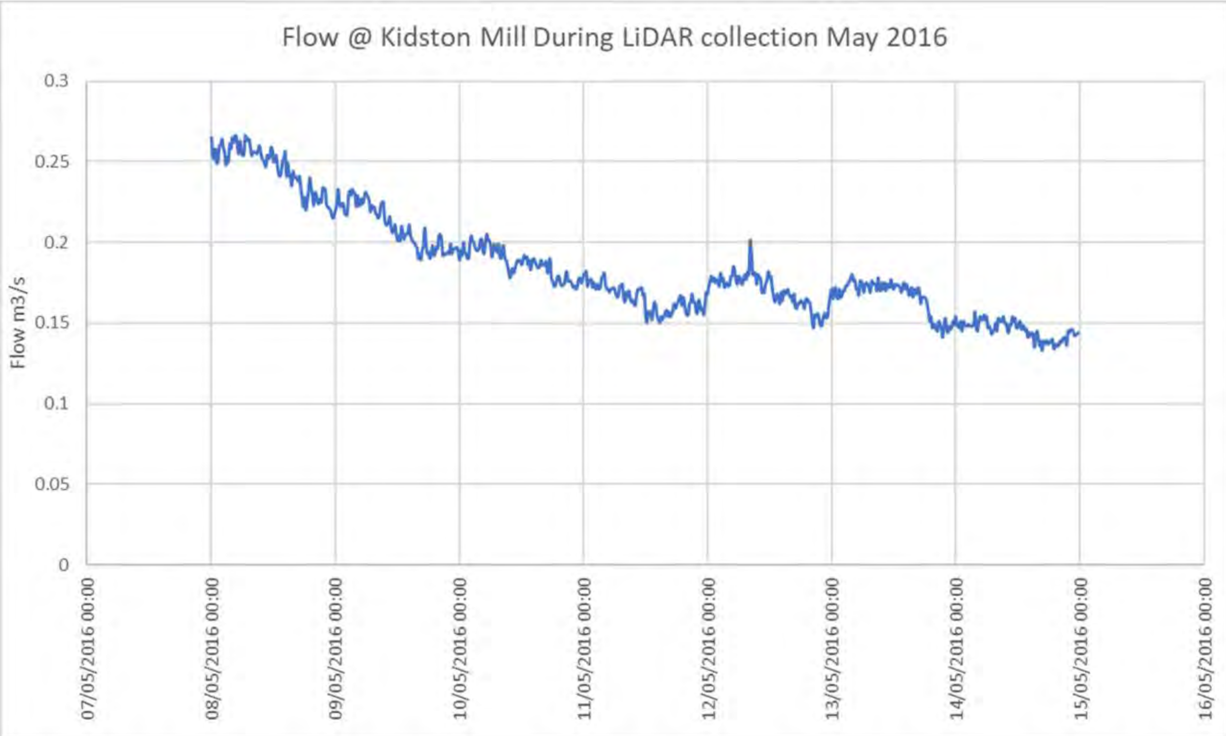

Figure 5-3. Low flows at Kidston Mill during Fugro LiDAR capture May 2016

Therefore, the Fugro DTM was used as a basis for both pre-NFM and post-NFM models wherever there was no implemented NFM which would alter the topography.

The choice had implications for estimating impacts as property thresholds available were surveyed as absolute metres above ordnance datum (MAOD). Therefore, rather than using water surface elevation (WSE) grids from HEC-RAS 2D, the depth grids were used along with a depth threshold based on when flooding might enter a house.

In summary the following DTM datasets were created:

5.1.1 Pre-NFM DTM

This DTM was developed from a composite of the best available data to represent the terrain before NFM was implemented (over period 2013-2015). This includes using the Fugro DTM (flown after this period) for areas not affected by the NFM installation.

- Fugro 0.5m DTM as base where no significant changes to topography or bathymetry
- Hatton Knowe existing model mesh
- Shiphorns existing model mesh
- Fugro DTM where available
- OS Terrain50 where required to in-fill small parts of buffered catchment

Using the Fugro DTM in the pre-NFM situation, it was important to remove any NFM features. These were filtered out of the Fugro DTM using Shiphorns model mesh, and patches on Middleburn and Craigburn where the DTM was blocked close to documented woody debris dam locations. The final version of the DTM was called DEM_4.tif.

5.1.2 Post-NFM DTM

The post-NFM DTM comprised:

- Fugro 0.5m DTM as baseline
- Kidston Ponds design mesh for post-NFM
- Hatton Knowe design mesh for post-NFM
- OS Terrain50 where required to in-fill small parts of buffered catchment

The final version was called DEM_2.tif.

5.2 Re-use of other detailed model data

The majority of models reviewed in Phase 1 included proposed designs which have since been applied to the watercourse and are represented within the latest 2016 Fugro LiDAR dataset. Table 5-1 summarises those model datasets which Phase 1 recommended to re-use via integration within the new whole-catchment model, which has been undertaken in Phase 2 (see Section 5.1). The Fugro 0.5m DTM was used where possible in preference to 1d cross-section interpolations, given its high resolution and capture during very low flows, meaning much of the bathymetry is incorporated.

Table 5-1 Recommended Model Datasets to Reuse based on Phase 1

Dataset Type	Description
Craigburn topographic survey	Collected in approximately 2014, to represent Craigburn channel bathymetry
Darnhall Mains topographic survey	Collected in approximately 2010, to represent Eddleston Water bathymetry and hydraulic structures in the vicinity of Darnhall Mains.
Eddleston topographic survey	Collected in approximately 2011, to represent Eddleston Water bathymetry and hydraulic structures within the lower reaches through Peebles. Not included as 2d DTM considered more valuable.
Hatton Knowe interpolated 2D design model mesh	Channel restoration design 2D model mesh given absence from most recent 2016 LiDAR dataset
Kidston Ponds interpolated 2D design model mesh	Enhanced pond storage design 2D model mesh given absence from most recent 2016 LiDAR dataset

Most model designs focused on local reach designs and hydraulic benefits rather than a whole-catchment assessment or detailed appraisal. As such, the existing models only improved local understanding directly associated with the interventions designed and do not assist with how these interventions integrate and respond across the whole catchment nor their magnitude of benefit at varying locations across the catchment. The existing models have simulated their interventions predominantly using design events with limited calibration and sensitivity testing of modelling parameters.

In summary, the Fugro DTM was used in preference to older 1d survey, as the along-stream interpolation from survey introduces more approximations than using the detailed 2d 0.5m LiDAR. The listed models above

5.3 Land Cover

The project aimed to use Open Data where possible to make it, and the whole catchment model, more transferable between partners. CORINE2018 has been used, which has a coarser resolution (25ha) than for example LCM2015 (0.5ha), but given the scale of the catchment and the fact the NFM measures (Figure 5-1) can be represented at much higher resolution, the CORINE2018 was considered appropriate. Given the better resolution, it would be good practice to use the higher resolution LCM2015 data in other studies if a license is available.

CORINE2018 was first clipped to the catchment boundary, and supplemented with 3 other water layers: OS OpenRivers, OS Open Water Lines (buffered by 3m), OS Open Water Areas. The water layers were then attributed with a different, new land-class.

Two layers for pre-NFM and post-NFM were derived for use with a corresponding DTM.

5.4 Spatial data of NFM Measures

The data in Figure 5-1 provides a complete inventory of the different types of NFM that have been installed until autumn 2019, although additional changes in the landscape will be made continuously[8]. There are a range of different measures from native tree-planting to engineered log-jams as described on the Tweed Forum website[7], which have been represented in different ways in the model as discussed in Sections 6 and 7.

8 https://tweedforum.org/our-work/projects/the-eddleston-water-project/

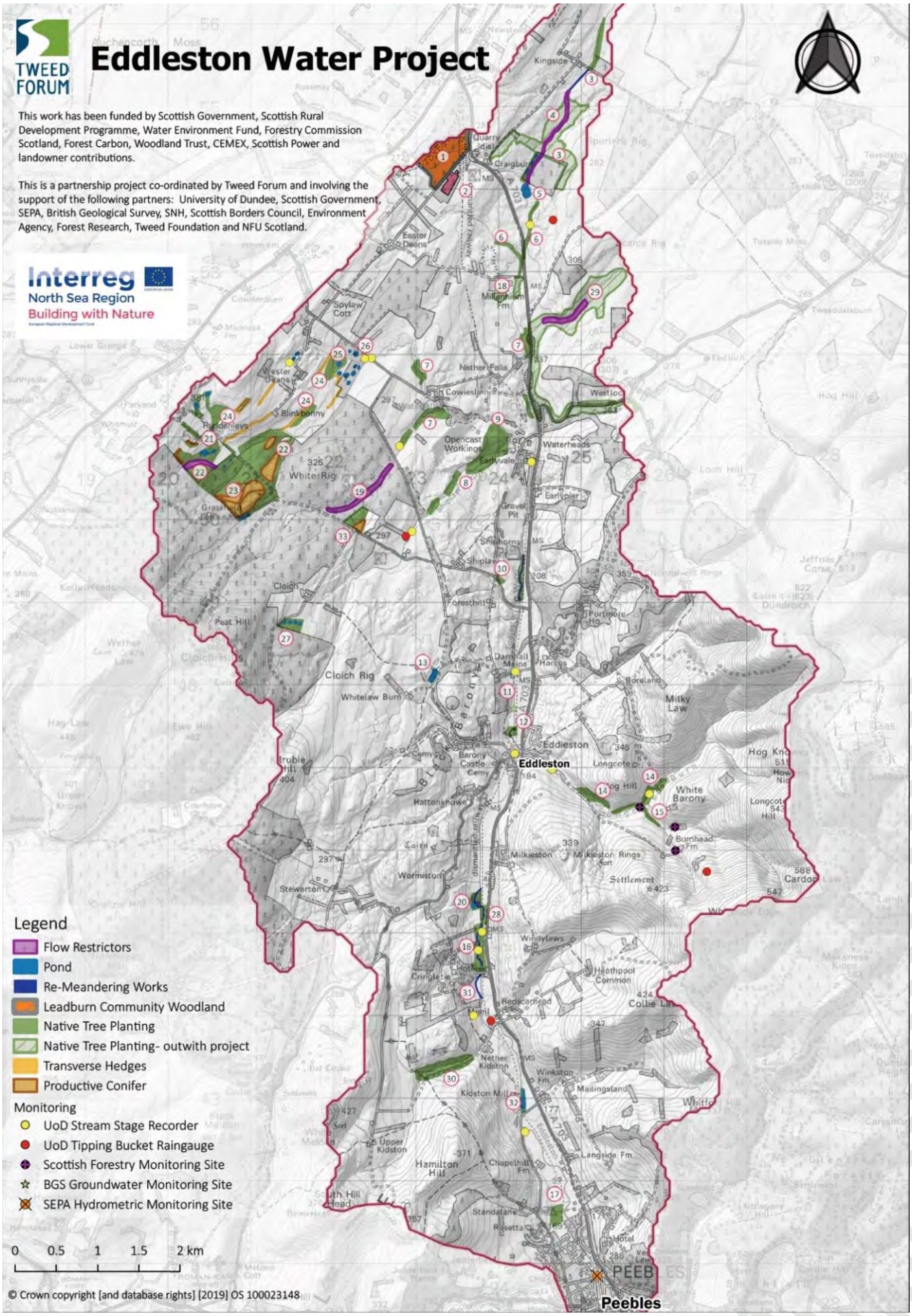

Figure 5-1 NFM measures (after the Tweed Forum 2019)

6 Whole Catchment Model Build

6.1 Introduction

A HEC-RAS 2D model based on 2D flow area was constructed as recommended following Phase 1. A key component of this has been the use of a pre-NFM DTM and post-NFM DTM. Section 5-1 discusses the problems with the offset in the DTM.

6.2 Representing NFM in the whole catchment model

Representing the effects of NFM on catchment processes (Hankin et al., 2016) has been discussed in a range of recent publications (see Hankin et al., 2017b and Addy and Wilkinson, 2019), and there has been a surge in demand for understanding of how much model parameters can or should be shifted to represent changes with national research council funding [[9]]. Often modelling studies have pre-existing models for some or all of the catchment, but in addition, parts of the catchment are lumped, so it is then difficult to conceptualise how the processes will influence the lumped response in for example an FEH rainfall-runoff boundary.

The Evidence Directory (Burgess-Gamble et al., 2018) provides a technical section on representing NFM in different models using a matrix, which also suggests different ways of incorporating changes, for example textbook changes to friction or losses. However, NFM tends to be a mixture of measures that are different in every catchment and there has not been a consistent design guide (there is the SEPA NFM Handbook, but no engineering design guide as for SUDs), so many features such as engineered log jams or leaky barriers are constructed differently. This leads to different effective porosity, roughness, weir coefficients and inlet losses, making it very difficult to standardise. A CIRIA design guide has been commissioned [[10]], so implementation may standardise in the future, but until that is the case, it becomes more difficult to generalise, and the losses across an NFM feature in the watercourse would best be derived from direct measurements to set the different coefficients and emulate the losses. In this study, there are flow gauges, although each in-stream measure is different and so the energy losses across them can only be estimated in their integrated effects on the downstream flow monitoring stations. At the large catchment scale, and in the absence of detailed information it is better to use a parsimonious number of model parameters if possible, and simply represent the integrated impact of these structures as an increase in friction (see Addy et al., 2019).

The focus in this project has been on how river restoration features that change topography and friction influence the hydraulic flow pathways, storage and conveyance across different scales. The 0.5m DTM has provided high resolution with which to study these changes, and the HEC-RAS 2D model is capable of representing the storage at this resolution, and the cell conveyance – which is especially accurate when combined with break-lines that line the cell faces with an embankment or along a river centre-line. Whilst there are approximations due to sub-surface bathymetry this has been minimised here as discussed in Section 5.1, whereby the LiDAR was flown on a day with low flow. Thus, it is possible to estimate changes in storage and flows in relation to the relatively small-scale NFM interventions and across the river restoration. To do this, the terrain data has also been supplemented with design meshes for post-restoration where necessary.

The influence of woodland is very uncertain at the small scale, and studies have shown that large percentage area of land-use change is needed before event hydrographs are modified significantly. The wet canopy evaporation changes and infiltration changes resulting from woodland have not been investigated in detail here, so only frictional changes are assessed

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[9]https://nerc.ukri.org/research/funded/programmes/nfm/

[10]https://www.ciria.org/Research/Projects_underway2/Guidance_on_natural_flood_management_RP1094.aspx

here. The current version of HEC-RAS 2D cannot represent the distributed changes in losses, although the new version, 5.1 will have this capability, including the use of a distributed hydraulic conductivity [11] (was due for release April 2020).

Global losses due to improved soil infiltration can be approximately represented by changes to the BFIHOST catchment descriptors. This is described in Section 7-7 and emulates the whole catchment response assuming soils that are in a better condition at a broad scale. Work on multiple catchments in the EA-Defra study (Defra, 2002) on the impact of agricultural soil conditions on floods, reported an estimated increase in HOST-derived standard percentage runoff between about 0.5 and 12% in the total volume of runoff entering each of the investigated rivers during storm events. Here we assume a similar change (10%) is possible through land use practices that improve soils or plant trees to increase infiltration.

A single simulation was undertaken assuming that BFIHOST improved everywhere by 10%, (this method was not used in the other scenarios). Once HEC-RAS 2D version 5.1 is released, this approach can be improved through representing distributed changes to losses, or through using a variable hydraulic conductivity, although these are also uncertain. Here the comparisons demonstrate the impact for the whole catchment, and it is instructive to compare the changes in peak flows should we improve soil storage throughout the catchment, and compare the quantum of change with what is expected from climate change.

6.3 HEC-RAS-2D model setup and testing

This Section reports on the preliminary testing of a basic HEC-RAS-2D *direct rainfall with losses model* that was set up for Eddleston Water to help demonstrate its capability and provide confidence that it meets the steering group requirements for Phase 2. JBA has previously set up a direct rainfall and losses HEC-RAS-2D models for a number of catchments, and it has been found that the accuracy is very dependent on the resolution of the DTM, and on the relative influence of baseflows. The average BFIHOST for Eddleston Water is 0.54, and in catchments where BFIHOST < 0.65, the direct runoff part of the streamflow is typically well estimated at the catchment outlet in comparison with design hydrology so this approach produces realistic model outputs. It is also possible to include internal inflow boundaries in the model and add baseflows (or total runoff) directly, to estimate the full streamflow hydrograph and assess interaction with hydraulic structures. HEC-RAS 2D is versatile in that different hydraulic structures can be included directly in the 2d mesh, and it represents sub-grid topographic detail sufficiently accurately to give confidence that many distributed NFM changes can be incorporated in the new whole-catchment model.

Figure 6-1 shows output from the HEC-RAS-2D model using a 20m resolution, 182,000 cells, diffusion wave solution (full momentum solver also available). This illustrates how the software can use a relatively coarse numerical grid, whilst handling the sub-grid 0.5m resolution Fugro DTM, permitting the generation of a high definition flood map with impacts or changes to impacts taking into account NFM. Additional time has then been spent adding 'break-lines' in the mesh to prevent unrealistic flow connectivity between cells separated by e.g. major road embankments (see Figure 6-3).

[11]https://www.sedhyd.org/2019/openconf/modules/request.php?module=oc_program&action=view.php&id=32&file=1/32.pdf

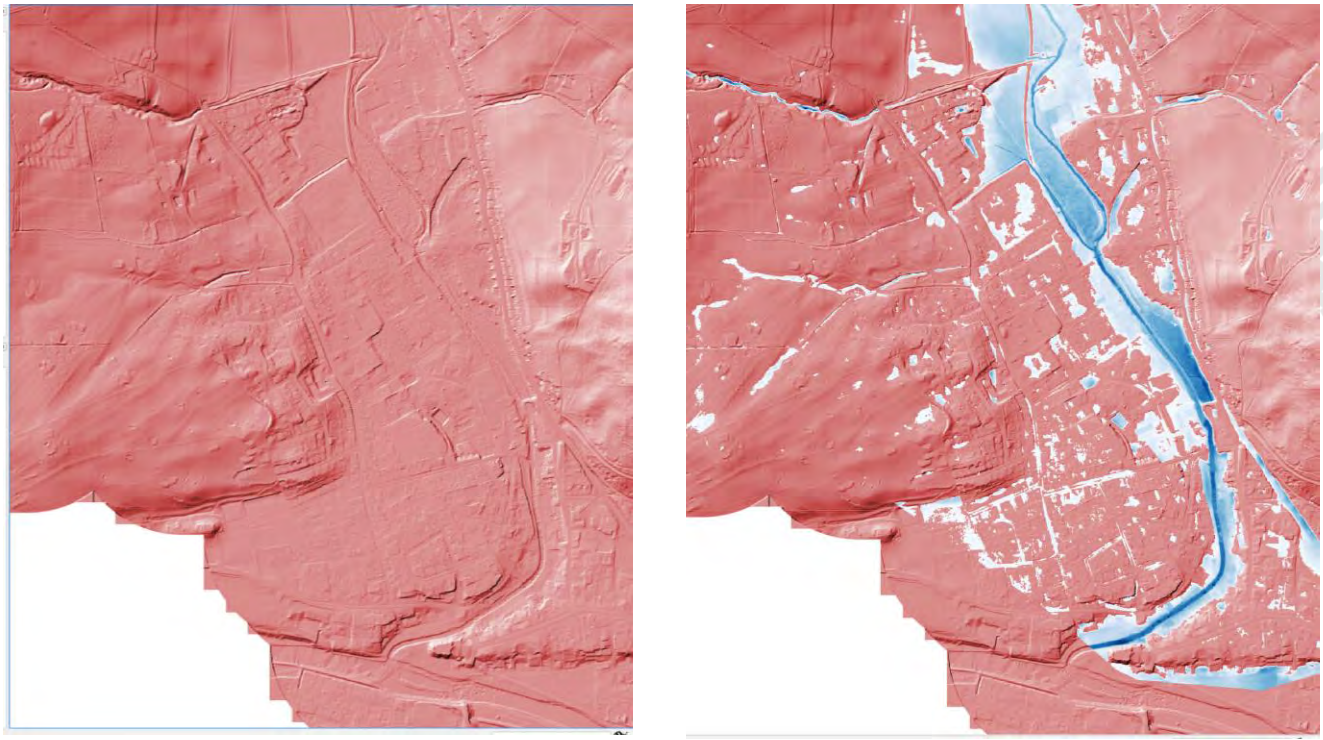

Figure 6-1 Detailed LiDAR and demonstration of HEC-RAS 2D for Eddleston Water

Following some initial simulations, water was found to back up where there is an artificial barrier in the DTM, so following broadscale surface water mapping approaches, 'cut-throughs' were added (Figure 6-2) to ensure flow pathway connectivity. These can be replaced with culvert units for greater accuracy, although simple flow pathways are used here.

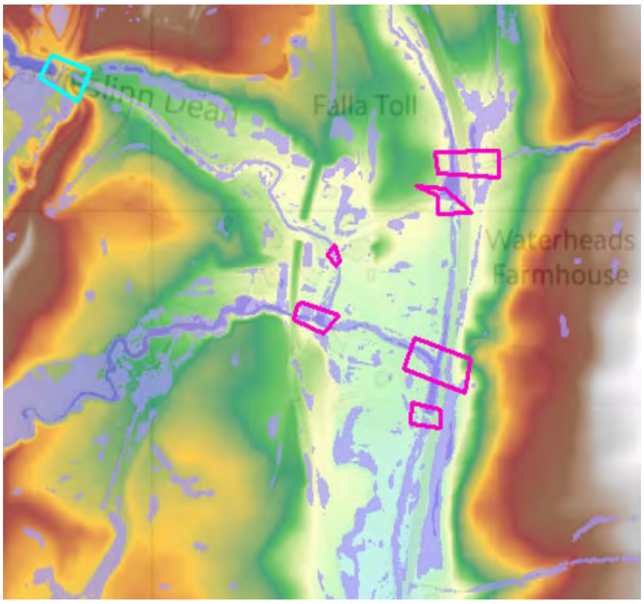

Figure 6-2 Editing of cut-throughs in DTMs

6.4 Mesh and break-lines

Figure 6-3 shows how the mesh has been refined around major embankments and channels where more detail is required. HEC-RAS 2D uses sub-grid topography (0.5m LiDAR) to compute storage versus level and conveyance versus level tables that are then used in the numeric solution. The conveyance tables are across cell faces, so for areas where there are significant embankments (or areas of convexity) a break-line along the apex will ensure there is no leakage until the embankment height is overtopped. These have only been included for some significant embankments, along with break-lines along the main channel to ensure the flows are perpendicular to the cell faces in direction of greatest flow, and to ensure that the bed roughness can be properly represented. A transect of the elevation of each of these adjusted mesh faces then appears like a cross section – in other words the model is using a large number of cross sections much like in a surveyed situation but spaced every 20m.

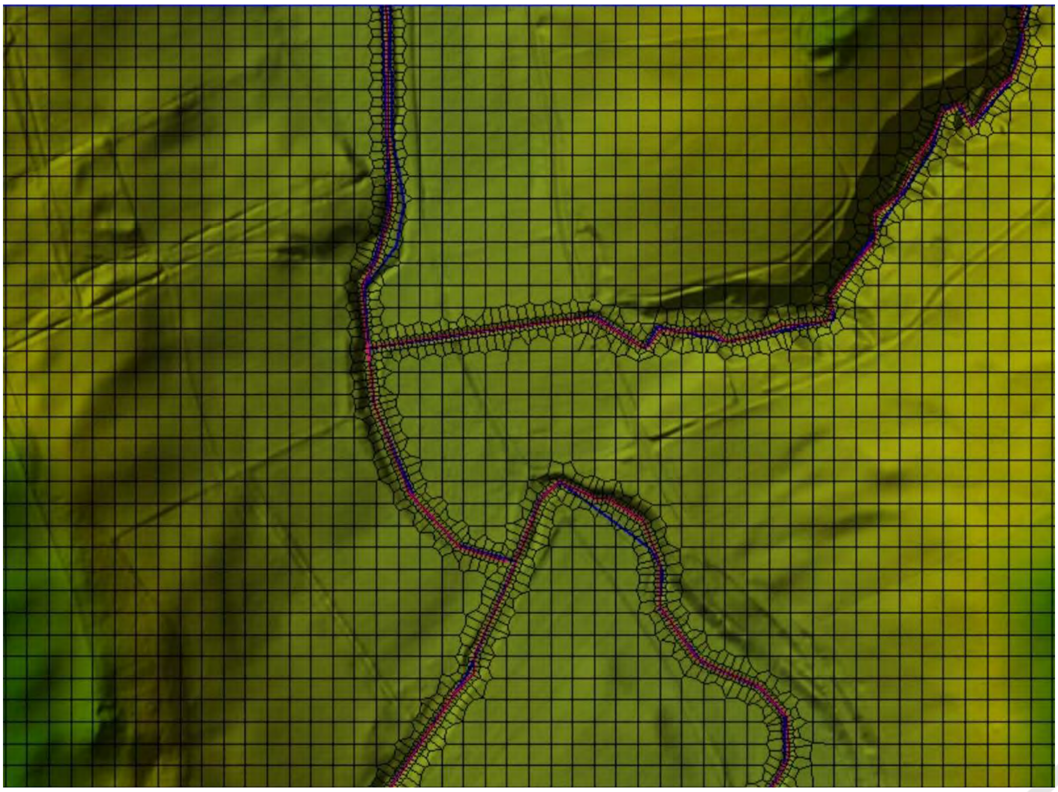

Figure 6-3 Mesh refinement

6.5 Boundary conditions

The downstream boundary was set using a normal depth condition – estimating the slope from repeated sampling of the DTM perpendicular to the final cross section, S = 0.002. If the flooding mechanism in parts of Peebles is a backwater effect from the larger river Tweed this will not be captured in the modelling here, and further analysis would be required to, for example, adjust damages derived in later sections having altered the boundary conditions.

For the initial simulations, a 2d flow area was driven by a precipitation boundary over the whole mesh using estimated net rainfall. Further into the calibration process, the ReFH2 baseflows were also included as a direct inflow distributed along the main stem of the channel.

6.6 Roughness

The basic Manning's roughness grid used in this model was made using CORINE 2018 land classes, with a channel roughness of 0.04, although this was increased during calibration to provide better agreement with the real events to 0.055 and also across different land-types (See Table 6-1). This is within the range of values typically used for broadscale modelling, and suited to the larger 20m cells used to represent a large part of the floodplain (for example, values as high as 0.1 have been used in the creation of broadscale flood maps in the UK). The land cover was based on a composite raster made from OS OpenData comprising OS Open Rivers, Open Water Lines and Water Areas. These three feature datasets combined, form a good approximation to the Detailed River Network and have the advantage of being OpenData, so the GIS data can be shared.

Table 6-1 provides the values that were used in the final design flow simulations although some Monte-Carlo simulations exploring the influence of the uncertainties in these parameters were undertaken later in the analysis (see section 7.4.1) estimate the uncertainty in the predictions.

The key calibration events (October 2012 and December 2015) were undertaken in autumn / winter so are seasonally consistent but due to vegetation the roughness may need upward adjustment for new summer storms.

Table 6-1 Roughness calibration for broadscale model

Land covers	Calibrated Mannings 'n' (or value based on literature)
Broad-leaved forest	0.1
Coniferous forest	0.1
Discontinuous urban fabric	0.025
Green urban areas	0.03
Mineral extraction sites	0.055
Mixed forest	0.1
Moors and heathland	0.07
Natural grassland	0.055
Non-irrigated arable land	0.055
Pastures	0.055
Peat bogs	0.065
Sport and leisure facilities	0.03
Transitional woodland shrub	0.1
Water / waterbodies	0.055
Engineered log-jams	0.2
Community woodland	0.1
Transverse hedgerows	0.15
ponds	0.055
Re-meandering works	0.075

7 Model proving and representing NFM

7.1 Introduction

This section uses available data to compare the calibrated model with event data for pre-NFM and post-NFM scenarios at different scales. It also discusses how different NFM features can be represented and how that influences model stability, runtime and accuracy. For model comparison, matching the observed hydrographs at different scales is important, although the key comparisons were made at the flow monitoring gauge furthest downstream at Kidston Mill. In addition, the shape of the hydrographs, the peak flow and timing of peak flow are important. For one of the events a post-event trash line survey was available, so this was compared.

7.2 Event Modelling

The calibrated event net rainfall profiles from the analysis presented in Section 4 were used to drive the whole catchment model for each event. The June event has uncertain rainfall inputs, and the July flood peak was over estimated, so the October 2012 event, which followed a period of wetting up has been used as the pre-NFM calibration event. The other two events were considered unusual and therefore not used in calibration, although the June 2012 event was the only event with a trash-line survey, so the depth grid was exported and compared in the following section.

7.2.1 June 2012

The rainfall for this event which was known to have an unevenly distributed rainfall that was not captured well by the Eddleston hydrometry, so this was supplemented with other gauges. The peak flow was over-predicted by 16% using the HEC-RAS 2D model and it is considered there is a lot of uncertainty due to input errors (Figure 7-1). However, this was the only event with a trash-line survey post-flood, so despite the poor fit, the depth grid was exported and is shown in Figure 7-2 in comparison to the survey.

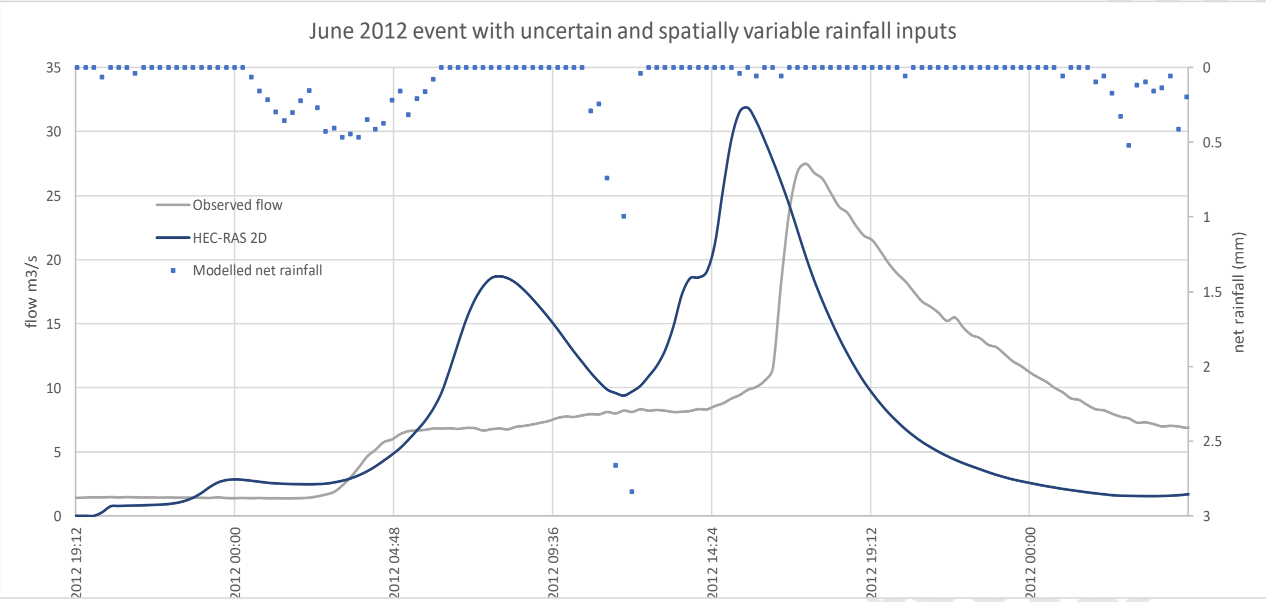

Figure 7-1 June 2012 event with large input-errors and 16% over-prediction

A favourable comparison was made, albeit the flooding is slightly over-predicted (to be expected given the over-predicted peak) for an area of the right bank where a post-event trash-line was surveyed. The outline can be seen overlaid in Figure 7-2 (see also Figure 7-8 further below) which is a pseudo-3d image of the HEC-RAS 2D model outputs overlaid on the DTM. The area on the right of the image towards Eddleston village was not surveyed, although it is reported there was water in this area.

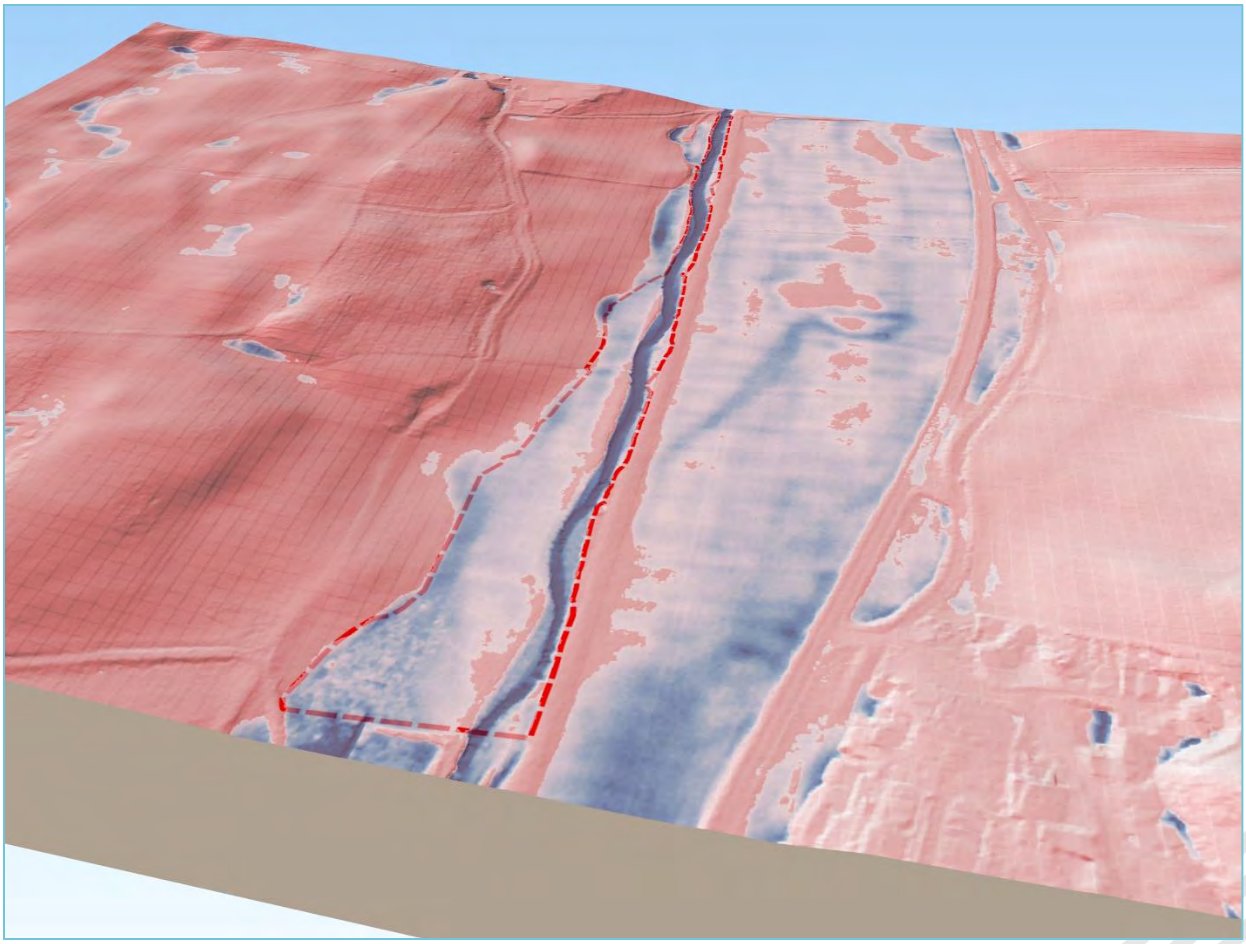

Figure 7-2 Comparison of HEC-RAS 2D simulation of June 2012 event with some trash-line survey evidence (Looking upstream from Eddleston village).

7.2.2 July 2012

This summer event following the June event was also initially over-predicted and indicated that the timing and sensitivity to the rainfall are important. Figure 7-3 shows the HEC-RAS 2D over-prediction in brown with the observed flow in black (dashed) and the ReFH2 modelled flow with baseflow in blue, or without in yellow. The light-blue series shows the modelled baseflow, which is also allowed to be adjusted using DAYMOD to give the fitted baseflow in green.

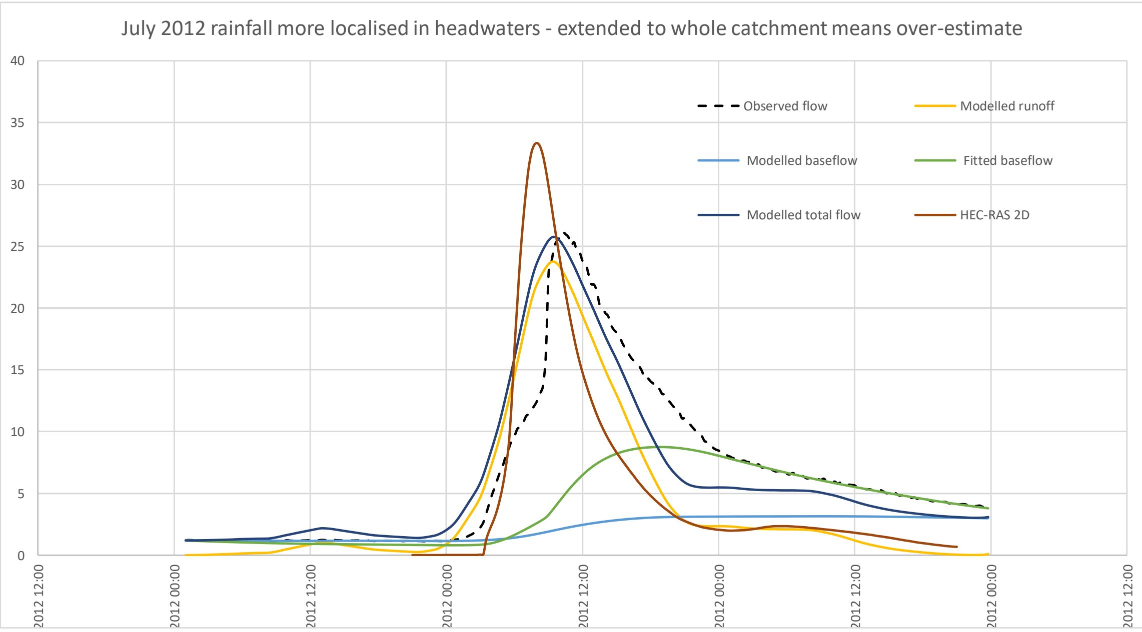

Figure 7-3 July 2012 simulation using ReFH2 calibrated net rainfall

7.2.3 Oct 2012

This event occurred after wetting up over a longer period and was thought to be more uniform over the catchment, so makes a better testing event of similar magnitude to assess model performance against in general. Adding the baseflow (represented as an orange line in Figure 7-4) improved the timing and peak flow correspondence.

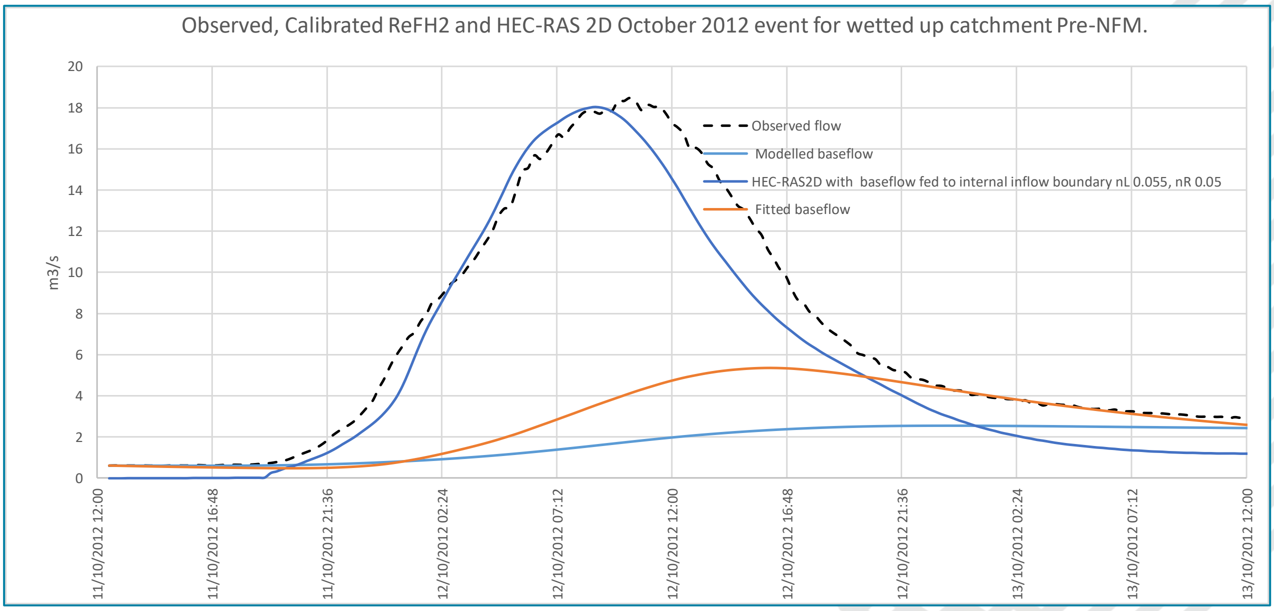

Figure 7-4 Oct 2012 simulation using ReFH2 calibrated net rainfall

7.2.4 December 2015

This event (Figure 7-5) was the only truly post-NFM event (the Dec 2014 event was before all NFM work was completed) that was available at the time of this investigation, but is challenging because of the multiple peaks. The main behaviour is captured, and it would be possible to adjust the ReFH2 baseflow such that the peak flows are less over-estimated.

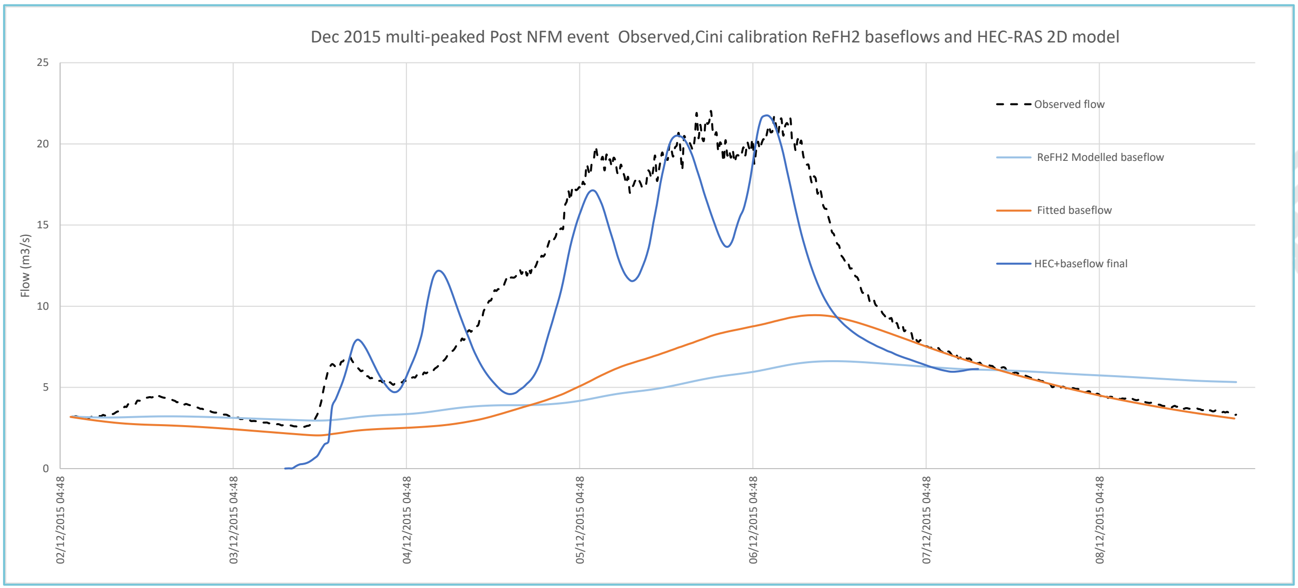

Figure 7-5 Dec 2015 simulation using ReFH2 calibrated net rainfall with baseflow

7.2.5 Post calibration events (Boxing Day 2015 and Storm Ciara 2020)

Following the calibrations described above, some further work was undertaken to understand the model performance for other events. The ReFH 2.2 calibration was described in Sections 4.3.7 and 4.3.8. These new storms were only reasonably well predicted potentially due to soil moisture conditions and unevenly distributed rainfall, so were not considered useful for further comparative analysis between with and without NFM. The analysis does potentially point to the need for improved distributed hydrology and or continuous simulation (using for example ReFH 2.3), which could be achieved through using a distributed losses approach (as recommended once HEC-RAS v 5.10 becomes available) or through the use of a distributed rainfall-runoff model such as Dynamic Topmodel (see method in Hankin et al., 2019).

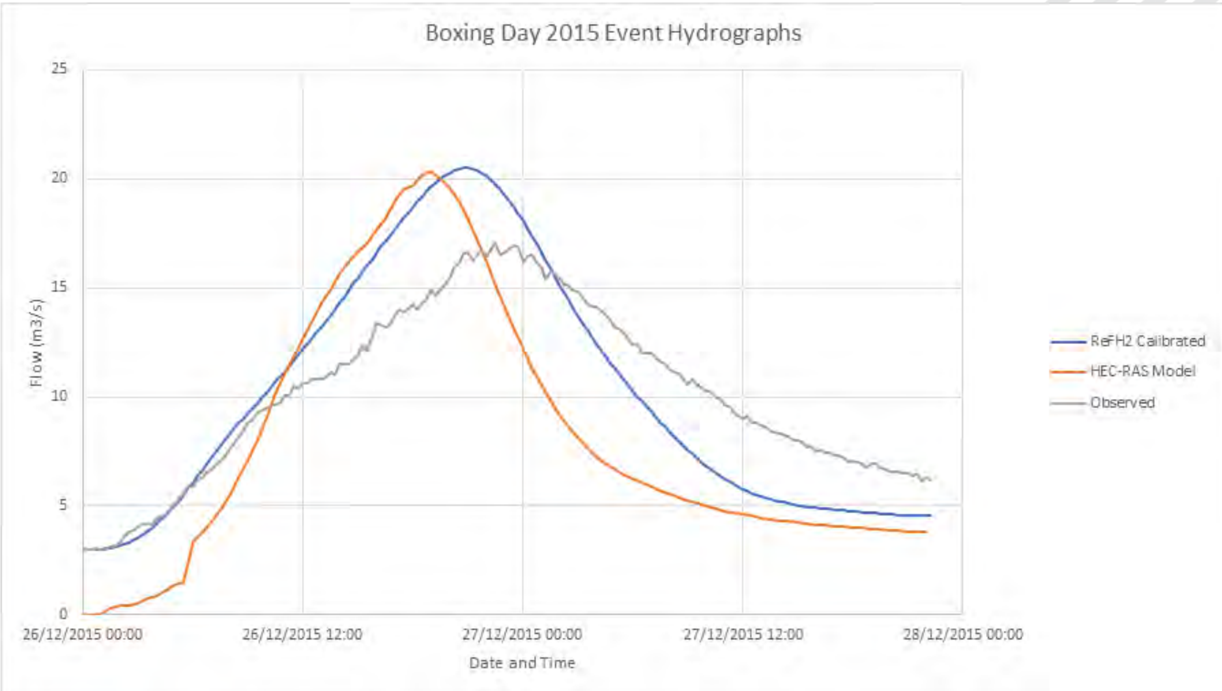

Figure 7-6 Boxing Day 2015 simulation using ReFH2 calibrated net rainfall with baseflow

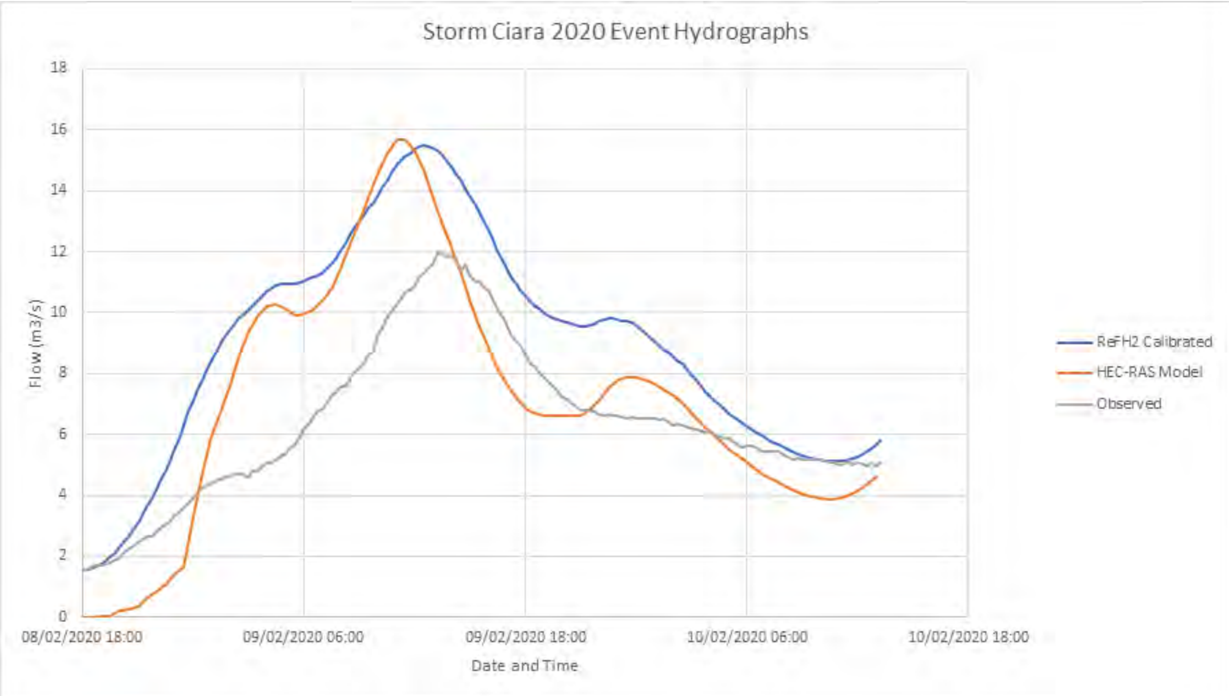

Figure 7-7 Storm Ciara, Feb 2020 simulation using ReFH2 calibrated net rainfall with baseflow

7.3 Testing NFM Representation in the Model

There are different ways of representing NFM in a hydraulic model (for example see Addy and Wilkinson, 2019, Hankin et al., 2017b), specifically the engineered log-jams (Figure 7-8) that have been implemented as measures to encourage storage of flood water on the floodplain in the upper catchment. Logistically it is difficult to incorporate the details of all the structures in a large-scale model, not least because the representation of flows over and through porous barriers introduces the need for finer detail, smaller time steps and additional calibration coefficients. This section explores different representations of over 30 ELJ's in a reduced domain HEC-RAS 2D model of Middle Burn constructed especially for this purpose. Constructing a sub-model of a smaller catchment is a useful technique to explore risk in more detail. The two methods considered are:

1) Use of an embedded hydraulic structure in the 2d mesh comprising an embankment with rectangular culvert. Flows can pass through the culvert designed to be the same shape as the orifice under the log-jam, and over the embankment as a weir flow.
2) Use of increase friction to represent the overall head loss due to the ELJ structure at a larger scale

Figure 7-8 Photo of leaky barrier Middle Burn

Figure 7-9 shows how in the fine-scale Middle Burn model, each of the ELJ's has been represented using hydraulic structures directly in the mesh. The gaps underneath were estimated from photographs (they were mostly set 1m wide and 0.2m high). Each barrier has a box culvert with inlet loss coefficient (0.4) and Manning's roughness of (0.1) and a relatively low weir efficiency over the top (1.5). The porosity of the structure cannot be changed, so the gap underneath represents all the flow through and under the structure. The mesh was refined around these structures and simulations were undertaken with and without them in place.

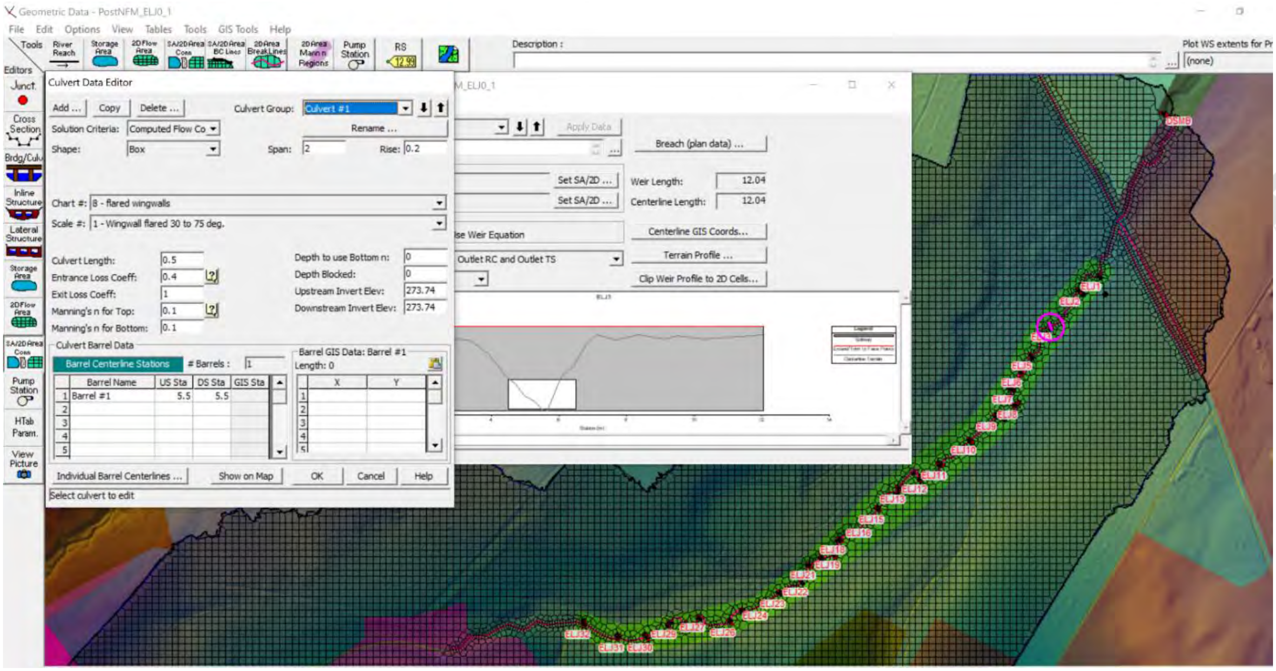

Figure 7-9 Smaller domain HEC-RAS 2D model of Middle Burn and representation of over 30 Engineered Log Jams

Using these typical ranges of coefficients and parameters gave an improved fit to the best post-NFM event available (Dec 2015). The main difficulty was to attain the full attenuation of the final peak in the storm sequence shown in (Figure 7-10), but the ELJs (hydrograph shown as purple dotted line) bring the final peak in the sequence down towards the data (black-dashed).

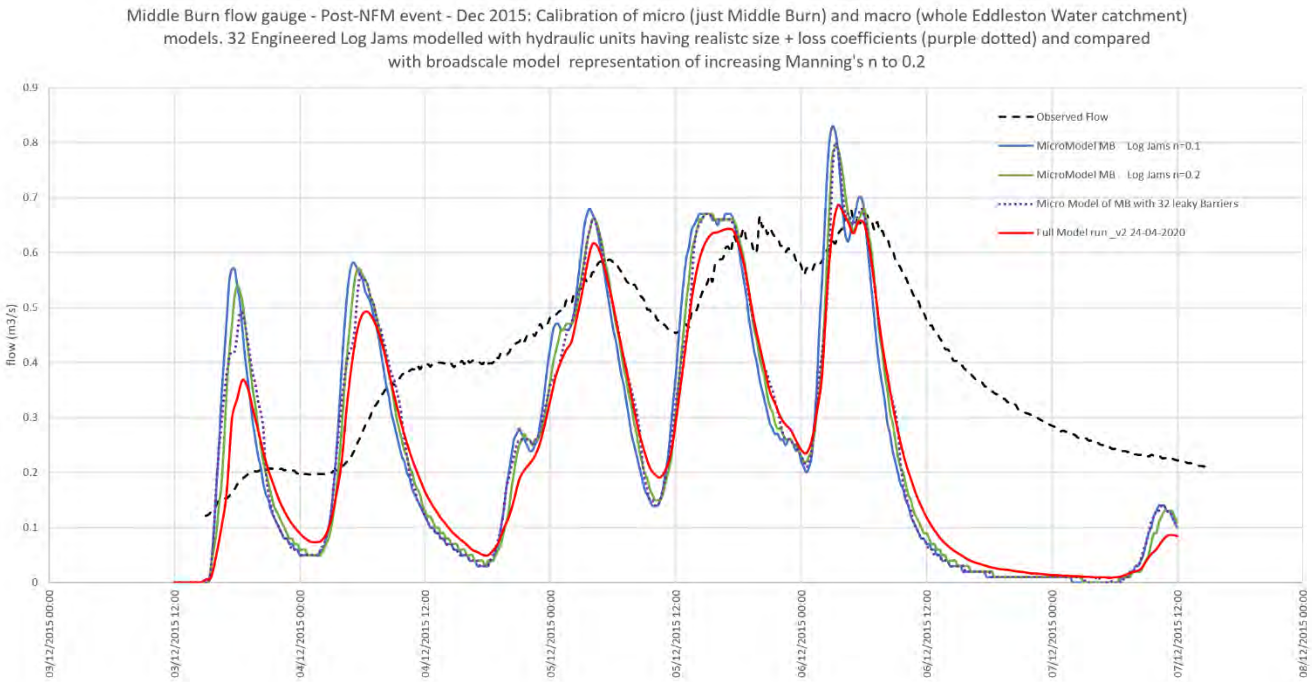

Figure 7-10 Comparison of representation of engineered log jams in Middle Burn model against data (black-dashed) using hydraulic structures (purple dotted), friction (solid green) and compared with whole-catchment model (solid red)

The model was also run with no barriers, and the more approximate representation (increased Manning's roughness) proposed as the representation in the full whole catchment model for cross-scale calibration in Section 7.4. Manning's n was not increased above 0.2 based on the summary paper by Addy and Wilkinson (2019).

Focussing on the final peak in the sequence, the simulation where n=0.2 (green hydrograph) closely matches the finer hydraulic representation of the attenuation using 32 ELJs in the purple dotted hydrograph. This December event is difficult to test against (at the time of writing it was the only one) – the data is uncertain, and the fine-scale model representation relies on estimating different dimensions and coefficients correctly. Nonetheless, the more increased friction representation of the effect of NFM measures yields similar behaviour in terms of peak flow attenuation resulting from the ELJ's at the *reach-scale*.

In addition to the predictions using the two methods here, the predicted hydrograph from the broad-scale model is also included in Figure 9-10, and demonstrates that there is likely to be some mesh-size dependence in the Manning's n, which in this case improves the calibration further. As a final check, an additional simulation was undertaken using the full momentum equations for the ELJ as hydraulic structures, yielding similar hydrographs to the default diffusion wave.

When the literature values of increased roughness for engineered log jams are used the overall output is demonstrated with NFM (blue depth grids) and without NFM (green depth grid) the increased roughness in Figure 7-11. This type of representation creates less issues with larger models, and the outputs are more commensurate with the type of data that might be available for calibration – such as trash-line surveys (Figure 7-2).

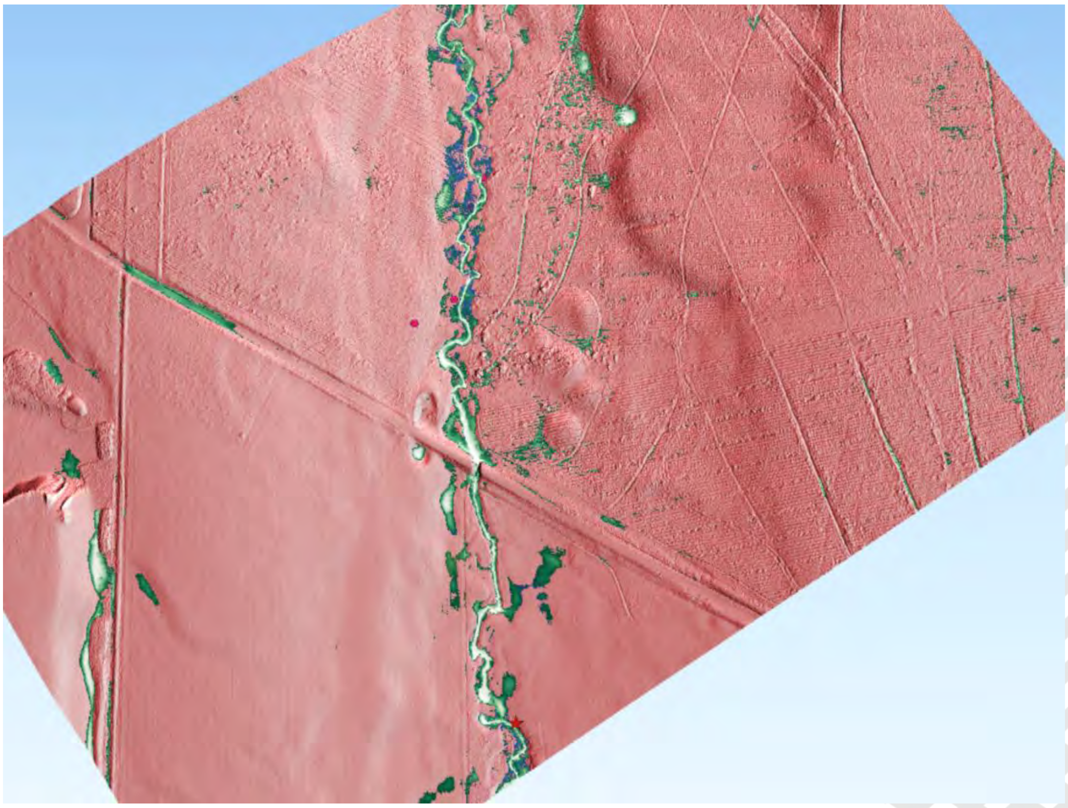

Figure 7-11 Broadscale representation of engineered log jams with increased friction (green depth grid is for pre-NFM and blue for post-NFM)

Overall, the finer-scale model has been used to demonstrate the more approximate hydraulic representation of the leaky barriers can yield similar reach-scale attenuation. Readers are referred to Appendix A, where the fine-scale representation of the structures was further experimented with in the broad-scale model. The key issue there becomes the need to refine length and time scales for flow stability through the structures, and consequent difficulties this can present in terms of simulation times.

The next section proceeds to calibrate the broad-scale model using the more approximate representation of the NFM features using increased friction at the whole-catchment scale.

7.4 Broadscale model calibration

The preceding section provides the pre-NFM (October 2012) and post-NFM (Dec 2015) calibrated events, whereby the effective Manning's roughness was increased across much of the different land-use types, and in the channel to 0.055 in places. The use of large cells (20m) means that the effective parameter lumps a range of losses, from turbulence to obstructions, and it has been common to have large values of floodplain up to 0.1 in flood mapping studies.

However, the model was not over-calibrated, for instance these changes can make a less significant change to the total flow than altering the baseflow contribution, which has been driven by ReFH2 and groundwater discharges are very difficult to estimate and only increase uncertainty. Whilst there is a lot of observational data (Figure 2-1), not all of it could be used in calibration, yet multi-scale calibration was achieved at gauges with reliable data for both pre-NFM and post-NFM situations and representative of small, intermediate and whole catchment scales (summarised in Figure 7-12). For the post-NFM event, focus was made on obtaining realistically estimated peak flows, with the model unable to represent the 'memory' of the groundwater response in the multiple peaked post-NFM event (ideally a single-peaked post-NFM event would have been available).

At the small scale, Middle Burn (with the engineered log-jams and native tree-planting) and Shiplaw Burn (native tree planting) were considered, and in the whole-catchment model the Manning's n was increased up to values suggested in the literature (Addy et al., 2019) of 0.2. Figure 7-12 shows the level of agreement for the pre-NFM (Oct 2012) and post-NFM event (Dec 2015) available at the time of modelling (there have been subsequent high flows in 2020). The pre-NFM calibration for Middle Burn is over-predicting, although provides a good fit for Shiplaw Burn. Both gauges gave strong post-NFM fits with the higher value of Manning's n of 0.2. Further analysis of representing log-jams using hydraulic features were described in Section 7.3, although as recommended in Section 9, such approaches require even more detailed through-time measurements of upstream and downstream water levels around every feature in order to be able to calibrate the different weir, loss, friction and porosity coefficients with confidence.

At the intermediate scale, halfway along the catchment at Eddleston Village the ratings give catchment-consistent flows, and the calibration was good for both pre-NFM and post-NFM. The timing and agreement with the pre-NFM and post-NFM peak flows is also good at this intermediate scale (Figure 7-12), reflecting that the focus of attaining a good fit at Kidston Mill has not been to the detriment of poor internal model performance as can be the case.

The most important large-scale or whole-catchment gauge was Kidston Mill, there being no rating at the March Street level gauge. A lot of emphasis was placed on achieving a good pre-NFM and post-NFM calibration here. It is reasonable to use these calibrated values, whilst admitting they are one possible solution, and that other combinations of Manning's and distributed losses could yield similar or better results considering parameter uncertainty (see Section 7.4.1).

The outputs at different locations were thus compared and refined at the key gauges (and where data was not missing or suspect) across small, intermediate and large (whole-catchment) scale and hydrographs from the final pre-NFM and post-NFM calibrations are shown in Figure 7-12, noting the *focus of this task was at the gauge furthest downstream at Kidston Mill, and the gauging stations discussed above*.

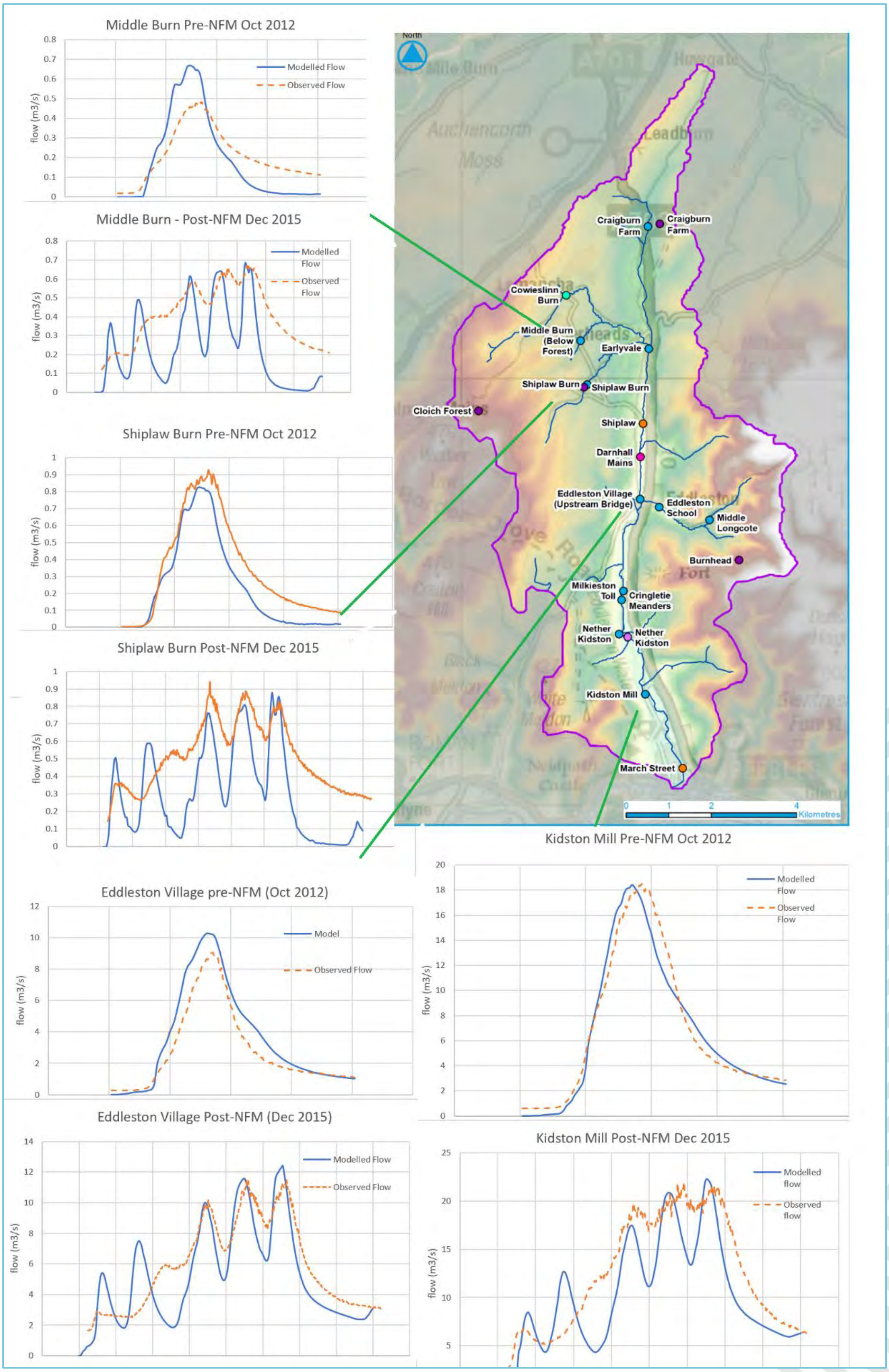

Figure 7-12 Multiscale pre-NFM (2012) and post-NFM (2015) calibration.

It would be possible in the future to undertake further distributed calibrations, and also use a riparian zone where the majority of overland flow occurs, and which is more sensitive to changes in roughness. This could include distributed rainfall to avoid the under-prediction at Craigburn, and with some further mesh refinement higher up the catchment system to improve model instability at places like Longcote where there was less work on the mesh.

7.4.1 Uncertainty analysis

To explore sensitivity to the distributed roughness, a limited uncertainty analysis was undertaken using Monte-Carlo simulations in which the before and after roughness grids for all land cover types were varied randomly by +/- 20%.

Table 7.1 reports the change to the calibrated peak flows at key stations for the 10 year design event plus or minus 2 standard deviations based on the 40 simulations.

Table 7.1 Impact of model uncertainty from limited Monte-Carlo analysis

Profile	Pre-NFM Mean+/-2SD	% change	Post-NFM Mean+/-2SD	% change
Kidston Mill	13.65+/-0.67	+/-5%	12.73+/-0.59	+/-5%
Middle Burn	0.62+/-0.02	+/-3%	0.59+/-0.05	+/-8%
Shiplaw Burn	6.66+/-0.16	+/-2%	6.21+/-0.24	+/-4%
Eddleston Village	8.61+/-0.17	+/-2%	8.08+/-0.34	+/-4%

The more important change here is the 5% change at Kidston Mill when making predictions at the whole catchment scale, and shows that the uncertainties due to roughness alone can be as large or greater than the change in peak flows that we are aiming to quantify. This does not mean that the relative change cannot be detected, as evident in the consistent reduction in the mean peak flows between pre-NFM and post-NFM, it means that it is harder to detect, and that predictions using a wider range of combinations should generally be considered to understand change. The K-S test can be used to detect the significance of change depending on the sample size (used in this context in e.g. Hankin et al., 2016).

7.4.2 Comparisons with Trash-line evidence

The only spatial survey of flooding was for a part of the right bank just upstream of Eddleston, with the model outputs compared in Figure 7-13 below, and in pseudo 3d in Figure 7-2.

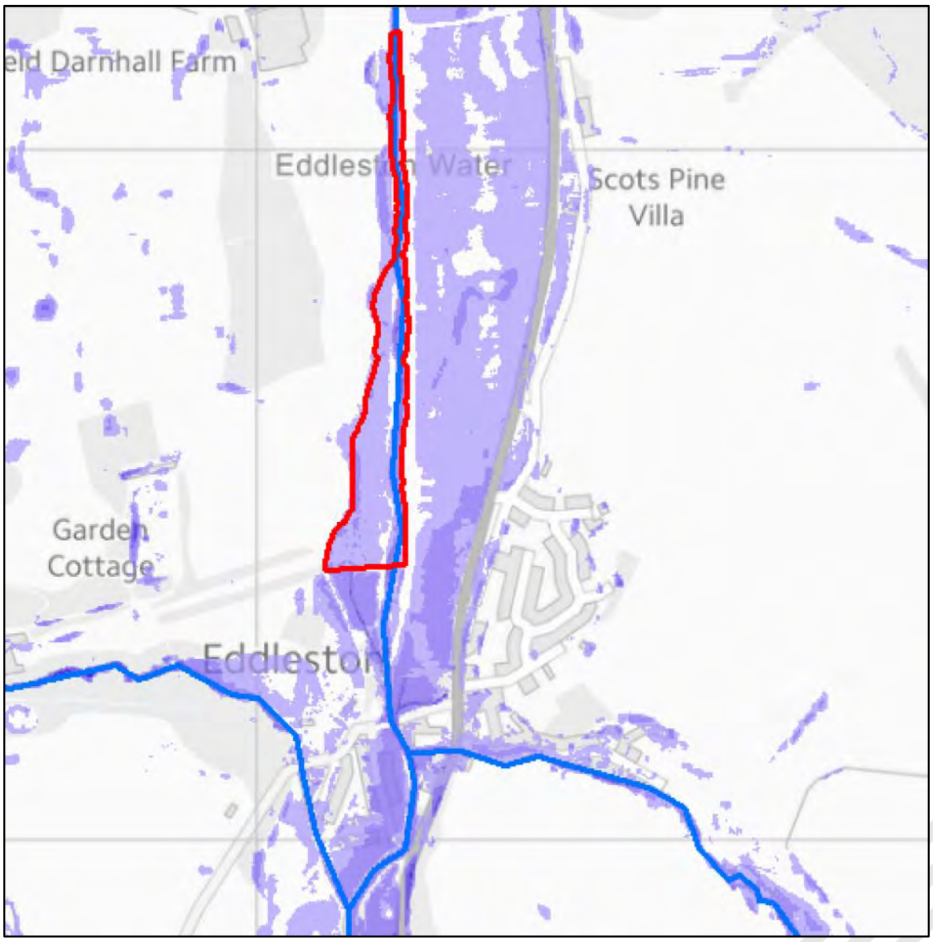

Figure 7-13 2d Comparison with trash-line survey for June 2012 event (see also Figure 7-2)

7.5 Testing representation of storage exchange due to re-meandering

To test the suitability of the model to represent change to the channel restoration and re-meandering, the older, pre-restoration Peebles DTM was used in the vicinity of the Cringletie meanders. The before and after DTMs are shown in Figure 7-14. There is a 0.1-0.2m step between the two DTMs which may require correction to the figures provided here in the future.

The changes to the depths and flows in the vicinity of the Cringletie meanders (Figure 7-15), for which the nearest hydrometry sites are further downstream at Milkieston and Nether Kidston (the closest hydrometry upstream is at Eddleston Village).

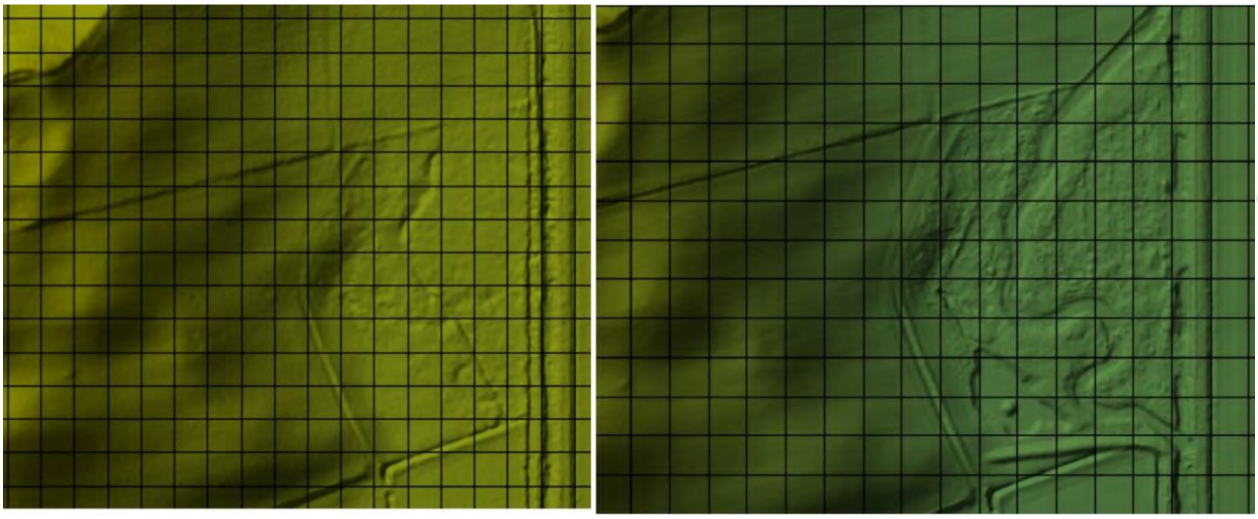

Figure 7-14 Cringletie Meanders represented before (left) and after restoration (right) and before mesh refinement

Figure 7-15 compares the resulting peak depth grid with pre- and post-restoration using the two available DTMs near Cringletie. In particular, based on integrating the depth grids pre- and post-restoration within the pink zone (approximately 300m by 150m) using zonal statistics, the peak volume stored on the floodplain has increased by 6%.

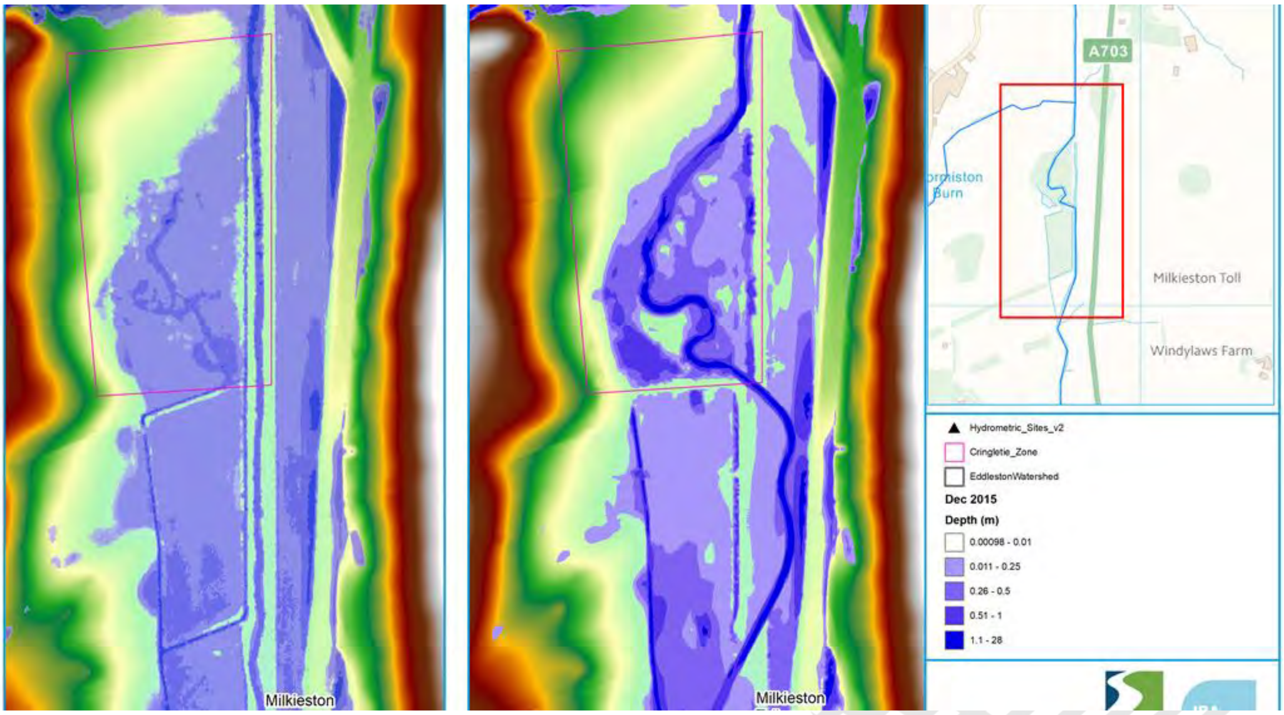

Figure 7-15 Cringletie Meanders maximum depths for calibrated 2012-2015 events. Volume stored on floodplain in pink zone increased by 6% increases from 8,700m^3 to 9,216m^3 or 6%

7.6 Timing analysis

Some comparisons were made with the predicted timings of flood peaks along the system and comparing with other flow gauges. Figure 7-16 shows how the pre-NFM hydrographs change in their timing between the Middle Burn Gauge and the Earlyvale gauge, and it was identified that the timing between these was 1 hour in the pre-NFM model, and more like 2 hours in the post-NFM scenario similar to the observations. However, there is a problem with explaining this as purely the result of the NFM since the post event simulation is multi-modal, and very different in character. The final peak of the multiple peaks is clearly noisy and the spike at the end is largely what gives rise to a later peak time arrival in the 2015 event.

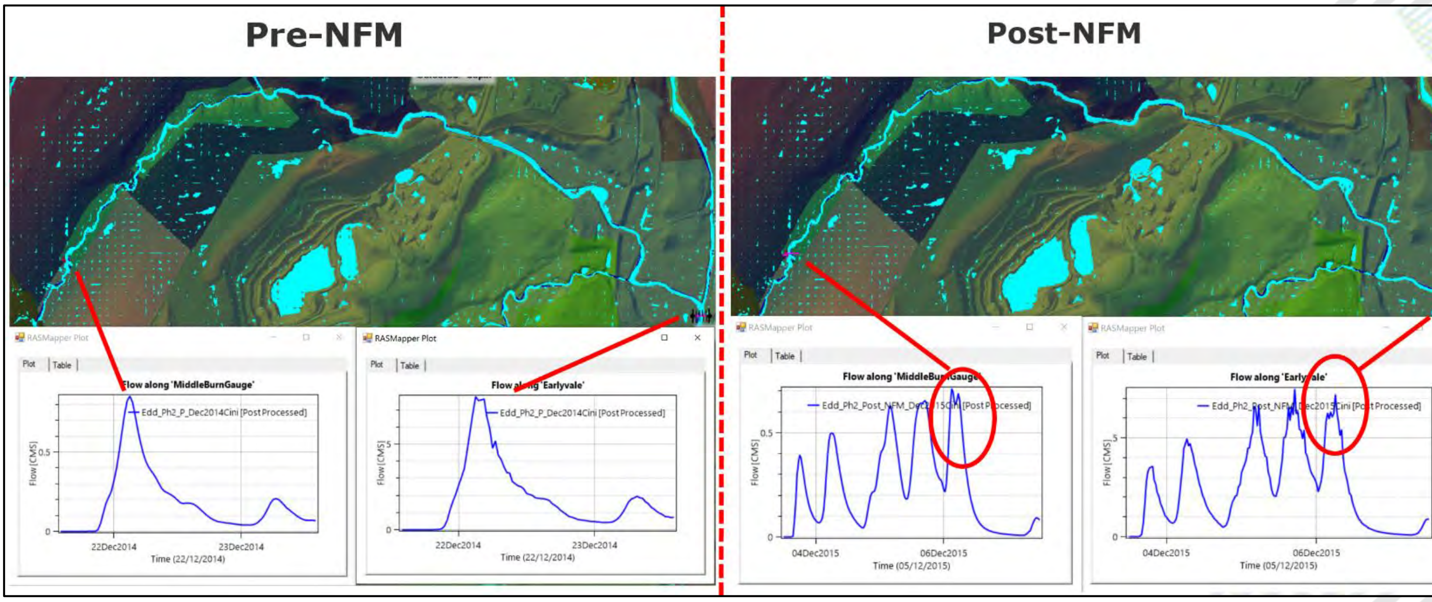

Figure 7-16 Calibrated pre-NFM (2012) and post-NFM (2015) events between Middle Burn and Earlyvalue with increase in timing of sharp last peak 1 hour.

7.7 Broadscale representation of land-use change and comparison with climate change 2050

It is useful to compare whole-catchment improvements as if soil structure improvement and woodland were undertaken throughout the catchment. There remain large uncertainties in predicting changes to antecedent soil moisture, infiltration capacity, wet canopy evaporation and friction resulting from tree-planting at small and large scales (Carrick et al., 2018, Dadson et al., 2016), especially for individual storm events and in specific locations. Whilst there is relatively strong evidence on the long term average changes to hydrology resulting from conifers and their impact on water resources, there is less evidence for how changes to hydrology should be implemented for particular storms and antecedent conditions in catchments with different soils, land-use and geology. There is some evidence for enhanced wet canopy evaporation losses even during winter (see summary in Hankin et al., 2016), but magnitude is dependent on local windspeeds and humidity deficits during the event. These areas are all the subject of further research in the UKRI NERC programme on understanding the effectiveness of NFM[12].

This study focusses on the hydraulic interactions resulting from changes to channel and floodplain storage and friction, and only investigates changes to losses due to land-use change approximately. This is partly due to the above uncertainties, but also because the current version of HEC-RAS-2D does not allow for distributed changes to rainfall, so it is difficult to represent changes to hydrological losses across the catchment until version 5.1 of the software is released.

To understand the broadscale sensitivity to losses, we simply emulated a catchment with greater baseflows and less runoff generation. This was based on increasing the catchment descriptor BFIHOST by 10% resulting in greater soil-storage (and initial soil storage) and generating approximately 10% less runoff, or the scale of change to runoff generation considered possible between soils with good or poor structure (Defra, 2002). Figure 7-17

[12] https://research.reading.ac.uk/nerc-nfm/

shows the resulting reduction in net rainfall owing to increased hydrological losses. This approach is approximate and the sensitivity of the runoff generation is perhaps not surprising since the soil storage potential is increased across the whole catchment. Refinement with a distributed losses model is recommended informed by emerging research from the NERC projects longer term.

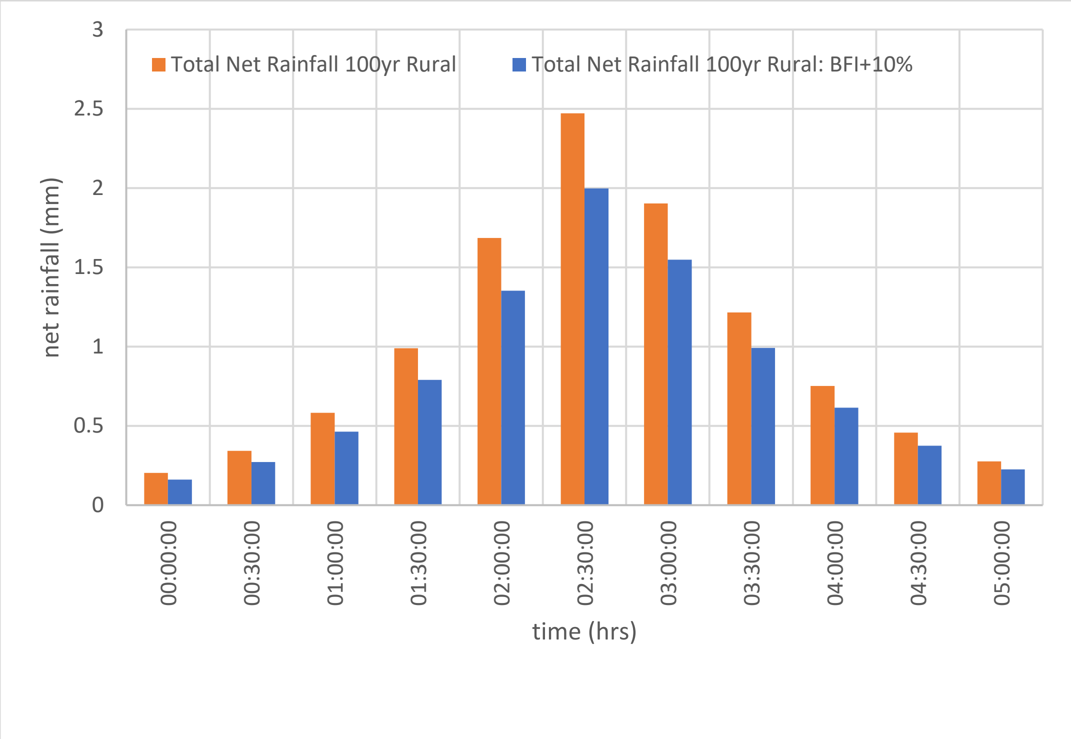

Figure 7-17 impact of increasing BFIHOST on net rainfall for 1% AEP (100 year RP) event

The reduction in peak flow at Peebles for the 100 year event is shown in Figure 7-18, which also shows the 100 year event pre and post NFM. The figure also includes the impact of a simple 20% increase in rainfall by 2050 on the same design event based on the Climate Impact Tool[13] expected increases in rainfall. This highlights that feasible whole-catchment improvements due to NFM will have to work hard to keep up with the anticipated impacts of climate change. NFM can keep working with increased flows and push more water into expandable field storage areas if designed carefully, so is a valuable addition to other risk management measures in the face of the climate emergency.

The figure shows how the time delay for soil/infiltration or related improvements can potentially increase significantly in relation to other approaches, should soil structure and runoff generation be reduced throughout the whole catchment using a range of land-use change from tree-planting to de-compaction.

[13] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/798032/Climate_impacts_tool.pdf

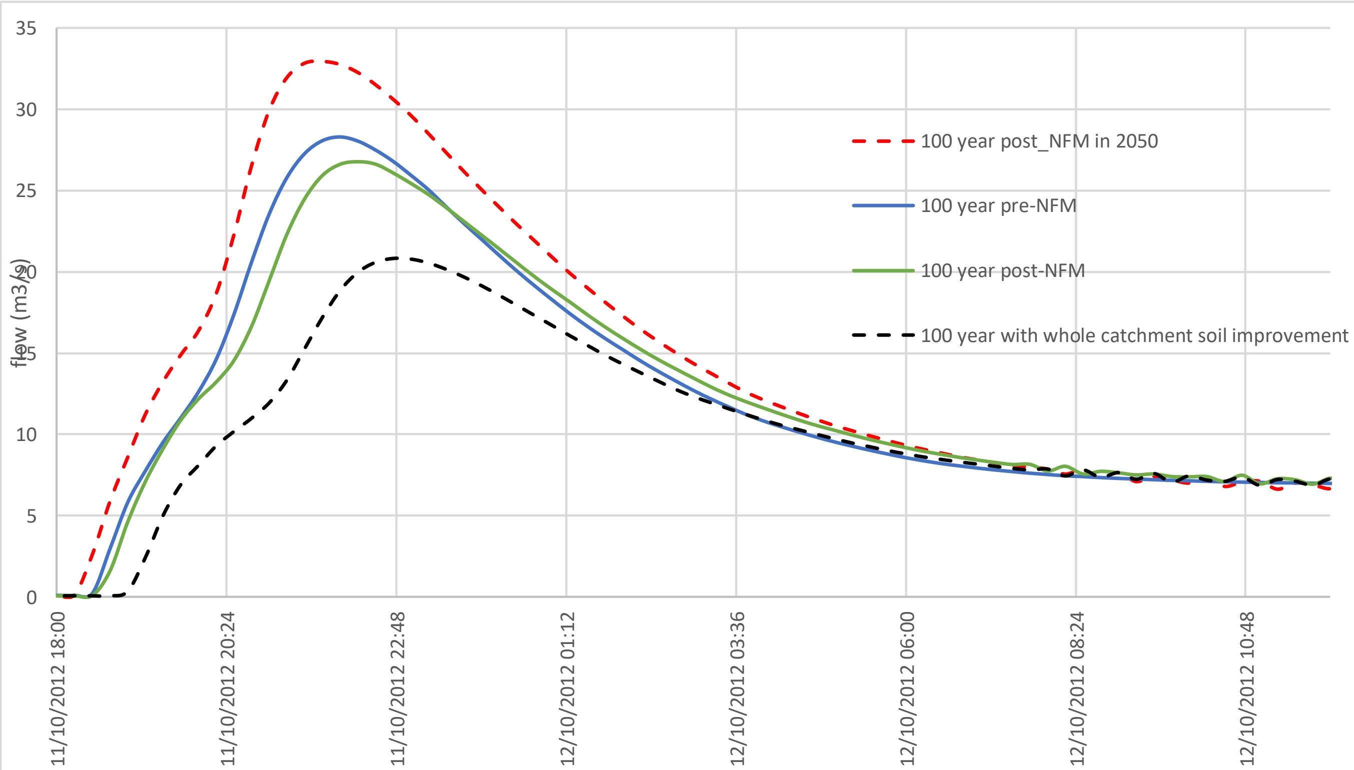

Figure 7-18 Whole catchment impacts of increasing BFIHOST on storage or projected climate change increases in rainfall in 2050

Table 7-1 summarises the changes in terms of percentage peak flow changes.

Table 7-1 percentage changes over baseline peak flow

Soils and climate change	Peak Flow	Change
RP100 Pre-NFM	28.29	
RP100 post-NFM	26.76	-5.4%
RP100 BFIHOST + 10%	20.83	-26.4%
RP100 + 20% Climate change (2050)	32.95	16.5%

7.8 Discussion of Synchronisation effects

Figure 7-19 shows the locations of the NFM measures in the upper catchment where it can also be seen that for the three western tributaries, Cowieslinn Burn, Middle Burn and Shiplaw Burn have different levels of interventions – in fact the Shiplaw Burn gauge only has native tree planting that has not yet reached maturity. It is therefore useful to compare how the different features represented in the other two tributaries result in a slowing down of the hydrograph and note any changes to synchronisation.

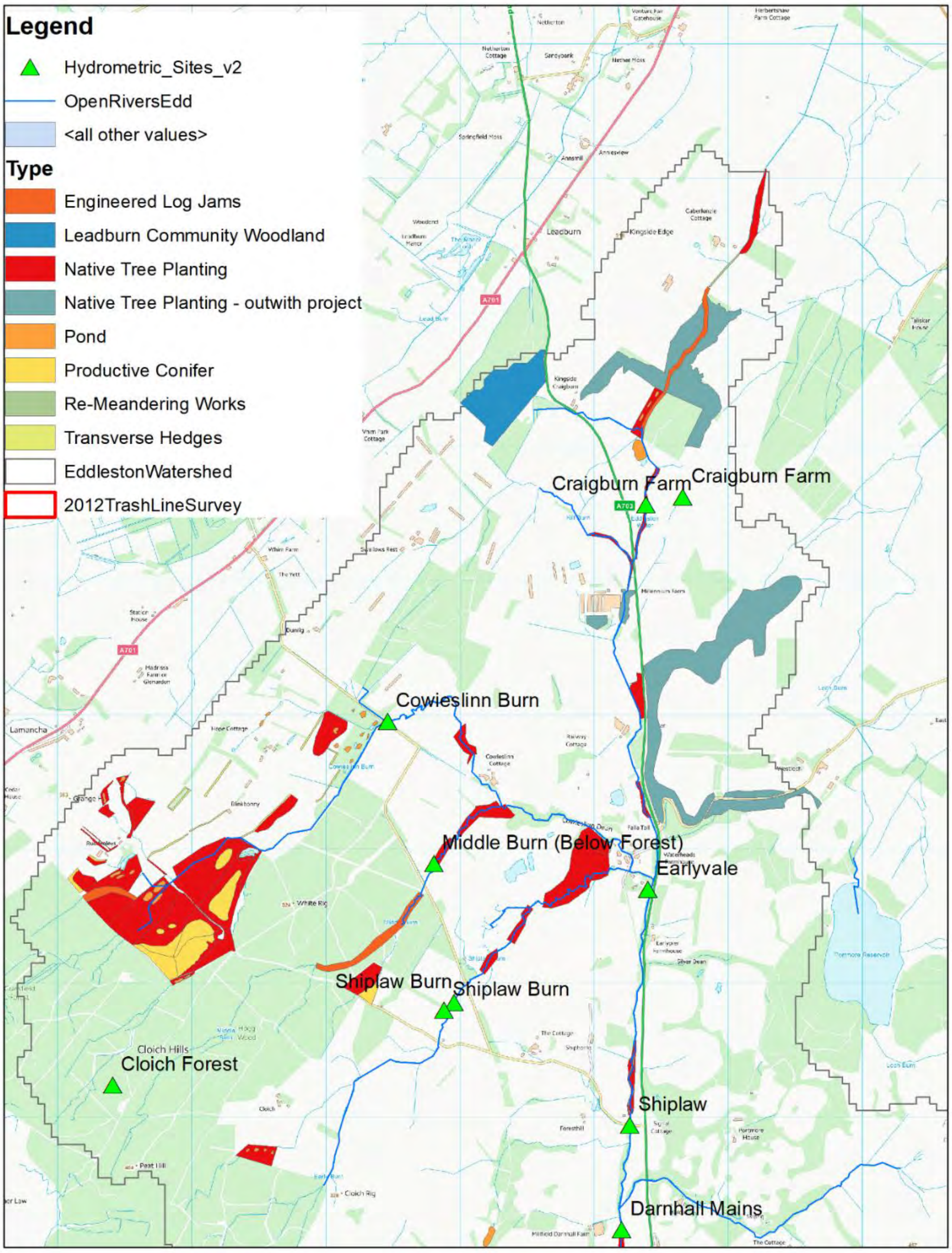

Figure 7-19 NFM in the upper catchment with respect to tributary interaction

Figure 7-20 shows hydrographs at different locations for the pre-NFM and post-NFM 100-year return period around the Earlyvale gauge as indicated. The additional delay in the peak at Earlyvale (inset lower right) is partly from these upper catchment changes and those that can be seen on Middle Burn (inset upper left). The results tend to suggest that the overall delay at Earlyvale is not as great as the sum of the delay from Middle Burn and from upstream on the main stream above Craigburn Farm. This requires further analysis but suggests a synchronisation effect – it may be more beneficial to target slowing the flow in the slower rising tributaries of the system.

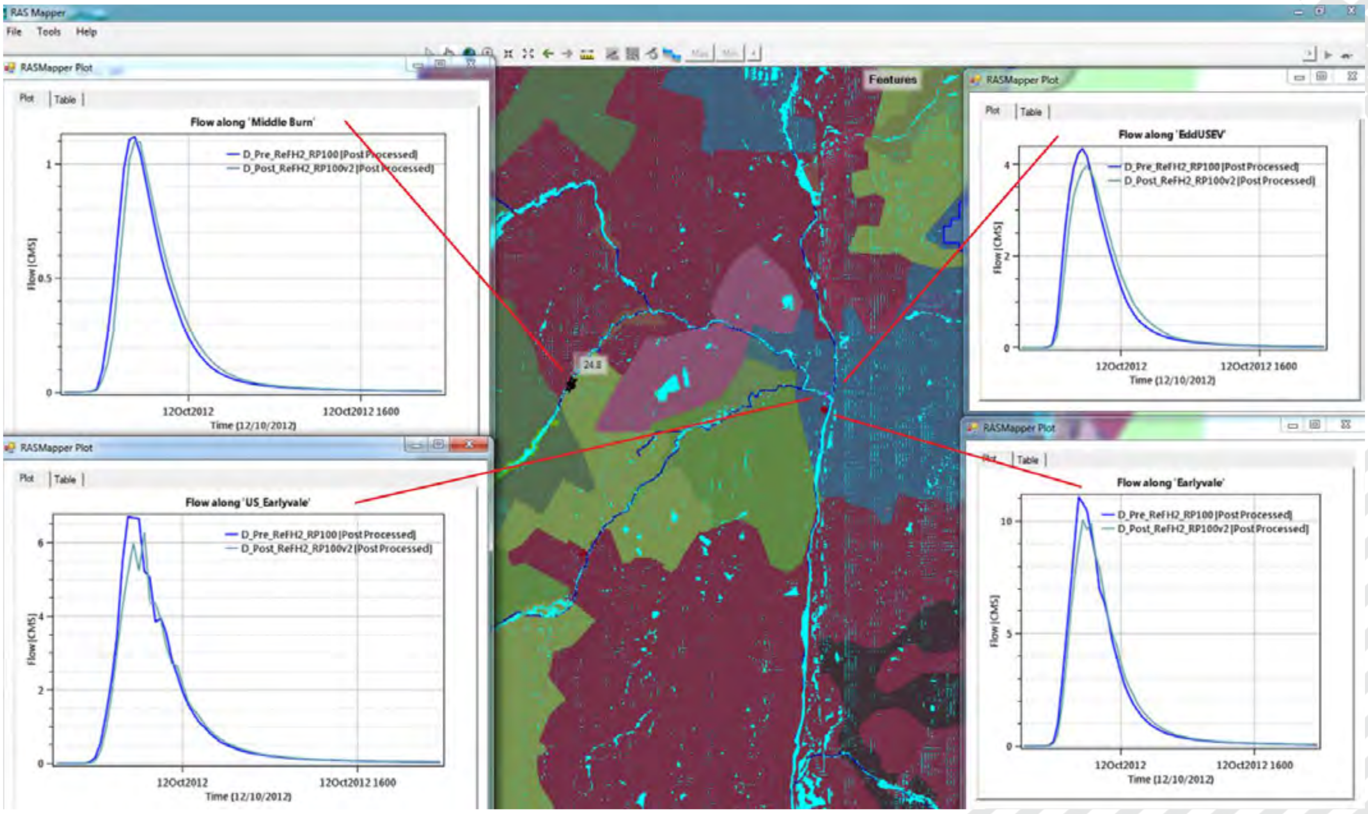

Figure 7-20 NFM in the upper catchment with respect to tributary interaction

Figure 7-21 focusses on the changes in timing contributing to slowing the peak down downstream of the confluences at Earlyvale (lower right). It appears that more of the slowing down emanates from the upper catchment and there is the possibility that by slowing down the western tributaries and the northern main flows, the net result is to in-part retain the original synchronisation, rather than help even further by de-synchronising the peaks. Both northern and western NFM measures will however attenuate and reduce the peaks, and potentially de-synchronise them from the faster rising tributaries in the lower half of the catchment. This type of phenomenon has been investigated by both Metcalfe et al., 2017 and Pattison and Lane, 2016, albeit both studies were based on modelling and not observation.

This does suggest that it is worth using the 'whole system model' to be more strategic about spatial NFM strategies when significant work is about to be implemented. This means targeting the slower rising tributaries for slowing down further than the faster rising tributaries that might otherwise create a synchronisation issue.

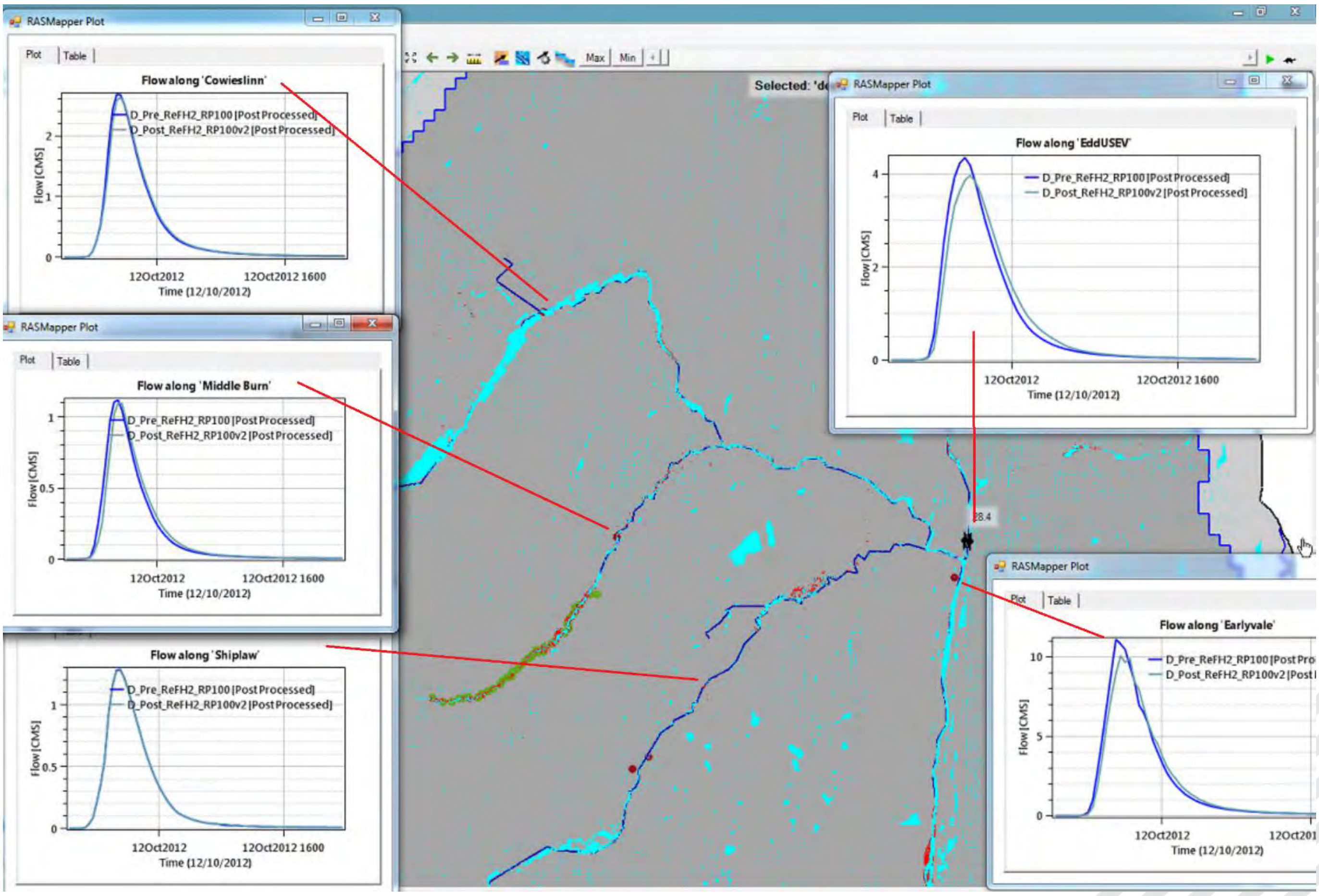

Figure 7-21 NFM in the upper catchment with respect to tributary interaction

7.9 Model Limitations and uncertainties

The approach demonstrated has a number of limitations of the new broadscale model which are highlighted here, some of which can be improved upon with new releases of software and as new data becomes available, and some of which can be improved by refinement of the mesh and distributed roughness. All models make assumptions, and the type of model set-up here is based on the broad-scale modelling of the medium scale 70km^2 Eddleston Water catchment. The approach taken is a direct runoff and losses model, and simulates the rapid runoff component, driven by the net rainfall for the whole catchment based on the ReFH losses model. ReFH version 2.2 model was used, and losses were calibrated against six real flood events for which there is good flow data at different Tweed Forum hydrometry sites (at the small, intermediate and whole catchment scales), and some spatial information from limited trash-line surveys. The ReFH baseflow hydrograph has also been fed into the main stem of the watercourse to ensure greater consistency with the total flow.

7.9.1 Direct Runoff and Losses Approach

The modelling has demonstrated that the direct runoff and ReFH2 losses approach can be used with reasonable accuracy at the whole catchment scale for real events where the initial soil moisture is first calibrated using DAYMOD. This is contingent on having accurate rainfall inputs, but where rainfall is less spatially uniform, or has to be supplemented, the input errors can dominate and be larger than the shift in response that we are trying to detect. Therefore, statistical approaches analysing many events are likely to be more informative, and such analysis is currently being undertaken by University of Dundee.

The modelling approach assumes hydrological losses due to infiltration are lost and only returned to the main channel via the broadly represented baseflow internal inflow boundary that was set up for the main stem of the river. Referring back to Figure 3-1, this technique has enabled the water balance to be more reasonably closed based on ReFH2 assumptions than in previous direct-runoff studies. However, the modelling approach lends itself to event-based modelling -whether that is real events captured using DAYMOD, or design events used to investigate risk in terms of sensitivity to change (especially for NFM changing hydraulic behaviour), as in the next section. The model has not been set up for continuous simulation, where a through time soil moisture accounting approach would be needed.

7.9.2 Event-Based modelling

Whilst six real events have been modelled (with two additional ones added following the calibration), obtaining accurate antecedent and event rainfall records is essential to obtaining a realistic prediction. Of the six events calibrated using the ReFH2 DAYMOD software, four gave a reasonable fit and these were considered to have more spatially uniform rainfall. As rainfall becomes less representative, and data from wider studies becomes available, the uncertainties in the input errors can dominate, demonstrated by the spatially non-uniform June 2012 event, and the data from the newly installed rainfall sensors had to be supplemented using other stations.

8 Risk Reduction due to NFM

8.1 Introduction

The pre-NFM and post-NFM DTM and roughness grids were next used in combination with the suite of ReFH 2 design events for nine probabilities compatible with the earlier Peebles Flood Studies Report. The simulations undertaken with the pre-NFM and post-NFM and were for the 20%, 10%, 4%, 3.33%, 2%, 1.25%, 1% 0.5% and 0.1% AEP ReFH2 events (10, 25, 30, 50, 75, 100, 200, 1000 Return Periods respectively). The rainfall and baseflow and antecedent conditions were the same between pre and post-NFM comparisons.

Figure 8-1 shows the result of simulating the pre-NFM (solid lines) and post-NFM events (dashed lines) using a combination of the ReFH2 design event net rainfall combined with the ReFH2 baseflow inputs along the inflow boundary along the main stem of the river. It becomes apparent from the charts that the NFM remains effective at different magnitude events, and is considered to be due to more flooding being pushed into expandable areas of floodplain in the headwaters and in proximity to the NFM changes (see later).

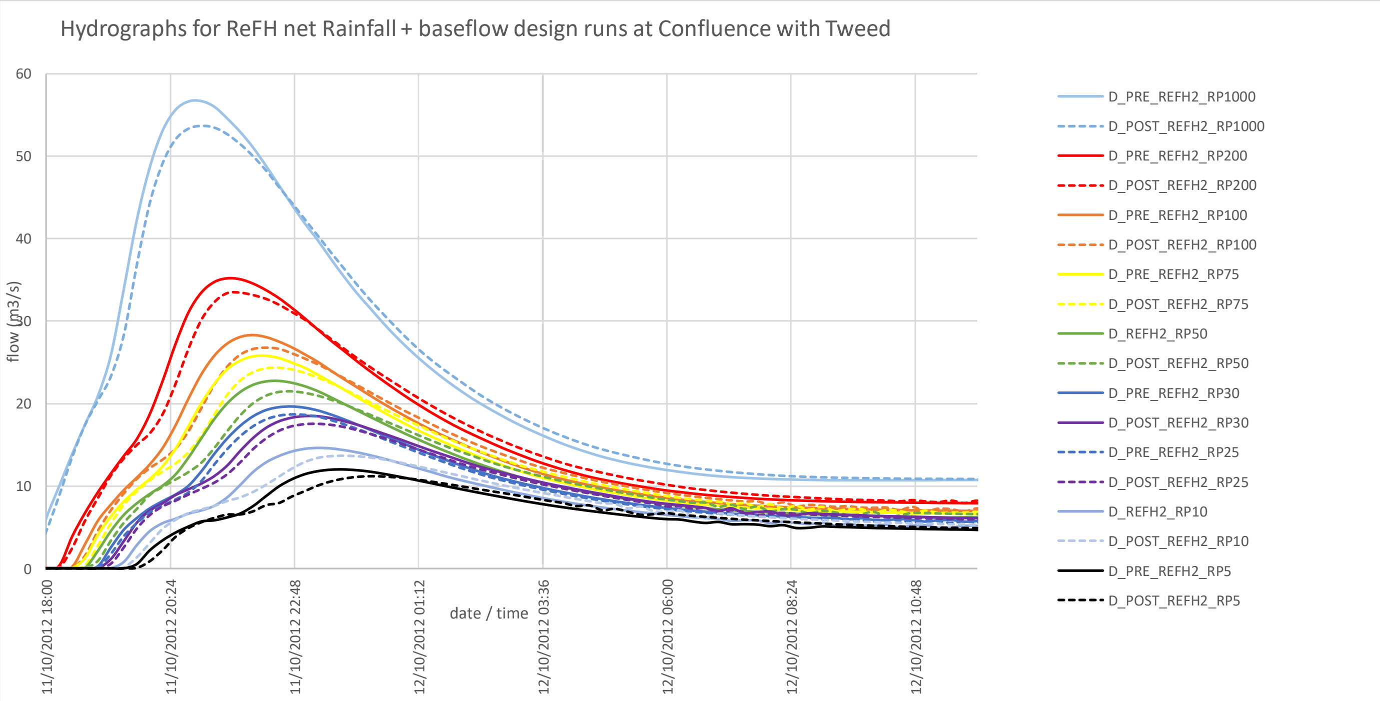

Figure 8-1 Predicted changes to hydrograph at the outlet to the model near confluence to Tweed (Tweed levels conditions are not considered)

The relative changes to the peak flows are summarised in Figure 8-2 and vary between 6.9% for RP5 and 5% for RP1000, and these should be expressed with the model uncertainty, for example: peak flow reduction is 7% +/- 5%. Whilst this shows relatively small changes for the large number of interventions in Eddleston, it is to be expected without large areas of land use change or more storage in the headwaters. However, the fact the changes are predicted to keep working at extreme flows (land-use change may not have the same effect as larger events may wet up the extra soil storage) suggest NFM is a useful, complimentary measure that can be used in combination with traditional risk reduction measures such as defences, especially to help reduce the growing impacts of climate change.

Design Event	Peak Flow Baseline	Peak Flow (NFM)	% Peak reduction	Time Delay
RP1000	56.68	53.64	5.4%	00:00
RP200	35.19	33.42	5.0%	00:15
RP100	28.29	26.76	5.4%	00:15
RP75	25.77	24.34	5.5%	00:15
RP50	22.77	21.51	5.5%	00:15
RP30	19.67	18.51	6.3%	00:15
RP25	18.68	17.58	5.9%	00:30
RP10	14.63	13.69	6.4%	00:30
RP5	12	11.17	6.9%	00:30

Figure 8-2 Predicted changes to peak flows and peak flow timings at the outlet to the model near confluence to Tweed. Change values should be read with approximately +/- 5% uncertainty.

8.2 Impact Estimations Using Multi-Coloured-Manual

The water surface elevation grids were exported from HEC-RAS 2D accounting for the pre-NFM and post-NFM DTM's and the impacts computed using JBA in-house software FRISM, which implements the Multi-Coloured-Manual depth damage curves. At this point, the offset in the Fugro DTM becomes significant, so mainly because the surveyed doorstep threshold surveys were measured on a different datum. Therefore, the depth grids were exported, and an assumed doorstep depth threshold was used in this instance. Should the DTM offset issue be resolved so the doorstep thresholds are compatible with the WSE grids then these calculations could be refined in the future. Due to these uncertainties and the fact that the damages calculated from the whole catchment model include surface water impacts, comparisons between the flood damages calculated here and for the Borders Flood Studies are not directly comparable.

8.2.1 Property impact estimations

Table 8-1 provides the increase in expected impacts in terms of property counts for areas centred on Peebles and Eddleston Village. It should be noted that the risk here includes surface water flooding as the whole model is driven by rainfall. The detailed methodology is provided in Appendix B.

The reduction in properties at risk with NFM is typical in that there are not large differences in properties impacted pre and post NFM, as it has the effect of lowering levels across many properties, but not removing properties from being at risk. The reduction in impacts is better assessed using the reduction in damages which is depth dependent (Table 8.2).

Table 8-1 Properties flooded pre- and post-NFM

Return period	Properties flooded pre- and post-NFM			
	Peebles		Eddleston	
	Pre	Post	Pre	Post
5	67	67	6	6
10	69	67	6	6
25	73	70	10	9
30	79	73	11	10
50	84	73	14	13
75	90	79	16	16

100	93	84	16	16
200	97	91	18	18
1000	119	106	24	24

8.2.2 Average annual damages

The combined average annual damages for Eddleston and Peebles are shown in Table 8-2. The reduction in risk expressed as Average Annual Damage overall is 3.4%, commensurate with the changes in the hydrographs explored earlier, which should also be expressed with a similar level of uncertainty. The change is large through time and considering scheme lifetime and the fact the NFM continues to reduce risk at more extreme events.

Table 8-2 Damages avoided using NFM

Return Period	Pre-NFM Damages (£k)	Post-NFM Damages (£k)	Difference (£k)
5	2,562	2,494	-68
10	2,644	2,567	-78
25	2,801	2,680	-121
30	2,869	2,728	-140
50	3,040	2,855	-185
75	3,200	2,998	-202
100	3,307	3,103	-204
200	3,622	3,383	-239
1000	4883	4,291	-592
Annual average damage	937	905	-32

Allowing for 15 years of canopy closure and a ramping up of the AAD avoided over 30 years, the change shown would equate to 30-year Present Value Benefits of approximately £608k. This is of a similar magnitude to the range of present value benefits the central estimate of the net benefits of timber in Figure 8-3, based on the natural capital assessment undertaken in a separate report[14].

[14] Ecosystem Service Benefits of Eddleston Water NFM Measures: Economic Analysis. A report by JBA Consulting for Tweed Forum BIM name ATI-JBAU-00-00-RP-Z-0001-S3-P01-ES_Benefits_Assessment_Draft

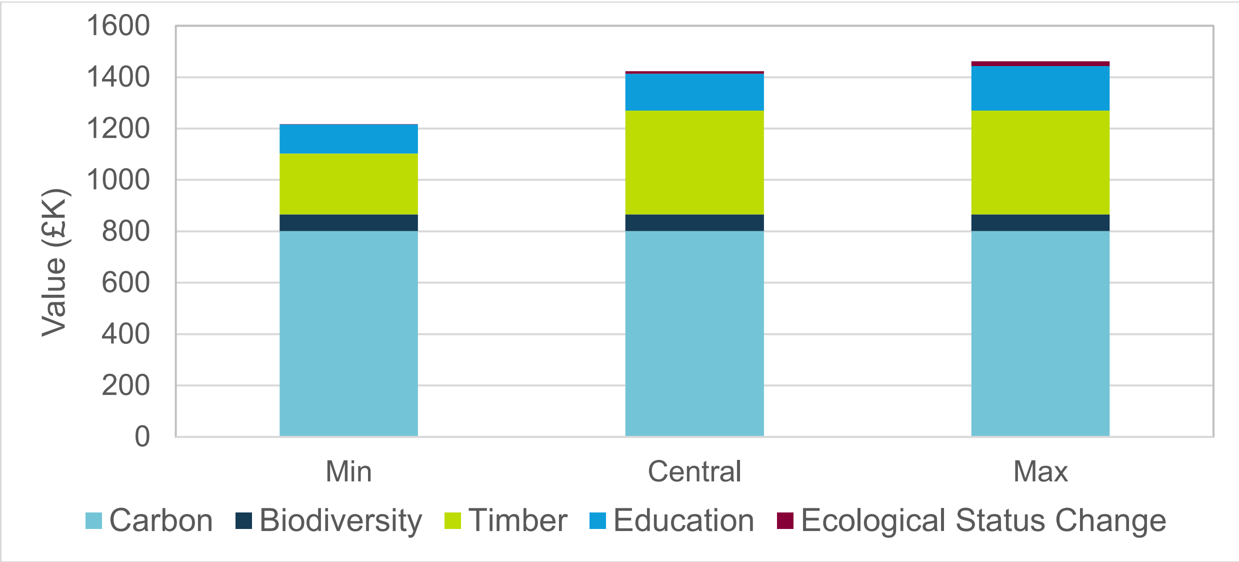

Figure 8-3 Outputs from Natural Capital Assessment (30yr Benefits)

9 Decision Support

9.1 Introduction

This Section introduces user-guidance to help assess NFM for other integrated Flood Risk Management Schemes, where NFM is used to supplement traditional risk reduction strategies. The guidance is centred around a decision tree approach (Figure 9-1), based on the concept that the effort involved for modelling NFM in combination with traditional flood risk management activities should be proportionate. Please also see the separate technical user-guide document.

9.2 Decision Support for modelling NFM

Figure 9-1 introduces the decision tree that is discussed in more detail in a standalone user-guide. The first assessment is regarding the level of risk in the catchment under investigation, and deciding whether a model is needed at all for assessing the flood risk reduction benefits of NFM, or whether there are no-regrets actions that can just be undertaken, such as tree-planting or soil improvements or runoff interception measures, for which there is existing guidance (e.g. SEPA NFM Handbook[15]) and forthcoming construction industry CIRIA guidance[16]. It is important not increase flood risk of flooding, so for instance riparian planting can create a backwater effect and raise levels upstream, or floodplain re-connection should clearly not introduce new pathways linking vulnerable receptors. Similarly, careful consideration should be given to potential changes in synchronisation where slowing down faster rising parts of the catchment could be detrimental.

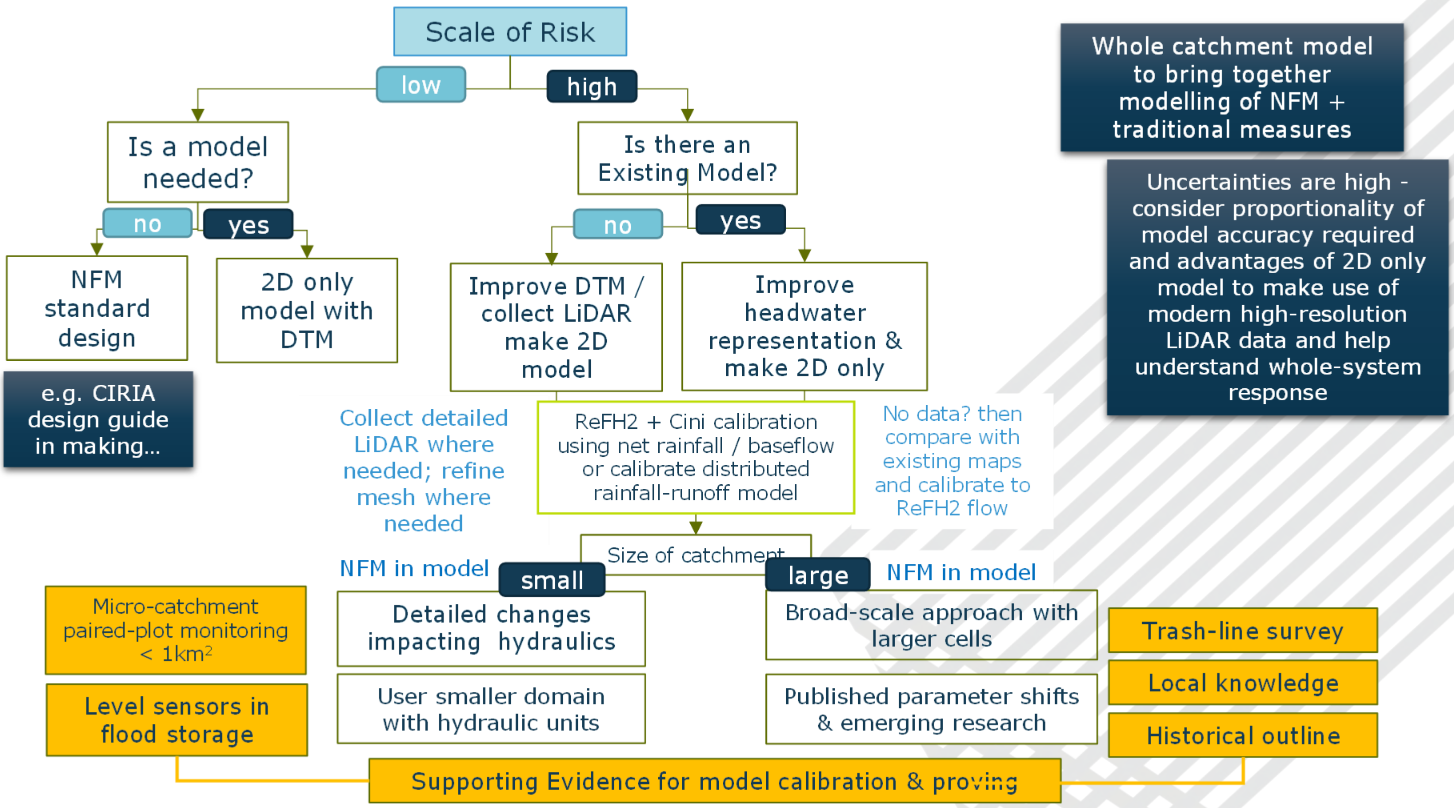

Figure 9-1 Decision Tree for support NFM modelling

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[15]https://www.nfm.scot/news-events/natural-flood-management-handbook-available-sepa

[16]https://www.ciria.org/Research/Projects_underway2/Guidance_on_natural_flood_management_RP1094.aspx

Where there are properties at risk, and an existing model has been built or is being built there are different ways of incorporating NFM features into those existing models. A matrix-diagram was provided in the EA-Evidence Directory Chapter[17] (EA / Hankin et al, 2017), which helps identify parameter shifts and tools to help from spreadsheet approaches to modifications to broadscale models as demonstrated in this project.

Where upstream boundaries are represented simply using for example FEH inflow boundaries, it becomes difficult to understand how flows from different parts of the whole catchment interact (giving rise to synchronisation effects), and when dynamic storage is filling during an event (ideally taking storage off the peak of the hydrograph). It is possible to make modifications to, for example, hydrological parameters, yet this does not necessarily reflect the distributed changes. Therefore, including new upstream 2D only models of the landscape, or a new whole catchment model as in this study can help understand how the different measures impact the risk for different events. Currently there are a range of licensable 2D modelling packages that can represent distributed changes in friction, storage and hydrological losses (or infiltration), and a range of publications and on-going studies providing guidance. For the particular freely-licensable software used here (HEC-RAS 2D), distributed changes to friction and storage have been demonstrated, and distributed changes to hydrological losses will be available in the next release, version 5.1.

The decision tree shows two key pathways for new or modified models of headwaters, both of which can be driven using ReFH2 losses model, which provides ability to model net rainfall (using a precipitation boundary in the model) for different land-use and soils and the corresponding baseflow with the use of an internal inflow boundary along the main channel.

The scale of the catchment is then also important, and it is easier for smaller catchments or represent the NFM features in more detail without recourse to excessively long run times. As a guide, using a modern i5/i7 processor, representing individual features such as leaky barriers and the smaller time steps this requires is practical for catchments 20km^2 or smaller. As the catchment gets larger, the run times become prohibitive, assuming the general land surfaces are represented with a 20m mesh or smaller. Computational speed increases all the time, so this will change with time. Depending on the scale, and how detailed NFM features are represented, different types of data are useful for validating. At the fine scale, the loss coefficients needed for a culvert unit as demonstrated in Section 7, requires roughness, entry losses and weir coefficients to parameterise the processes. These can be calibrated better if level sensor outputs are recorded for that individual feature, but costs for this can become prohibitive. At the larger scale, increased roughness for channels that are infilled with woody material are more reliant on engineering tables and recent research, and broadscale observations such as trash-line surveys are extremely valuable.

The monitoring evidence in Eddleston Water is more detailed and spatially distributed than in many catchments, although it should be clear from figures such as Figure 7-12 that there is still considerable noise and there will be potentially 10% uncertainty in the flows due to rating uncertainty (remember that at the time of writing there were no gauged flow events with rarity greater than 5-20%). This should therefore strike a note of caution – all of the changes in Table 8.2 show a change of 5-6% in the peak flow, so the uncertainty in the flows is almost twice that what we are trying to measure. This calls for two strategies:

1) Model uncertainties in more detail – expanding Section 7.4.1 and exploring the sensitivity of the model to the uncertainties in the parameters and input errors.
2) Undertake data analysis of large numbers of events and use statistical averaging to make inferences on change.

The first strategy is something that could be undertaken in a follow-on project, and it should be noted there are demonstrator publications to help with this in the field on NFM modelling

[17] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/654435/Working_with_natural_processes_using_the_evidence_base.pdf

(Hankin et al., 2019). The second strategy is currently being undertaken by the University of Dundee and was reported at the 2020 Scottish Flood Risk Management Conference. Further to this, it should be noted that ideally resilience of NFM could be tested against a range of events in larger catchments – as demonstrated for combinations of NFM and traditional risk-reduction approaches (Hankin et al., 2017a).

Using evidence to calibrate, validate or prove a model can be challenging at the large scale given the amount of natural variability in a catchment increases with its scale. For demonstration purposes, a small micro-catchment of the kind used in the NERC projects[18], in which a large percentage change in land cover or NFM measure is undertaken is one of the best ways of demonstrating the quantum of change needed to enact an effect on the hydrograph response. Ideally BACI design (Before-After-Control-Impact) experimental setup provides the strongest evidence for change (see Shuttleworth et al., 2019).

Some of the simplest techniques such as time-lapse photography through and event of for example storage features filling up can help improve models if the rates of filling or changes in relative levels are recorded and compared with the model outputs. The particular model used provides detailed post-processing such that the depths, levels, velocities accumulated volumes can be plotted through time and compared with this kind of observation.

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[18] https://nerc.ukri.org/research/funded/programmes/nfm/

10 Summary and recommendations

10.1 Introduction

In summary, a broadscale HEC-RAS 2D model has been used to represent the numerous and diverse, distributed NFM measures in the 70km^2 Eddleston Water catchment. The software has a flexible mesh allowing detail to be added where needed around, for example embankments, and it is capable of using the advances that have been made in the collection of increasingly high resolution terrain data (in this case 0.5m resolution LiDAR). It permits the representation of hydraulic structures in the mesh, which with appropriate loss coefficients can be used to refine the representation of NFM features that interact with hydraulics.

The model has been driven by the ReFH2 losses model and it has been demonstrated how this can be calibrated using 2 years of antecedent rainfall for particular events, and the net rainfall and baseflows can be used with the flexible boundary conditions in the model. A fine-scale model of Middle Burn was developed to compare different hydraulic representations of the impact of engineered log jams on the catchment response, and used to substantiate the 'increased friction' representation used in the broadscale model. The broadscale model was then calibrated using the Tweed Forum monitoring data across small, intermediate and large scales, and performance at the whole catchment scale using the Kidston Mill monitoring data was reasonably strong, yet it has been highlighted that the rating equations have not been based on high flows, so the uncertainties in the calibration data could be larger than the whole catchment changes we are trying to detect. A further limited Monte-Carlo analysis was undertaken into the impact of parameter uncertainty in the distributed Manning's roughness, highlighting how the uncertainty in the predictions can be as large as the scale of change we are aiming to detect. This is without considering the uncertainty in the flow gauge ratings and shows how difficult it is to quantify change due to NFM.

This does not mean the model cannot be used in a predictive sense, to understand how an engineered *change* in storage, friction or losses change the catchment response. This is done all the time with traditional engineered schemes and the calibrated model is then used to appraise risk. That approach has been undertaken here, and whilst the risk reduction of distributed measures is not huge, predicting changes of about 5%, the changes keep working for higher flows including those expected with climate change. This is because the measures typically encourage water onto floodplains or into fields which have more area in which to expand and provide landscape resilience. Building defences, whilst potentially protecting more people does not share this property: once a defence is overtopped it will continue being overtopped at higher flows.

Whilst broadscale representation of changes to storage and friction have been demonstrated, distributed changes of hydrological losses will only be possible when there is stronger evidence to support how processes of infiltration and wet canopy evaporation influence flows at a smaller scale. Such processes can be influenced by other meteorological variables, notably windspeed and relative humidity, so in this investigation some broadscale, whole catchment changes envisaging soil improvement on a big scale were demonstrated through altering the ReFH2 losses model. It will be possible to refine the HEC-RAS 2D model to include distributed changes to hydrological losses with the next release, but it would also be possible to refine how those runoff generation processes (surface and sub-surface) are represented in a distributed hillslope model such as Dynamic Topmodel. The reduction in flood peak and slowing of the catchment response is demonstrated, although it is noted that the potential impacts of climate change by 2050 would more than counteract the considerable improvement.

A User Guide has been developed following the decision tree that has been introduced in Section 9 which makes the modelling process contingent on scale of risk, size of catchment and existence or not of a model, although it is recommended that the modelling approach and calibration is proportionate as modelling of potentially uncertain change to future 'what-if' scenarios, is routinely undertaken for traditional risk reduction measures.

10.2 Recommendations

The following recommendations are made based on the application of a broadscale HEC-RAS 2D model to the Eddleston Water catchment using the ReFH2 losses model.

- Modelling of NFM measures and calibration should be proportionate in relation the scale of the risk and the size of the catchment, and a decision tree and user-guide provide some guidance on this for modelling NFM in other studies. There are a wide range of case studies that include NFM modelling in the recent Evidence Directory for Working With Natural Processes, which builds further on the SEPA NFM Handbook. There is also an increasing amount of material on building design at the UK and international levels. For example, some NFM changes to the catchment system, such as soil improvement could be considered as 'no-regrets' actions to reduce frequent-flooding without the need for modelling.
- Natural variability and measurement uncertainty (including input errors in rainfall and rating uncertainties) are large in hydrology, and unless NFM measures introducing significant storage are used, it is very difficult to measure responses to small-scale changes. Analysis of changes to time of travel or peak flow reduction are therefore best undertaken using a large number of events to reduce uncertainty, or through monitoring smaller catchments (here we focussed on Middle and Shiplaw burns) and making changes in a significant proportion of the area. Two of the three NERC projects on testing the effectiveness of NFM are taking this approach and have already generated statistically significant results.
- It is recommended that the hydrology and hydraulics simulations are undertaken for some larger flows once recorded. There is uncertainty in the rating equation at high flows, and uncertainty in the estimation of the probability or return period of the highest flows on record that were modelled here. This uncertainty in the probability will be reduced as more larger events are gauged with a longer record.
- Whilst the high resolution, 0.5m LDAR DTM has proven invaluable for computing for example changes to conveyance and storage, the DTM provided for the modelling has an offset difference to previous modelling studies of the catchment, and it is likely that it needs correcting. The MCM depth-damage curves were used with predicted depth grids and depth-based doorstep thresholds. Following the correction of the DTM it would be possible to use water surface elevation outputs and undertake the appraisal more accurately that would be more compatible with previous studies.
- The appraisal of risk reduction due to NFM has been demonstrated and compared with the Net Present Value of other ecosystem service benefits of the NFM. In future it is recommended that the NPV of the risk reduction and other enhanced services are included against other traditional "concrete-only" solutions that will not share the same improvements to natural capital.
- The new version of HEC-RAS 2D (v5.1) will allow more flexibility in representing distributed losses and it is recommended the model is updated such that for example the use of wider-woodland includes increased losses over the pre-NFM scenario, in addition to the changes in friction used here. It should also be considered that driving the HEC-RAS 2D with a distributed losses model (once available) or a distributed hillslope-hydrology model such as Dynamic Topmodel may provide improved process representation, and provide a best of both worlds approach (see Hankin et al., 2019) in the future, although it has been beyond the scope of the current project.
- The new whole-catchment model of Eddleston Water has allowed an exploration of how the whole system responds with many distributed changes. It allows us to study how different features are dynamically utilised (or not) and how they alter the synchronisation between peaks. The analysis suggests that it is worth using such a model to be more strategic about spatial NFM strategies before significant

NFM work is implemented. This means targeting the slower rising tributaries for slowing down further than the faster rising tributaries that might otherwise create a synchronisation issue.

- Uncertainty could be explored further than was possible here using additional Monte-Carlo simulations to understand influence of parameter uncertainty and input-errors on the model predictions – using a more detailed limits of acceptability type approach or GLUE type analysis (Beven and Binley, 1992, 2014). It is possible to estimate parameter uncertainties for a range of NFM and propagate the uncertainty in predictions of modelling NFM so that the uncertainty in its effectiveness can be estimated (Hankin et al, 2019). This has been undertaken here for a limited number (40) of Mannings roughness combinations. It would also be useful to explore model structural error with additional process representation. Improving the calibration of the real events will be possible as distributed losses or rainfall runoff processes are used, but here it has been possible to use the industry standard approaches and benefit from the way new high resolution data can be incorporated in the 2D modelling.

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10.3 Websites

https://www.nfm.scot/case-studies/eddleston-water-tweed-catchment

https://www.youtube.com/watch?v=NTrQk7mfSo8

A Testing detailed structures in the broad-scale model

Appendix A is a supplement to Section 7 which provided evidence that areas of increased friction could represent the attenuation afforded by multiple engineered log jams in a fine-scale model of Middle Burn. This section explores the practicality of incorporating the more precise hydraulic structures in the broad-scale model itself, and the pitfalls of adding fine-scale detail.

To test suitability of incorporating hydraulic features to represent leaky barriers more directly, the model was put to the test with some of the smallest features in Middle Burn, since these will be the hardest to represent. Figure 7-8 shows a photograph of one of these structures on Middle Burn. This comprises long logs of approximately 0.15-0.2m diameter laid and secured across a small channel, with tree-planting either side. It is a challenge to represent such as small feature in a 'whole-catchment' model that is 70km^2.

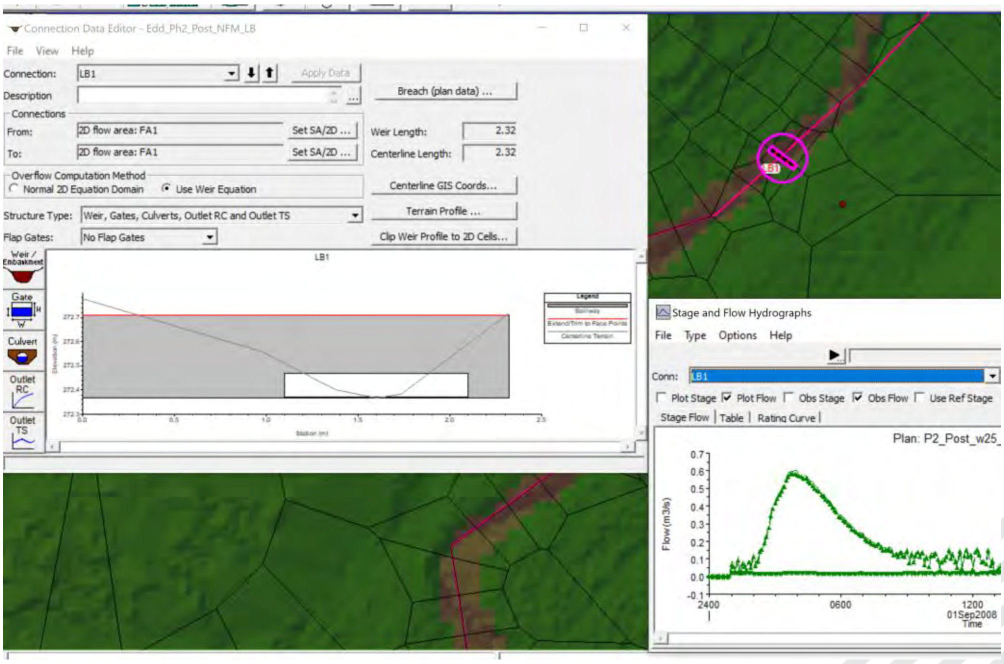

Figure A-1 Representation of leaky barrier in HEC-RAS for Middle Burn and hydrograph through box culvert

However, Figure A-1 shows how such an obstruction can be included as a hydraulic structure directly into the mesh in HEC-RAS 2D. It shows the fine-scale granularity of the 0.5m Fugro DTM and the cross section shown is based on this sub-grid data (inset right with box-culvert). HEC-RAS 2D allows automatic re-computation of the mesh around this feature to be able to incorporate it. To represent the effect of the logs, an inefficient weir coefficient of 1.4 was used, with a roughness of 0.1 and inlet losses of 0.4. These values should ideally be calibrated with reference to detailed upstream-downstream through-time levels for every structure, which may make full calibration of many structures in a large catchment unattainable if represented in this way. The flow through the 'culvert' is based on the same physical principles (Bernoulli losses) as other NFM publications aiming to represent the impact on hydraulics (e.g. Metcalfe et al., 2017).

The resulting change in the depth grid and tailwater for this leaky barrier can be seen in Figure A-2 in the immediate vicinity. Further downstream, a cross section has been drawn in the easy-to-use RAS-Mapper software, and a profile of the flows through time (or rating curve) is easy to create interactively (Figure A-3). Importantly, this is undertaken as a post-process – some software requires that such profiles are included at the start of a simulation. Further enhancements can be made by increasing the width of the barrier and increasing the roughness on the banks to represent the effect of the tree-planting which will of course take longer to take effect. The rating curve facility can also help derive high flow ratings where more model proving has been undertaken.

Figure A-2 uses the facility in the geometry editor to plot the flow over and through the leaky barrier in more detail for a higher flow. This provides flexibility to assess changes in levels or flows in relation to observations and correct the representation in some detail.

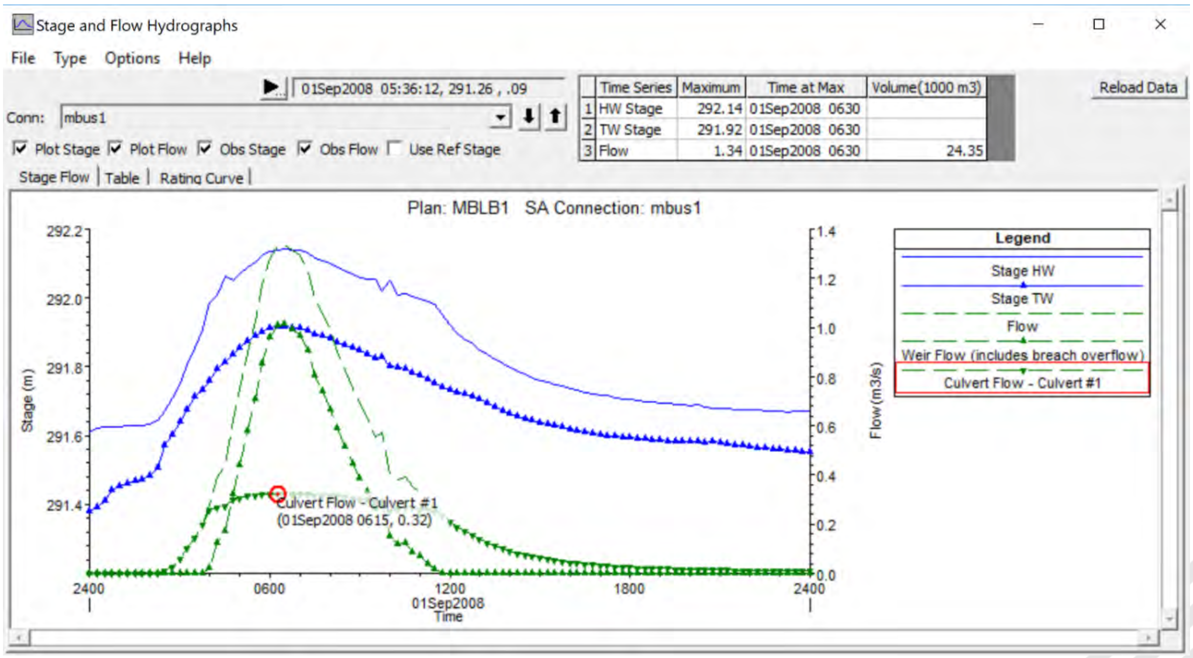

Figure A-2 Flow over and beneath leaky barrier: useful for quantification and design of leaky barriers

The change to the response can then be assessed for its impact further downstream at the Middle Burn gauge (circled in yellow in Figure A-3), although with such small change in cumulative volume (inset left) from a single feature (circled in blue), it is unlikely a change will be detected, and this is the case in the hydrograph inset right and highlighted in yellow. Notice that break-lines have been added around the embankment (circled in purple) to ensure mesh alignment – this is important to represent on Middle Burn as the gauge is downstream of the embankment which may itself cause flow attenuation. To observe change at the gauge, more of the leaky barriers must first be added.

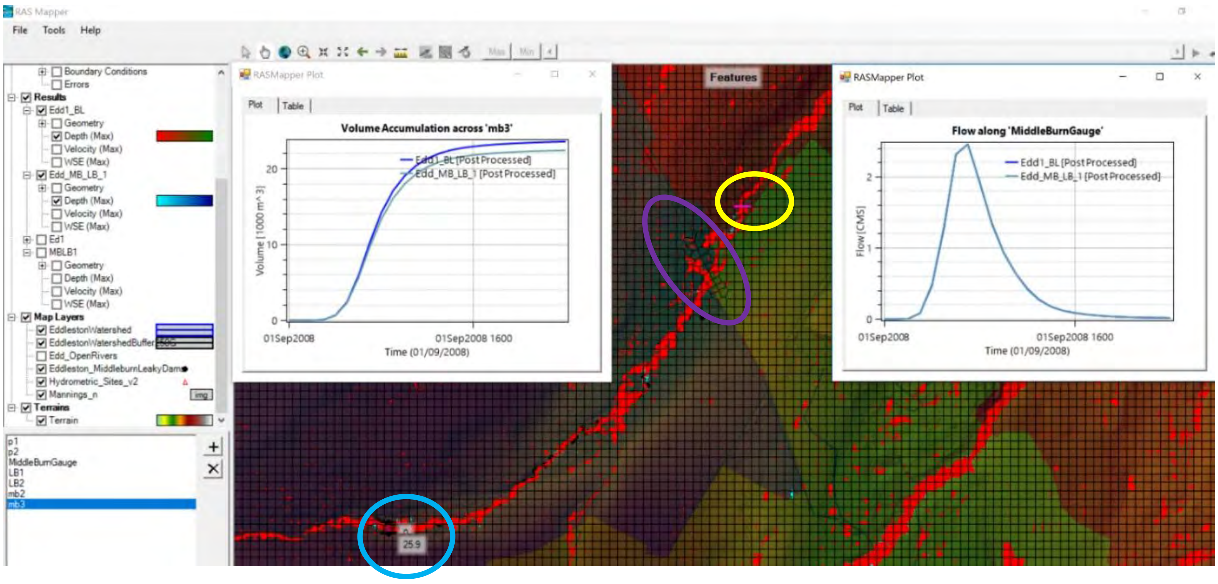

Figure A-3 Accumulated volume at leaky barrier, comparison at Middle Burn Gauge, and incorporation of break-lines to adapt mesh at road embankment. Change to volume accumulation highlighted inset left, and hydrograph inset right

However, this was not investigated further owing to two issues:

The 70km^2 model is typically simulated with a time step of 10s, and results in generally acceptable Courant numbers (Figure A-4) that are generally less than the 'pragmatic' values for the diffusion wave approximation in the HEC-RAS 2D manual. The Courant number (Figure A-4) is a measure of model stability, and with higher values, the solution becomes less accurate.

There are stability issues that become evident in Figure A-1, where the outlet levels are oscillating from the hydraulic unit. With smaller time steps and for example a more accurate numerical scheme, these can be reduced.

There are 3 calibration factors per leaky barrier represented in this way – the Manning's roughness, the inlet losses and the weir coefficient. These would need individual calibration to be sure that they are accurate, and compound the model uncertainty at this large scale, demanding level sensors upstream and downstream to get the coefficient correct. It should also be noted that the structures cannot yet represent a leakiness factor so the impact of this would be represented by the single orifice used, or multiple other ones that would also need to be added. Other software packages can include a leakiness factor, but this too must be estimated. As additional parameters are added to a model, the parameter uncertainty increases.

It was concluded that such direct representation of the structures can be useful in smaller scale models (see Section 7.3) where it is possible to use a smaller model time step and calibrate the energy losses across such structures. It is recommended that such an approach should be used in catchments less than 20km^2 and where there is strong calibration data.

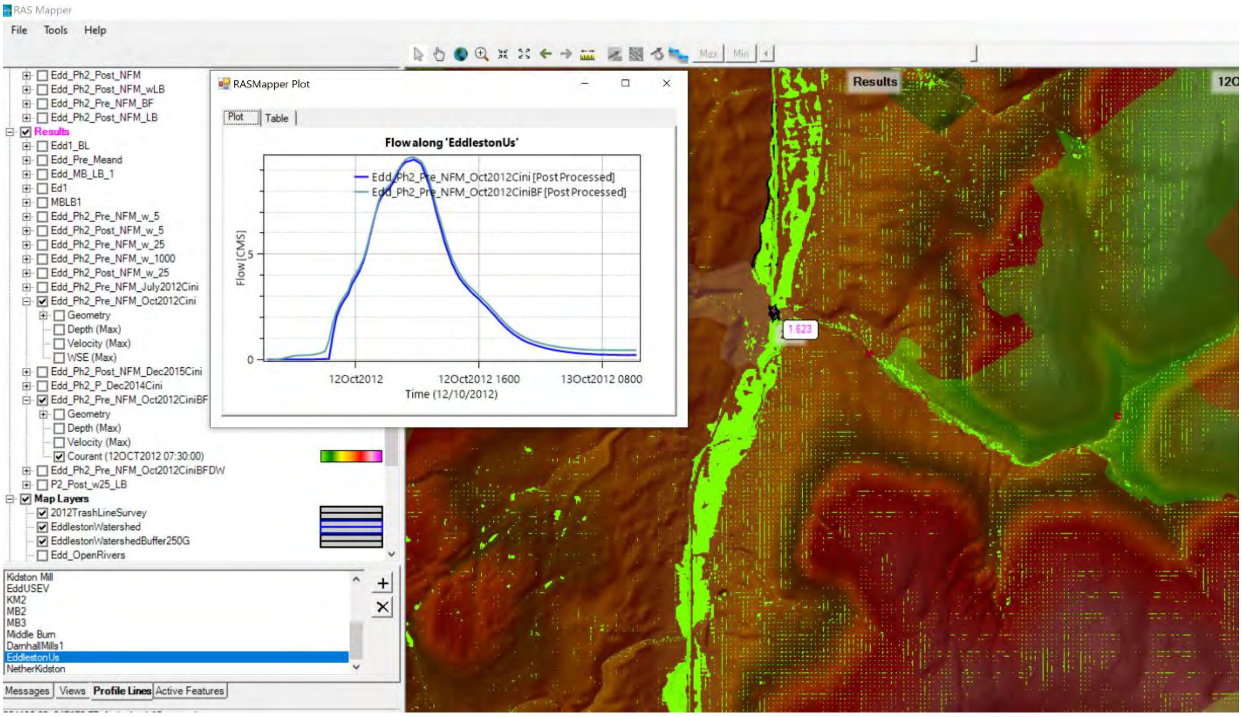

Figure A-4 Courant number output from HEC-RAS 2D for October 2012 event.

B Appendix B: Economic Damages

B.1 Approach

An economic appraisal has been undertaken to assess the benefits and cost effectiveness of the Eddleston Water Natural Flood Management (NFM) scheme. The appraisal consists of a simple benefit-cost assessment (BCA) using standard flood damage data and methodologies, combined with cost estimation. JBA's bespoke flood risk metric tool FRISM was used to calculate property damages.

B.2 Datasets

Datasets utilised include SEPA National Receptor Dataset and OS Mastermap data to determine property type and details so that damages could be accurately assessed.

B.3 Guidance

In accordance with the Environment Agency Flood and Coastal Erosion Risk Management appraisal guidance (FCERM-AG)[19], benefits are taken as annual average damages (AADs) avoided by utilising NFM, expressed as their present value (PV) using Treasury discount rates.

B.4 Flood damage estimation methodology

The appraisal period of the project for which damages have been calculated is 100 years.

Flood damage values have been estimated using the Flood Hazard Research Centre's (FHRC) Multi-Coloured Manual[20] (MCM) with additional guidance provided by the Multi-Coloured Handbook[21] (MCH).

2017 MCM depth damage curves were used in this study. The depth damage curves and prices (where relevant) were uplifted to account for inflation. The most recent Consumer Price Index (CPI) was December 2019 at 108.3. Based on a CPI at 101.4 in January 2017, the current CPI equates to an uplift of 6.4%.

B.5 Flood damage types

Flood damage assessment can include direct, indirect, tangible and intangible impacts of flooding, shown in Figure B-1.

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[19]Environment Agency (March 2010) Flood and Coastal Erosion Risk Management appraisal guidance

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

[21] The benefits of flood and coastal risk management: A Handbook of Assessment Techniques – 2019 edition

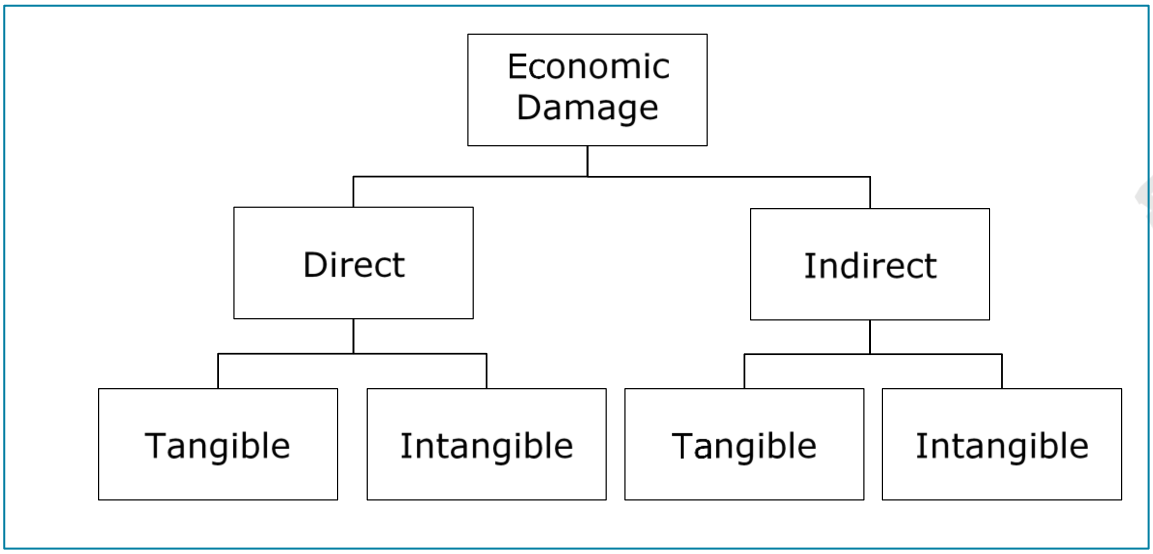

Figure B-1 Aspects of flood damage

Direct damages are the most significant in monetary terms, although the MCM and additional research provide additional methodologies, recommendations and estimates to account for the indirect and intangible aspects of flood damage.

The following flood damages have been appraised for this study:

- Direct damages – to residential, commercial and industrial properties. This includes base damages to building fabric, inventory and clean-up costs, as well as vehicle damages.
- Indirect damages – this accounts for costs incurred by the emergency services and temporary/permanent evacuation.
- Intangible damages – these damages account for things that cannot be assigned direct value, such as the fear of future flooding, loss of memorabilia, irreplaceable items, physical/mental health impacts, loss of community and loss of confidence in authorities and services. This is calculated for residential properties using DEFRAs risk reduction matrix.

Only direct tangible damages have been considered at this stage in the study, although there will be still be an influence from intangible and indirect damages.

B.6 Flood loss approach

The process to estimate the benefits of an intervention option is to plot the two loss-probability curves: for the situation now (pre-NFM), and with the proposed option (post-NFM), as shown in Figure B-2. The scale on the y-axis is the event lost (£); the scale on the x-axis is the probability of the flood events being considered. When the two curves are plotted, the difference in the areas beneath the curve is the annual reduction in flood losses to be expected from the scheme or mitigation approach.

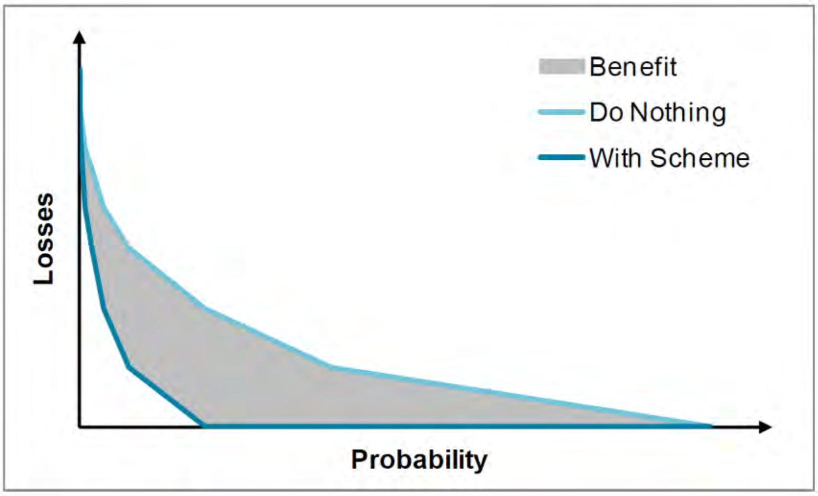

Figure B-2: Loss probability curve

To derive these two curves, straight lines are drawn between the floods for which there is data from the threshold event (the most extreme flood which does not cause any damage) to an extreme flood. The greater the number of flood event probabilities, the more accurately the curves can be plotted.

B.7 Direct property damages

The FHRC MCM provides direct damage and flood depth datasets for a range of property types including both residential and commercial properties. This standardised data for direct damages has been used in this study to assess the potential damage that may occur during different flood events, pre- and post-NFM.

Flood depth and damage estimates were calculated using FRISM (JBA's in-house flood damage calculation software). Data from hydraulic modelling were used to calculate FRISM outputs by comparing the assumed property threshold level with predicted flood depths to obtain flood depths within properties. FRISM is an ArcGIS add-in which computes a range of flood risk metrics based on receptor data and flood hazard. Within ArcGIS and prior to FRISM calculations, each property's footprint was mapped to a point using OS Mastermap data. This allowed a mean, minimum and maximum flood depth for each property to be generated in FRISM based on the range of flood depths within the building's extent. The damages were then calculated within FRISM using these data, generating a mean, minimum and maximum damage for each property. The mean flood depths and damage estimates were used for calculations in this study and form the basis for flood damages.

The following FHRC depth damage curve was selected for this site:

- Initial Appraisal (residential and commercial properties by type), Short Duration – No Flood Warning (assuming a worst-case scenario), Fluvial Water Damage.

SEPA's National Receptor Dataset was used to define property types. Changes and assumptions relating to these data are provided in Table B-1.

Table B-1 Direct flood damage assumptions

Data type	Data and any assumptions
Property data	SEPA's National Receptor Dataset
Depth damage data	Multi-Coloured Manual (MCM) 2017 data.
Flood depths	Flood depths were derived from the Eddleston Water hydraulic model for 5, 100, 200 and 1000-year return period fluvial flood events. The mean flood depths within each building have been used to determine flood damages.
Property threshold level	A global threshold level of 0.3m was set for all properties.
Basements	Basement and sub-floor level damages were not included for either residential and non-residential properties.
Residential property types	Defined by SEPA National Receptor Dataset property types (detached, semi-detached, terraced, flat) and assigned an MCM code.
Treatment of flats	All upper floor flats were removed from the appraisal. Flood depths unlikely to reach upper floor flats.
Non-residential property types	Defined by SEPA property types.
Property footprint areas	Defined by SEPA.
Capping of property damages	Property damage capping has been applied to both residential and non-residential properties (see note below).
Flood duration	Short flood duration – i.e. flooding assumed to last less than 12 hours.
Flood warning	Assumed no flood warning given.

B.8 Property damage capping

Total present value damages have been capped at the estimated market value of each property, preventing unrealistically high damage estimates.

The market values of residential properties were estimated based upon the average sale prices of property in Eddleston/ Peebles as published by the Scottish Assessors Association (SAA[22]).

B.9 Property dataset

The property dataset for Eddleston was derived from SEPA's National Receptor database, combined with survey data from Peebles gathered from a site visit.

B.10 Property counts

The total number of properties inundated for each return period are shown in Table B-2.

[22] https://www.saa.gov.uk/ [Accessed 13 December 2019]

Table B-2: Properties flooded pre- and post-NFM

Return period	Properties flooded pre- and post-NFM			
	Peebles		Eddleston	
	Pre	Post	Pre	Post
5	67	67	6	6
10	69	67	6	6
25	73	70	10	9
30	79	73	11	10
50	84	73	14	13
75	90	79	16	16
100	93	84	16	16
200	97	91	18	18
1000	119	106	24	24

B.11 Average annual damages

The combined average annual damages for Eddleston and Peebles are shown in Table B-3.

Table B-3: Average annual damages for Eddleston and Peebles combined

Return period	Pre-NFM Damages (£k)	Post-NFM Damages (£k)	Difference (£k)
5	2,562	2,494	-68
10	2,644	2,567	-78
25	2,801	2,680	-121
30	2,869	2,728	-140
50	3,040	2,855	-185
75	3,200	2,998	-202
100	3,307	3,103	-204
200	3,622	3,383	-239
1000	4,883	4,291	-592
Annual average damage	937	905	-32

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