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Eddleston Water Modelling User-Guide

User-Guide

July 2020

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Abbreviations

DEM/DTM	Digital Elevation Model / Digital Terrain Model
ELJ	Engineered Log-Jam
FEH	Flood Estimation Handbook
GIS	Geographic Information Systems
HEC	Hydrologic Engineering Centre (as in HEC-RAS)

LiDAR	Light Detection And Ranging
NERC	National Environment Research Council
NFM	Natural Flood Management
RAS	River Analysis System (as in HEC-RAS)
ReFH	Revitalised Flood Hydrograph
SEPA	Scottish Environment Protection Agency
TBR	Tipping Bucket Raingauge

1 Introduction to the User-Guide

1.1 Introduction

This Technical User Guide provides details of a new broadscale, whole catchment model of Eddleston Water with application to modelling a range of Natural Flood Management (NFM) measures in the Eddleston Water Project[1]. It provides advice on how to use the model and more generally how to apply similar approaches in other catchments. The target audience is future users and researchers with reasonable experience in hydraulic modelling. The guide also provides decision-support to help with the appraisal of integrated flood risk management schemes where NFM is used to supplement traditional risk reduction measures such as defences. It is based on the full report for the Tweed Forum, *Eddleston Water Hydrologic and Hydraulic Modelling of NFM: Phase 2, July 2020*.

1.2 Contents

The technical guidance includes the following:

- A decision tree and process diagram to help with modelling NFM in other studies/locations based on a proportionate approach considering the scale of risk, catchment size, uncertain evidence and adapting existing models
- An introduction to the whole catchment model and how it has been set-up, the datasets, assumptions and model limitations
- What the model can and cannot be used for
- The hydrology used to drive the model and model proving
- How the model can be interrogated and set up for other future scenarios
- How the model informs about the change in response to climate change, adaptation pathways and potential tipping points
- How to explore changes in the modelling interface resulting from NFM.

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[1] https://tweedforum.org/our-work/projects/the-eddleston-water-project/

2 Decision support with proportionate modelling

Based on the modelling investigations in the accompanying report, *Eddleston Water Hydrologic and Hydraulic Modelling of NFM: Phase 2, July 2020*, this guidance provides pragmatic advice that has been summarised in a decision tree (Figure 2.1). A wide range of distributed changes in the landscape are collectively termed NFM, from tree-planting to engineered log-jams (leaky barriers), channel restoration promoting reconnection with the floodplain and soil structure improvement. These all have different influence on flow pathways, temporary storage and infiltration rates, for which there is also varying strengths of evidence. This remains the subject of significant research in three on-going UKRI NERC projects[2].

The decision tree presented below promotes a proportionate modelling approach to capture the changes in these processes, supported by evidence where possible. All models make assumptions and have limitations in terms of the processes they attempt to represent and the corresponding parameter uncertainties. However, a model of the whole dynamically interacting catchment can help understand the effectiveness of distributed NFM and help plan future strategies for more NFM measures or model refinement.

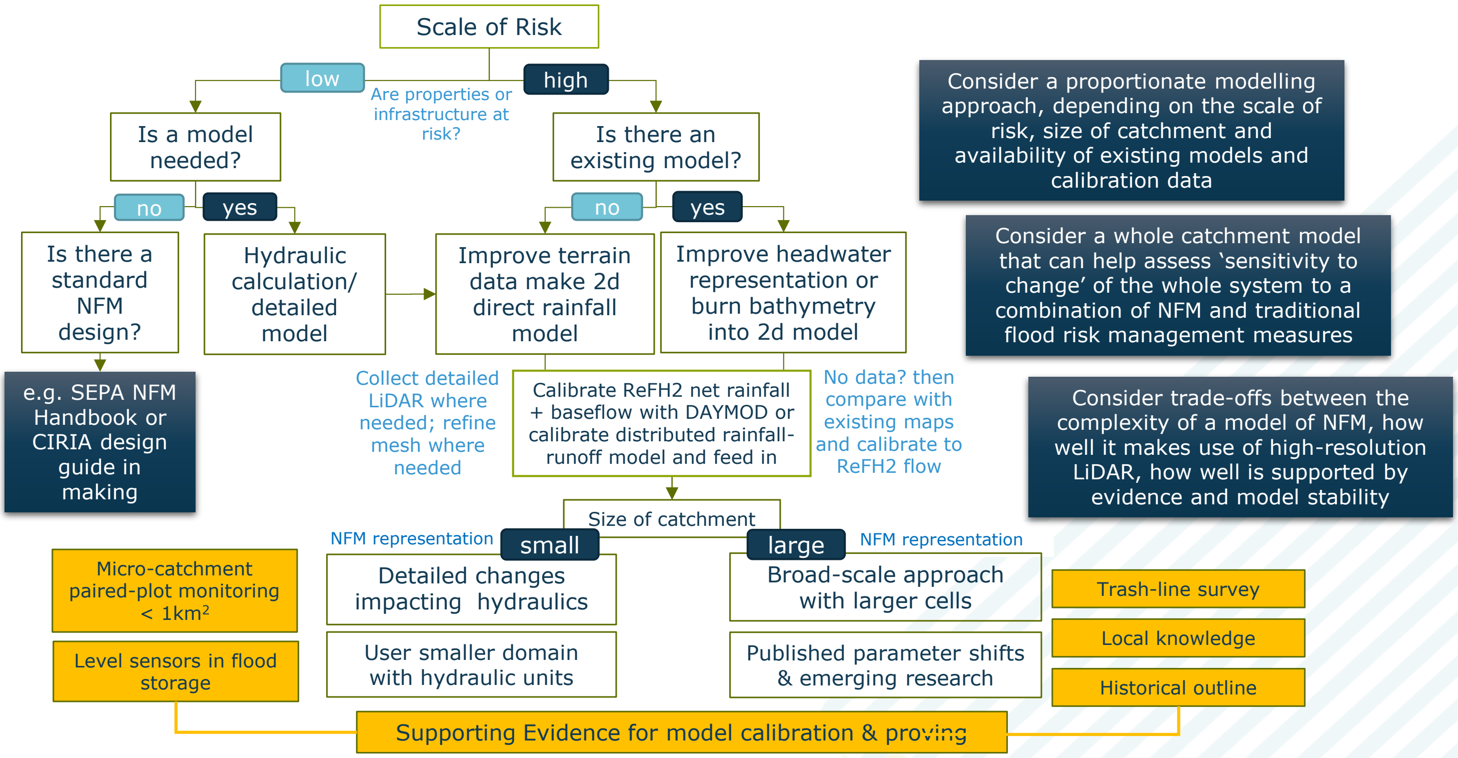

Figure 2-1 Decision Tree for support NFM modelling

Each of the key steps in the decision tree are discussed further below and a modelling process diagram at the end of Section 2.

2.1.1 Scale of risk

At the highest tier of the decision making process, an assessment should first be made of the level of risk in the catchment under investigation, based on for example the number of known properties at risk. This should influence 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 and provide multiple benefits. These could include tree-planting or soil

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

improvements or runoff interception measures, for which there is existing guidance (e.g. SEPA NFM Handbook[3]) and forthcoming construction industry CIRIA guidance[4]. However, some of these measures could increase risk, so some form of modelling or hydraulic calculation may be needed. For example, riparian planting can create a backwater effect and raise levels upstream, and floodplain re-connection should not introduce new pathways linking high flows to 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. New installations of NFM, much like traditional risk management measures, should consider sources, pathways, and receptors in this broad sense and different calculations and models can help with this.

2.1.2 Catchment scale

For studies considering the whole catchment with distributed NFM measures, the scale of the catchment is important, as it is easier in smaller catchments (or reach-scale) to represent the NFM features in more detail without recourse to excessively long model run times or model instability. As a guide, using a modern i5/i7 processor, representing individual features such as leaky barriers with hydraulic structures (requiring smaller time steps) the approach is practical for catchments 20km^2 or smaller if run times of the order of hours are required. As the catchment gets larger, the run times can become prohibitive for models with a reasonable resolution, assuming the general land surfaces are represented with a 10-20m mesh. Computational speed increases all the time, so this will change in the future.

Depending on the scale, and how detailed NFM features are represented, different types of data are useful for model proving. Catchment scale calibration of the overall hydrological response is of course dependent on the quality of flow gauging data, and the modelling strategy that is taken. For Eddleston Water it was found that the ReFH Calibration Utility (version 2.2 although 2.3 is now available, see WHS, 2020) can provide good calibration at the catchment outlet for some key storm events where the rainfall patterns were uniform across the catchment. The resulting net rainfall and baseflows were used to drive the HEC-RAS 2D model and provided reasonable multi-scale (i.e. at small, medium and whole catchment sites) calibration across the catchment.

However, in order to broaden the range of hydrological events that this direct rainfall and losses approach can represent accurately, improved distributed hydrology is required. Similarly, this is required for understanding how distributed land-use change resulting from NFM, change the distributed hydrological processes such as infiltration and wet canopy evaporation. A range of models can be used to represent these distributed changes (for example JFlow, Tuflow and the next release of HEC-RAS 2D), either through changes to the distributed net rainfall, or using a distributed hydraulic conductivity and altering local infiltration rates. However, quantifying the magnitudes of those hydrological changes for different land-use change, antecedent conditions for *individual* storms is still highly uncertain and the subject of much research (e.g. Page et al., 2020). Recent advancements have also been made using hybrid modelling approaches whereby the runoff from a calibrated distributed rainfall-runoff model is fed into internal inflow boundaries within the river channel represented in a 2D mesh (see Hankin et al., 2019), to provide a best of both worlds approach: realistic hillslope processes combined with 2d hydrodynamics between channel and floodplain. Papers have also been published in respect of the changes to hydraulics from peat restoration identifying that it is the increased friction of vegetation as opposed to in-channel storage (Shuttleworth et al., 2019).

For distributed hydraulic changes resulting from e.g. engineered log-jams, there are also a number of ways of representing the losses at fine and reach-scale as demonstrated in the full

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

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

Eddleston Water modelling report. Here a finer-scale model of the Middle Burn system was used to demonstrate the more approximate hydraulic representation of the leaky barriers using roughness can yield similar reach-scale attenuation as representing over 30 features individually. A key issue with the detailed representation is the need to refine length and time scales for flow stability through the structures, and consequent difficulties this can present in terms of very long simulation times for a whole catchment. In addition, the detailed representation requires the specification of roughness, entry losses and weir coefficients to fully parameterise the processes. These can be calibrated better if level sensor outputs are recorded for that individual feature, but time and costs for this can become prohibitive in a large network. At the larger scale, channels that are infilled with woody material can be represented with increased roughness using engineering tables and recent research (e.g. Addy and Wilkinson, 2019), and broadscale observations such as trash-line surveys are relatively easy to obtain, and valuable to help calibrate.

2.1.3 Uncertain evidence

The monitoring evidence in Eddleston Water is more detailed and spatially distributed than in many catchments, although for any catchment, there will remain considerable uncertainty (> 10%) in peak flow estimates for high flow events used for calibration. The broadscale model predicts approximately 5% reduction in the change in peak flows following the introduction of a range of NFM measures[5], so the uncertainty in the flows is almost twice that what we are trying to measure. This calls for two strategies:

1) Attempt to assess the uncertainty, or at least understand the sensitivity of the model to the uncertainties in the parameters and input errors (for example see Hankin et al., 2017a). A basic Monte-Carlo analysis was undertaken in the Eddleston Water modelling investigation, and model predictive uncertainty in peak flow was estimated at +/- 5%. This included uncertainty in the shift of the roughness parameters used to represent head loss resulting from engineered log-jams.
2) Undertake data analysis of large numbers of events and use statistical averaging to make inferences on change. This is currently being undertaken by the University of Dundee and was reported at the 2020 Scottish Flood Risk Management Conference[6].

Further to this, it should be noted that 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., 2017b).

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 different NERC projects, 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). The research has also investigated the resilience of different spatial strategies for the implementation of leaky-barriers taking into account performance failure (see Hankin et al, 2020).

Some of the simplest techniques such as time-lapse photography through an event of, for example, video footage of 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. HEC-RAS 2D provides detailed post-processing for comparisons with observations including depths, levels, velocities, accumulated volumes and flows, which can be plotted through time and compared with this kind of observation.

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[5] https://tweedforum.org/our-work/projects/the-eddleston-water-project/

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

2.1.4 Adapting existing models

Where upstream boundaries are represented using, for example, FEH inflow boundaries, it becomes difficult to understand how flows from different parts of the whole catchment interact during a real event (synchronisation effects) and how this response changes with many distributed NFM features. The whole catchment model approach helps with understanding when and where new NFM storage is filling during a real event, and whether volumes will be taken from the peak of the hydrograph, where it is more effective at reducing flooding. Where there are properties at risk, there is more likely to be an existing model, for which there are different ways of incorporating NFM features. A matrix-diagram was provided in the EA-Evidence Directory Chapter[7] (Burgess-Gamble et al., 2017), which helps identify parameters to change and summarises some useful tools, from spreadsheet approaches to modifications to broadscale models.

However, including a new broadscale rainfall-driven whole catchment model, of the kind set up for Eddleston Water, that makes use of new high-resolution LiDAR data can help understand how the different measures impact the distributed catchment response. 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 (Hydraulic Engineering Centre, 2020), distributed changes to friction and storage have been demonstrated, whereas distributed changes to hydrological losses is expected to be available in the next release, version 5.10.

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

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

2.2 Overall modelling process

Figure 2-2 brings together an overall strategy for combining a calibrated distributed hydrological-2d hydraulic model to investigate integrated flood risk management. Some of the steps may not be possible such as calibration for ungauged catchments, although model proving can be effective using local knowledge and trash-line surveys from particular events, or simply comparing model outlines with existing flood mapping can add value. The approach is generic and although the industry standard tools have been used in Eddleston Water, it would be possible to for example use a distributed hydrological model to drive the 2d model.

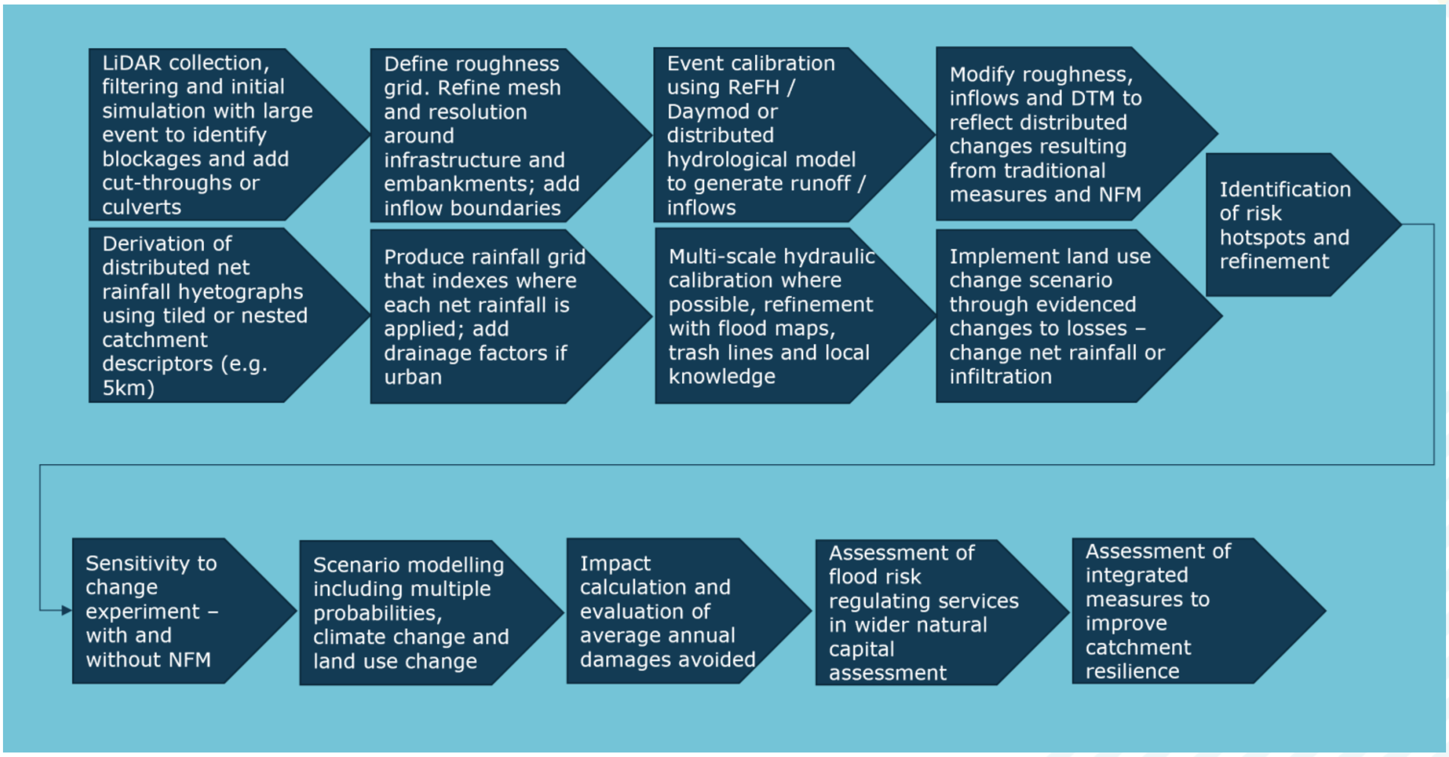

Figure 2-2 Generic Distributed Hydrological and 2D Hydraulic Modelling Process

3 Introduction to the Eddleston Water whole catchment model

The Eddleston Water whole catchment model is a broadscale, HEC-RAS 2D model, set up to investigate 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 for the whole catchment). It permits the representation of hydraulic features 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 ReFH2.2 losses model incorporating 2 years of antecedent rainfall for particular events and using net rainfall and baseflows. It was calibrated using the Tweed Forum monitoring data across small, intermediate and large scales, and the performance at the whole catchment scale using the Kidston Mill monitoring data was reasonably strong. Over the monitoring period investigated (2011-2018) there were not any extreme flows, so the uncertainties in the rating equations, and therefore the calibration data are likely to be greater than changes to hydrograph response that we are trying to detect.

3.1.1 Key datasets

The key datasets for the model are listed below, and where possible open datasets were used in the Eddleston Water modelling to facilitate wider sharing:

- A 0.5m resolution filtered Digital Terrain Model (DTM) for pre-NFM and post-NFM terrain:
  - Pre-NFM: **DEM_4.tif**
  - Post-NFM: **DEM_2.tif**
- The open-data CORINE 2018 land-cover dataset (higher resolution maps can be used if licensed)
  - Pre-NFM: **Landcover_baseline.shp**
  - Post-NFM: **Landcover_wNFM.shp**
- The collated level, flow time series for the Eddleston Water project hydrometry sites from the University of Dundee. Key sites for multi-scale calibration used were:
  - *Small scale:* Middle Burn and Shipton Burn
  - *Intermediate scale*: Eddleston Village
  - *Whole catchment scale*: Kidston Mill
- The TBR raingauge time series based on data compiled by University of Dundee and some local SEPA raingauges
- Ordnance Survey Open data including rivers, water lines and areas.

3.1.2 Model assumptions

All models make assumptions, and the type of model set-up here is based on the broad-scale modelling approach used to produce for example national Surface Water maps with a key difference being it is set up for the whole catchment. The approach is called a 'direct rainfall and losses model' (schematised in Figure 3-1), and simulates the rapid runoff component, driven by the net rainfall for the whole catchment based on the ReFH2 losses model (Kjeldson, 2007) which has undergone a number of refinements and is now on version 2.3[8].

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[8] See https://www.hydrosolutions.co.uk/software/refh-2/

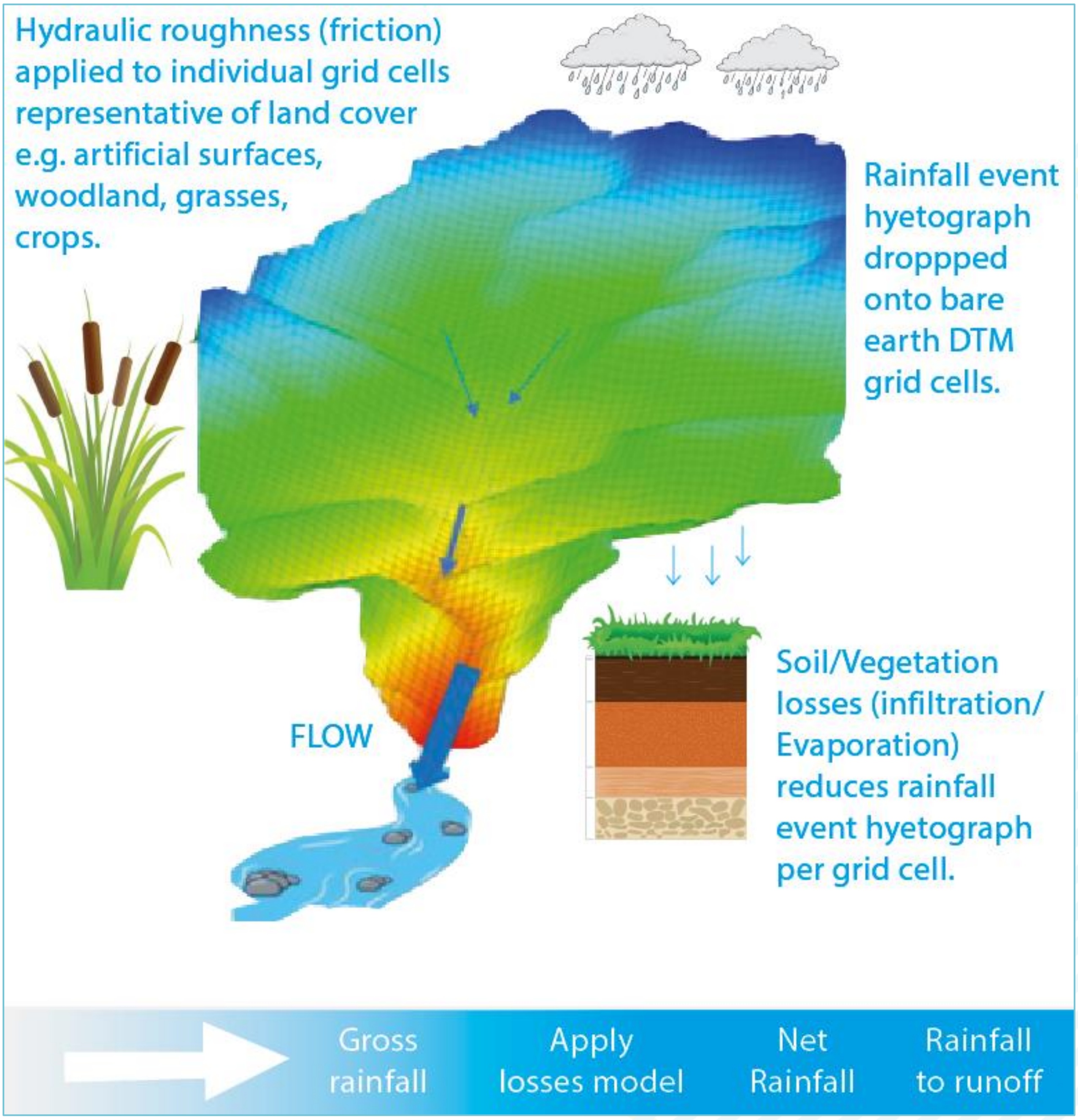

Figure 3-1 Schematic of direct rainfall and losses approach (copyright JBA)

The model is a broadscale 2D-only model suitable for taking advantage of new, higher resolution LiDAR datasets that are becoming more commonly available and more affordable. The key modelling specification and assumptions are:

- The model is set up in Version 5.07 of the license-free HEC-RAS 2D package[9] and the intention is to upgrade this to version 5.10 once available, to enable further improvements (e.g. distributed hydrological losses).
- The model simulates direct runoff driven by the net rainfall from the ReFH2 rainfall runoff and losses model for design and real storm events.

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[9] https://www.hec.usace.army.mil/software/hec-ras/

- ReFH2.2 calibration utility, or DAYMOD has been used to simulate real events, in combination with 2 years of antecedent rainfall and estimates of evaporative losses. This can be used in a distributed sense once spatially varying rainfall fields can be used as expected for HEC-RAS version 5.10. Alternative 2D hydraulic models can be used, and recent research has also demonstrated how distributed rainfall-runoff modelling can be used in a hybrid approach to drive a 2d hydraulic model (see for example Hankin et al., 2019).
- Baseflows are re-introduced along the main stem of the river where they contribute more significantly.
- The default 2D diffusion wave solver has been used, which can be improved in terms of accuracy using the full momentum equation solver although this can take considerably longer to run in the current version 5.07. This was undertaken for the refined Middle Burn model to demonstrate the diffusion wave approach gave very similar hydrograph response.
- Break-lines (see full Eddleston Water Report) have been incorporated into the mesh along significant embankments in order to reduce leakage of water that can occur. They have also been added along many of the stream centrelines, so the cell faces describe the cross-sections, and in-stream roughness can be represented more accurately. Time spent adding more break-lines can significantly add to the accuracy of a model, especially preventing leakage across areas of convexity in the terrain.

3.1.3 What can and cannot the model be used for?

The model can be used for:

- Understanding how the whole catchment responds to different events and distributed changes to hydrological and hydraulic processes resulting from NFM
- Understanding a range of ‘what-if’ scenarios and the impacts on flooding in the long-term. These changes could include:
    - Future rainfall events and projected events for climate change scenarios
    - Testing of future NFM scenarios, for example which tributary would it be more effective to site an extra 30 ELJs on if time and funding is secured?
- Prioritising where there are risk hot-spots where more detailed investigations can be made – This can be used in a number of ways:
    - Prioritising NFM in small catchments above communities at risk experiencing frequent flooding
    - prioritise development of a finer-scale model to provide greater accuracy such as that developed for Middle Burn
- Understanding flow-pathways and flow accumulations to help with siting of NFM in locations where flood flows can be managed better
- Understanding where there is potentially expandable field storage to accommodate the bigger flows resulting from climate change, enhancing the overall landscape resilience to flooding
- Estimating volumes of water stored on the floodplain.

The model cannot be used for:

- High spatial resolution queries. Whilst the broadscale model can be queried to look at, for example, flood levels at known flooding pinch-points or to derive damages at individual properties, strong conclusions based on this may require corroboration through more detailed modelling (e.g. Middle Burn model) or summarising at a sensible spatial unit, such as property damage reduction over a ward boundary rather than at an individual property point. The broadscale model has a relatively coarse numerical cell size (20m, but finer around channels and embankments), and although the sub-grid detail is included at the 0.5m resolution of the LiDAR, the accuracy of levels and flows also depends on how well the mesh has been refined around finer-scale features such as building edges, walls and whether drainage infrastructure is represented at all.

- Continuous simulation. The rainfall losses model is based on ReFH2.2, which is not suited for continuous simulation of losses, although going forwards this is possible in version 2.3. In addition, the model is currently set-up to model storage as depressions in the landscape and does not model how these would drain-down between events. To change this, each feature or new large features where behaviour for multi-peaked events would need to be represented using an appropriate hydraulic unit such as an embankment coupled with a box culvert to allow a slow drain-down, or through using the distributed hydraulic conductivity approach (e.g. Green-Ampt scheme in Tuflow). These approaches would benefit from sensitivity testing to Cini and level measurements in depressions prior to the flood event. They can also slow the model run-time down, and it may be better to build a finer-scale model of a portion of the catchment of interest if multi-peaked events require modelling. It is still important to model multimodal events if possible, since it can be the peaks later in a sequence that cause worse flooding.
- Distributed losses. Currently, the model uses losses averaged over the whole catchment. Once version 5.1 is released it will be possible to distribute the rainfall and therefore losses based on variable hydrology. However, it is important to understand that there are still large uncertainties in the size of the hydrological changes in response to NFM in terms of infiltration, wet canopy evaporation and friction.
- Flood forecasting – the model is a broadscale model and whilst the peak and shape of the hydrograph for the key event on record are well matched, it has a tendency to predict the peaks early.

3.1.4 How has NFM been represented?

There are several different ways to emulate the effect of NFM on catchment processes in the model centred around storage, friction and losses. These represent physical processes that are easily related to, but the difficulty is deciding by how much to change the ‘effective’ friction or the losses to represent what happens in reality, with several recent summary publications attempting to address this (see for example Hankin et al., 2017a, Addy and Wilkinson, 2019 and Page et al., 2020)

The current modelling has focussed on changes impacting hydraulics and hydrodynamics, including flow-restrictors based on engineered log-jams[10], re-meandering, storage such as ponds and riparian tree-planting. The changes have been implemented through simple changes to friction and the topography whereas the distributed losses due to, for example, changes in infiltration have not been modelled in detail pending release of version 5.10.

A finer-scale model of the Middle Burn tributary was constructed using different representations of engineered log-jams designed to push water onto the floodplain to enable temporary high flow storage. It was found that detailed representation of the leaky-barriers using hydraulic units could be emulated in their effect on the hydrograph using increased friction at the reach-scale. This helps with the broadscale model representation, since the use of such units requires smaller time steps to maintain model stability, and the large model can then require prohibitively long run times. The broadscale model therefore represents these

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[10] https://tweedforum.org/our-work/projects/the-eddleston-water-project/eddleston-water-project-a-natural-flood-management-gallery/

structures as increases to friction. The same approach has been used for tree-planting, using values from ranges in hydraulics literature[11] 0.1 to 0.15 as described in the full modelling report. Those undertaking new work with the Eddleston Water model are referred to the full report and the wider research to ensure that appropriate values are used. Significant changes to topography such as re-meandering, scrapes or ponds have been modelled using a modified DTM, and these modifications can come from earlier models or surveys (or proposed plans if looking at future NFM proposals) and become incorporated into the terrain used for the model.

For the Eddleston Water model (see full report), the changes in Table 3-1 were recommended, with improvements for when the next version of HEC-RAS 2D is released.

Table 3-1: Representing Nature Based Solutions in new model runs

NBS or NFM phenomenon	How to	Evidence	Limitations
Slowing the flow with roughened up landscape or tree-planting in riparian flood zones	Increase the modelled friction for the new surface by increasing Manning's either using a new Manning's grid or using 'Manning's overrides'	See Addy and Wilkinson summary paper[11] 2019, the Shuttleworth et al., 2019 paper, and the main Phase 2 report for values used.	Does require more research on grid-size dependence
Slowing the flow with engineered log-jams or leaky barriers	At the broad scale increase friction in the mesh elements representing the channel. Representation of the channel can be improved through modifying the mesh cell spacing by for example including a break-line along the centreline and spacing cells more finely. For smaller catchments where a more detailed model is built, hydraulic units can be used such as embankments with culverts.	Phase 2 Eddleston Water project report. Addy and Wilkinson[11] provide a recent summary Hankin et al paper[10]	Broadscale and fine-scale representations benefit from measurements. At the broadscale trash-line surveys and water surface slope can help, at fine-scale more measurements are needed to calibrate multiple coefficients in the hydraulic units. Once these are more representative of the energy losses the confidence increases in the predictive power of the model.
Increased storage / floodplain re-connection through using deflectors or re-meandering approaches	Change the Digital Terrain Model (DTM) by adding depressions or embankments. It can be important to add break-lines along the top of significant embankments to avoid leakage across cell-faces.	A range of studies summarised in the EA WWNP Evidence Directory (Burgess-Gamble et al, 2018)	To properly represent drain-down from storage between multiple events hydraulic units should be added to study in more detail
Increased hydrological losses due to improved	Currently a broad-scale approach was used	This area of science is most uncertain –	Most approaches for broadscale modelling

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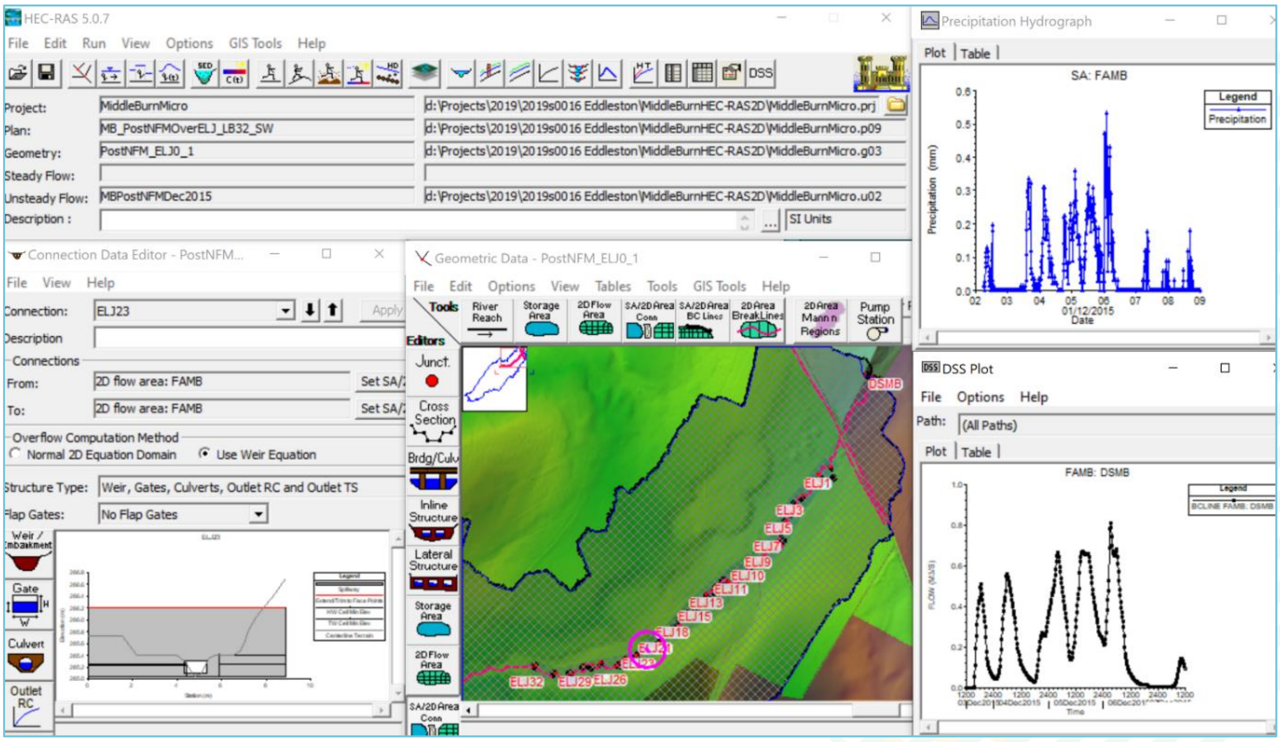
[11] Chow VT. Open Channel Hydraulics. International Edition. McGraw-Hill; US. 1959. 680 p

infiltration, soil storage and wet canopy evaporation	which should be improved in version 5.10 when both distributed losses or infiltration will be possible.	the translation of changes in model parameters to reflect how infiltration and soil storage change and in turn influence the hydrograph. Broadscale assumptions on distributed soil moisture is the most simple approach (e.g. used in the creation of national scale Surface Water flood maps[12]).	do not feed the infiltrated flows back to the channel at a later time. In the current model, the ReFH baseflows are fed back into the channel but timing and volumes are not things that are easily predicted.

3.1.5 What does the HEC-RAS 2D model look like?

The HEC-RAS 2D interface is shown in Figure 3-2 which highlights the main user interface, the geometry editor (with hydraulic unit representation of leaky barrier shown), and the unsteady boundary condition data (inset precipitation shown) predicted outflow (DSS plot inset). There are many other controls in HEC-RAS 2D but it includes a very detailed technical manual available once installed[13].



Project: MiddleBurnMicro — d:\Projects\2019\2019s0016 Eddleston\MiddleBurnHEC-RAS2D\MiddleBurnMicro.prj
Plan: MB_PostNFMOverELJ_LB32_SW — d:\Projects\2019\2019s0016 Eddleston\MiddleBurnHEC-RAS2D\MiddleBurnMicro.p09
Geometry: PostNFM_ELJ0_1 — d:\Projects\2019\2019s0016 Eddleston\MiddleBurnHEC-RAS2D\MiddleBurnMicro.g03
Steady Flow:
Unsteady Flow: MBPostNFMDec2015 — d:\Projects\2019\2019s0016 Eddleston\MiddleBurnHEC-RAS2D\MiddleBurnMicro.u02
Description :
SI Units

Connection: ELJ23
Description
Connections
From: 2D flow area: FAMB
To: 2D flow area: FAMB
Overflow Computation Method
○ Normal 2D Equation Domain ● Use Weir Equation
Structure Type: Weir, Gates, Culverts, Outlet RC and Outlet TS
Flap Gates: No Flap Gates

Path: (All Paths)

Figure 3-2 The HEC-RAS 2D interface showing example windows

The GIS post-processing part of the model is called RAS-Mapper (Figure 3-3) and more outputs from this are shown in later sections when exploring model outputs.

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[12] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/297429/LIT_8986_eff63d.pdf

[13] https://www.hec.usace.army.mil/software/hec-ras/download.aspx

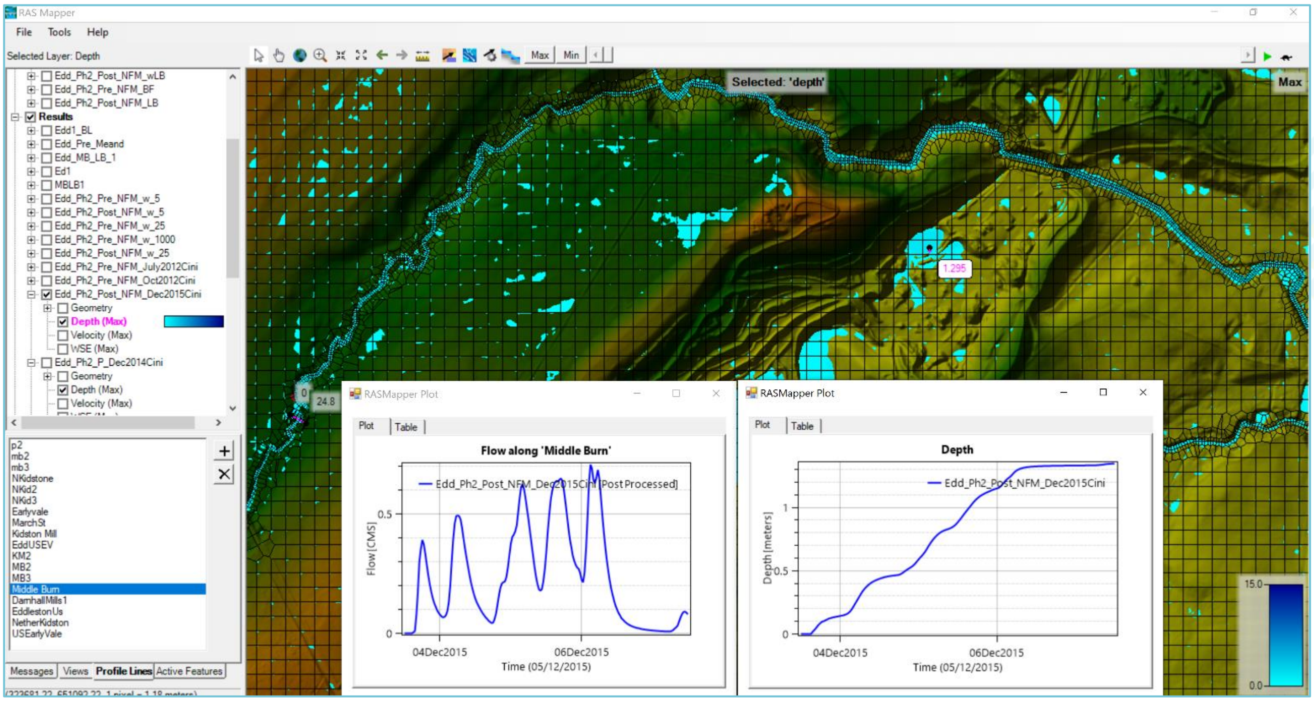


Figure 3-3 The HEC-RAS 2D RAS-Mapper interface with example time series plots inset

3.2 Simulated scenarios

The following is provided for future appraisers and researchers wanting to develop the model further or run of new 'what-if' scenarios.

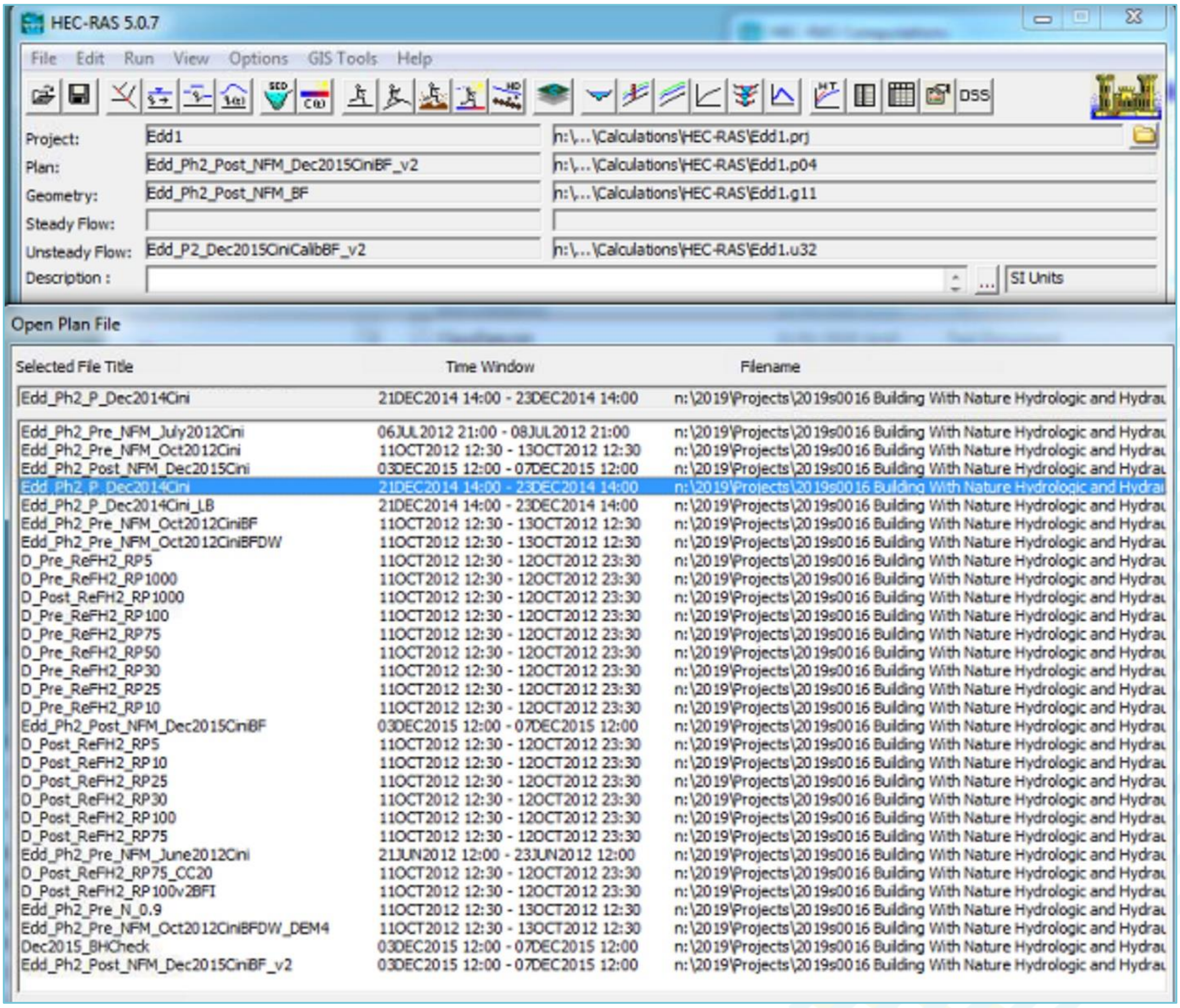
3.2.1 How are the model project and plans set up?

The model is setup with a series of plans that describe the scenarios that have been modelled. These are summarised in Table 1, with a screenshot of the plans in the modelling interface shown in Figure 3-4.

Table 3-2: Summary of key model plans

Scenario	Plan	Terrain and land cover	Comments
June 2012 calibration event	Edd_Ph2_Pre_NFM_June2012Cini	DEM_4PreTerrain + Mannings_n_C18_Pre_NFM	Over-predicted but used as has a partial trash-line survey
July 2012 calibration event	Edd_Ph2_Pre_NFM_July2012Cini	DEM_4PreTerrain + Mannings_n_C18_Pre_NFM	Rainfall not uniform over catchment
Oct 20212 calibration event	Edd_Ph2_Pre_NFM_Oct2012CiniBFDW	DEM_4PreTerrain + Mannings_n_C18_Pre_NFM	Key pre-NFM calibration event
Dec 2014 event –	Edd_Ph2_P_NFM_Dec2014Cini		not used in calibration
Dec 2015 multi-modal event	Edd_Ph2_Post_NFM_Dec2015Cini	DEM_4PostTerrain + Mannings_n_C18_Post_NFM	Key post-NFM calibration event

Pre-NFM design events	D_Pre_ReFH2_RP5 .. .. D_Pre_ReFH2_RP1000	DEM_4PreTerrain + Mannings_n_C18_Pre_NFM	
Post-NFM design events	D_Post_ReFH2_RP5 .. .. D_Post_ReFH2_RP1000	DEM_4PostTerrain + Mannings_n_C18_Post_NFM	



Project: Edd1 n:\...\Calculations\HEC-RAS\Edd1.prj
Plan: Edd_Ph2_Post_NFM_Dec2015CiniBF_v2 n:\...\Calculations\HEC-RAS\Edd1.p04
Geometry: Edd_Ph2_Post_NFM_BF n:\...\Calculations\HEC-RAS\Edd1.g11
Steady Flow:
Unsteady Flow: Edd_P2_Dec2015CiniCalibBF_v2 n:\...\Calculations\HEC-RAS\Edd1.u32
Description :
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Selected File Title	Time Window	Filename
Edd_Ph2_P_Dec2014Cini	21DEC2014 14:00 - 23DEC2014 14:00	n:\2019\Projects\2019s0016 Building With Nature Hydrologic and Hydrau
Edd_Ph2_Pre_NFM_July2012Cini	06JUL2012 21:00 - 08JUL2012 21:00	n:\2019\Projects\2019s0016 Building With Nature Hydrologic and Hydrau
Edd_Ph2_Pre_NFM_Oct2012Cini	11OCT2012 12:30 - 13OCT2012 12:30	n:\2019\Projects\2019s0016 Building With Nature Hydrologic and Hydrau
Edd_Ph2_Post_NFM_Dec2015Cini	03DEC2015 12:00 - 07DEC2015 12:00	n:\2019\Projects\2019s0016 Building With Nature Hydrologic and Hydrau
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D_Post_ReFH2_RP1000	11OCT2012 12:30 - 12OCT2012 23:30	n:\2019\Projects\2019s0016 Building With Nature Hydrologic and Hydrau
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D_Pre_ReFH2_RP75	11OCT2012 12:30 - 12OCT2012 23:30	n:\2019\Projects\2019s0016 Building With Nature Hydrologic and Hydrau
D_Pre_ReFH2_RP50	11OCT2012 12:30 - 12OCT2012 23:30	n:\2019\Projects\2019s0016 Building With Nature Hydrologic and Hydrau
D_Pre_ReFH2_RP30	11OCT2012 12:30 - 12OCT2012 23:30	n:\2019\Projects\2019s0016 Building With Nature Hydrologic and Hydrau
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D_Pre_ReFH2_RP10	11OCT2012 12:30 - 12OCT2012 23:30	n:\2019\Projects\2019s0016 Building With Nature Hydrologic and Hydrau
Edd_Ph2_Post_NFM_Dec2015CiniBF	03DEC2015 12:00 - 07DEC2015 12:00	n:\2019\Projects\2019s0016 Building With Nature Hydrologic and Hydrau
D_Post_ReFH2_RP5	11OCT2012 12:30 - 12OCT2012 23:30	n:\2019\Projects\2019s0016 Building With Nature Hydrologic and Hydrau
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D_Post_ReFH2_RP75	11OCT2012 12:30 - 12OCT2012 23:30	n:\2019\Projects\2019s0016 Building With Nature Hydrologic and Hydrau
Edd_Ph2_Pre_NFM_June2012Cini	21JUN2012 12:00 - 23JUN2012 12:00	n:\2019\Projects\2019s0016 Building With Nature Hydrologic and Hydrau
D_Post_ReFH2_RP75_CC20	11OCT2012 12:30 - 12OCT2012 23:30	n:\2019\Projects\2019s0016 Building With Nature Hydrologic and Hydrau
D_Post_ReFH2_RP100v2BFI	11OCT2012 12:30 - 12OCT2012 23:30	n:\2019\Projects\2019s0016 Building With Nature Hydrologic and Hydrau
Edd_Ph2_Pre_N_0.9	11OCT2012 12:30 - 13OCT2012 12:30	n:\2019\Projects\2019s0016 Building With Nature Hydrologic and Hydrau
Edd_Ph2_Pre_NFM_Oct2012CiniBFDW_DEM4	11OCT2012 12:30 - 13OCT2012 12:30	n:\2019\Projects\2019s0016 Building With Nature Hydrologic and Hydrau
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Edd_Ph2_Post_NFM_Dec2015CiniBF_v2	03DEC2015 12:00 - 07DEC2015 12:00	n:\2019\Projects\2019s0016 Building With Nature Hydrologic and Hydrau

Figure 3-4 The HEC-RAS 2D plans within the software

3.2.2 How can I re-run the model for new scenarios?

These HEC-RAS 2D plans can be used as templates or starting points for the development and running of new 'what-if' scenarios. The GIS data for the scenarios are provided as electronic deliverables so this can also be edited rather than starting from scratch to modify, for example, the location of tree-planting or new storage areas. A good starting point is to open an existing plan (above) and either edit the geometry or boundary conditions and save that with a new filename. HEC-RAS 2D will then force you to make a new plan – so that results are not overwritten for the plan you started with. When focussing in on an area the model can be improved by modifying the mesh, and checking that the model is stable. It has been simulated here with quite relaxed time steps that give a pragmatic stability condition (see the HEC-RAS 2D manual and Appendix A of main Eddleston Water modelling report), although this can always be improved and users can switch to the full momentum equations to improve accuracy around hydraulic structures if needed.

3.3 Interacting with the model

There are a range of methods for extracting model results and understanding the model outputs. Key methods include:

- Clicking on the DSS (Data Storage System) button, identifying a boundary condition location such as the downstream limit of the model and plotting the hydrograph (see bottom right of Figure 3-2) – which can then be copied and pasted for analysis in MS Excel
- Opening the RAS-Mapper part of the software (see Figure 3-3 and next section) and viewing the model results in terms of:
    - Spatial maps of flood depth, flood velocity and a range of other outputs such as shear stress
    - These maps can be exported to a raster '.tif' format and used in GIS for example for more detailed mapping or, for example, flood volume calculations
- Depth-time series by right clicking anywhere in model domain and plotting the time series
- Set up a cross-section profile anywhere in the model domain and plot:
    - Flow (discharge) hydrograph time series
    - Cumulative flow volume
    - Stage-discharge rating curve
- Within the geometry editor water level (depth) time series can be plotted in for instance the vicinity of any structures or boundaries.

The next few sections provide some demonstration outputs especially with regards to using RAS-Mapper and also how these outputs can then be used to estimate damages or damages avoided.

3.4 How can I Interrogate the model for hydrographs?

It is possible to query the model as a post-process, as described in the previous section the RAS-Mapper interface is opened and a profile line is drawn across the river (highlighted with red circle in Figure 3-5) and having named the profile, the user right-clicks on its name in the list to display for example the hydrograph. The figure shows the peak flow reduction between pre and post NFM scenarios for Middle Burn based on the whole catchment model.

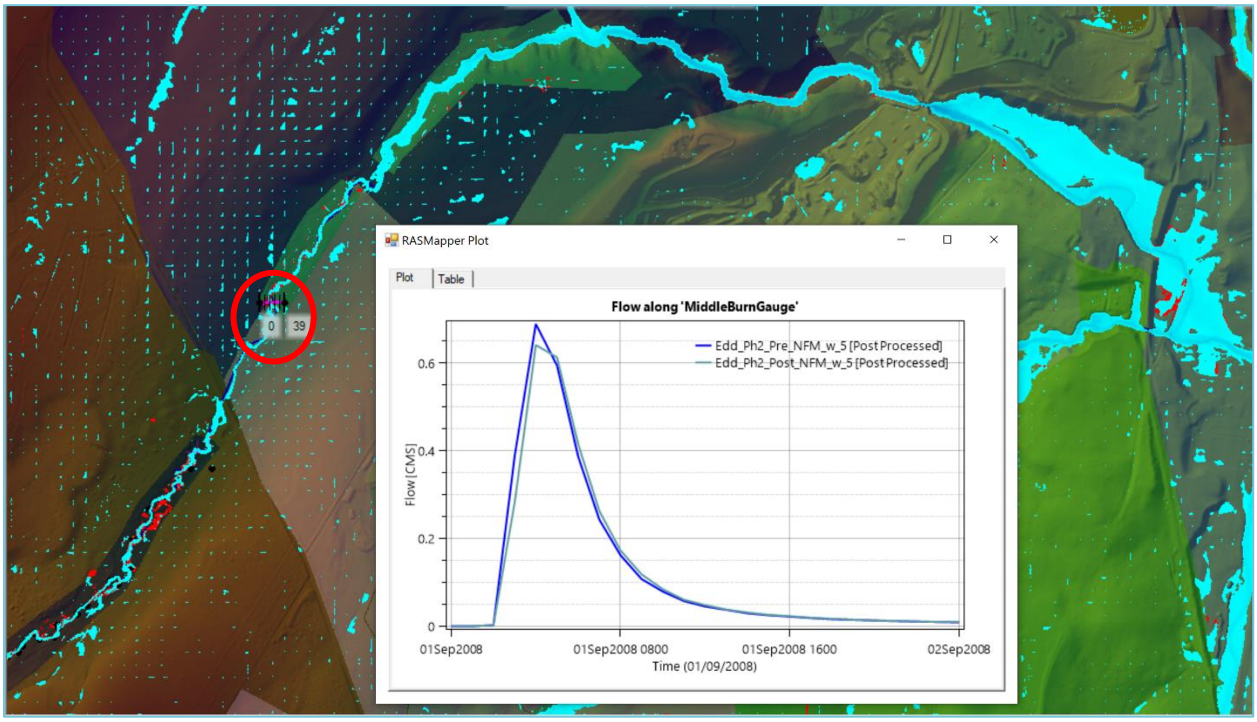
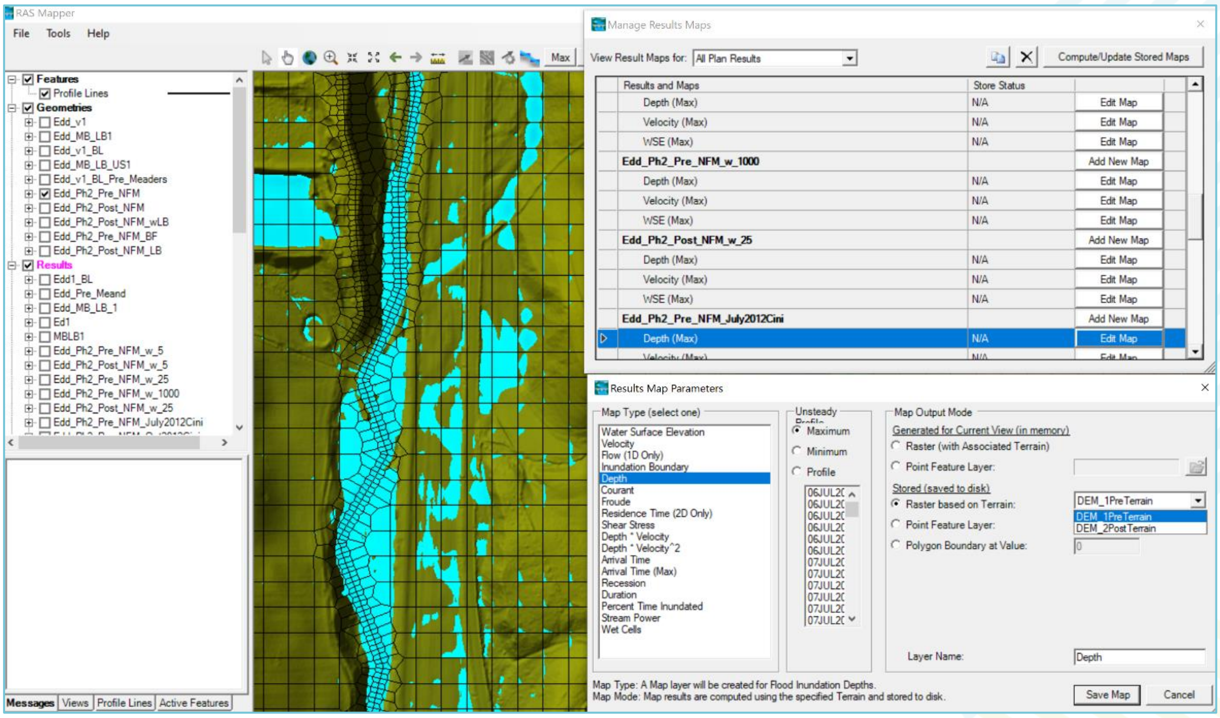


Figure 3-5 Generating a hydrograph

The model flood depth grids shown in RAS-Mapper can also be exported as a .tif for use in GIS and for example assessing the impacts against property data as shown in the next section. This is achieved through right clicking on the Results layer and 'Managing Results Maps' (Figure 3-6). The user selects the relevant depth or velocity grid and selects 'stored (saved to disk)'. The depths are then mapped back to the DTM – so ensure that the correct one is selected.



View Result Maps for: All Plan Results

Results and Maps	Store Status	
Depth (Max)	N/A	Edit Map
Velocity (Max)	N/A	Edit Map
WSE (Max)	N/A	Edit Map
Edd_Ph2_Pre_NFM_w_1000		Add New Map
Depth (Max)	N/A	Edit Map
Velocity (Max)	N/A	Edit Map
WSE (Max)	N/A	Edit Map
Edd_Ph2_Post_NFM_w_25		Add New Map
Depth (Max)	N/A	Edit Map
Velocity (Max)	N/A	Edit Map
WSE (Max)	N/A	Edit Map
Edd_Ph2_Pre_NFM_July2012Cini		Add New Map
Depth (Max)	N/A	Edit Map
Velocity (Max)	N/A	Edit Map

Map Type (select one): Water Surface Elevation, Velocity, Flow (1D Only), Inundation Boundary, **Depth**, Courant, Froude, Residence Time (2D Only), Shear Stress, Depth * Velocity, Depth * Velocity^2, Arrival Time, Arrival Time (Max), Recession, Duration, Percent Time Inundated, Stream Power, Wet Cells

Unsteady Profile: ● Maximum ○ Minimum ○ Profile

Map Output Mode

Generated for Current View (in memory)

○ Raster (with Associated Terrain)

○ Point Feature Layer:

Stored (saved to disk)

● Raster based on Terrain: DEM_1PreTerrain (DEM_1PreTerrain, DEM_2PostTerrain)

○ Point Feature Layer:

○ Polygon Boundary at Value: 0

Layer Name: Depth

Map Type: A Map layer will be created for Flood Inundation Depths.
Map Mode: Map results are computed using the specified Terrain and stored to disk.

Figure 3-6 Saving depth grids to .tif for use in GIS

3.4.1 How can I investigate distributed losses?

The new version of HEC-RAS 2D will have a new flow solver and allow for spatially varying precipitation. This means that it will be straightforward to invoke spatial patterns to hydrological losses, reflecting more local hydrology in place of the catchment-wide ReFH losses that are used in the current model. This has for instance been achieved for national scale surface water mapping, through varying the FEH descriptors rainfall on a 5km gridded basis so the net rainfall at each location reflects more localised soil (and condition). The impacts of soil condition on this more local basis will still be subject to large uncertainties at the whole catchment scale discussed in the main report. There are also two key other approaches currently in use for representing distributed losses:

- Use of a distributed hydraulic conductivity so that soil infiltration rates can be computed through time depending on soil moisture conditions. Some 2d modelling packages such as Tuflow permit this, and model the resulting infiltration using a Green-Ampt scheme.
- Use of a distributed rainfall-runoff model to predict the delivery of flows to individual reaches of channel and incorporating these using inflow boundaries in for example HE-RAS 2D (see Hankin et al., 2019).

3.4.2 How do I compute impacts?

Damages and average annual damages can be estimated by simulating multiple probability design events and using the Multi-Coloured-Manual[14] depth-damage curves as demonstrated in the main report (Appendix B). The user needs to export the maximum depth grids or water surface elevations from RAS-Mapper (Figure 3-6) and intersect these with property-point data or building footprints. The damages are estimated for different property-types using the MCM curves for each design event and then weighted using the annual exceedance probability. This gives the long-term average annual damage, and damages-avoided (assuming well-placed NFM) can be estimated as the difference in damages between baseline and NFM scenarios. There can be disbenefits of poorly-NFM (such as unwanted backwater effects) which can be in-part avoided using whole catchment model to explore solutions. It is also important to consider other pathways such as failure mechanisms, or at least reduce their potential impacts.

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[14] https://www.mcm-online.co.uk/

4 Summary

4.1 Introduction

This technical user-guide provides guidance on the use of the new broadscale model of Eddleston Water and the wider implications for application of the technique elsewhere. Decision support has been developed to meet this aim, which recommends a proportionate modelling approach, depending on the scale of risk, size of catchment and availability of existing models and data. There are trade-offs to be made between the complexity of a model of NFM, how well it can be supported by evidence, model stability and model run-time. The whole catchment modelling approach is recommended for assessing changes in response resulting from spatially distributed NFM in the wider catchment.

NFM is a generic term that can represent a broad range of measures from engineered log jams to tree-planting and floodplain reconnection. It has been represented in relatively simple ways in the broadscale Eddleston Water model, but it has been possible to calibrate the model reasonably well across multiple scales for some key flood events. This makes it useful for testing 'what-if' scenarios, where NFM can be represented alongside traditional measures to understand the overall risk-reduction and help with more integrated flood risk management. The following recommendations are made with regards to using the Eddleston Water broadscale model or the same approach for wider studies (see also the full modelling report for more details):

- 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 provides 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 (Burgess-Gamble et al., 2017), which builds further on the SEPA NFM Handbook. There is also an increasing amount of material on NFM design at the UK and international levels (WWF, 2016). For example, some NFM changes to the catchment system, such as soil improvement could be considered as 'no-regrets' actions to reduce 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 or large scale land-use change are implemented, it is very difficult to measure changes in hydrograph response. It is recommended that smaller sub-catchments are used both in monitoring and modelling as 'demonstrators' of how NFM works before scaling up findings using better constrained models. Two of the three UKRI NERC projects on testing the effectiveness of NFM are taking this approach.
- It is recommended that the hydrology and hydraulic simulations are undertaken for a range of storm events, including extreme flows giving rise to flooding if available. There is greater uncertainty in rating equations at high flows, and in particular uncertainty in the estimation of the probability or return period of the highest flows on record in Eddleston Water.
- Whilst the high resolution, 0.5m LiDAR DTM has proven invaluable for computing for example changes to conveyance and storage, the DTM should be checked for offset issues such as those encountered in the Eddleston Water project, as this and the quality of the filtering of woodland at the outset of a project.
- The appraisal of risk reduction due to NFM or NFM in combination with traditional measures is possible with the new class of 2D models that allow embedded hydraulic structures in a flexible mesh. It is useful to put the damages avoided for NFM in context of wider natural capital assessment, such that the multiple benefits are recognised alongside flood risk regulating services.

- The new version of HEC-RAS 2D (v5.10), or other existing proprietary software (TUFLOW, JFlow, etc), 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. A generic process diagram of applying similar techniques is provided in figure 2-2, which also provides alternatives such as the distributed hydrology modelling and the 2D hydraulic software.
- Lessons can be learned from the new whole-catchment model of Eddleston Water and applied to other studies. The model has allowed an exploration of how the whole system responds with many distributed changes, and a range of sensitivity to change experiments. 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 spatially strategic about NFM 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 that could impact a downstream community.
- Uncertainty can always be explored further. Monte-Carlo simulations can be undertaken to understand influence of parameter uncertainty (especially the effective roughness) on the model predictions – using for example the 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).

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