The Rivers Trust Life-IP
Natural Course Project:
Strategic Investigation of
Natural Flood Management in
Cumbria
Technical Report
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Purpose

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Executive Summary

This study has investigated Natural Flood Management (NFM) in a tiered approach across the Eden, Kent and Derwent catchments in Cumbria, to help prioritise where different NFM measures are likely to be more effective. Commencing with a rapid overland flow modelling approach using a 2m resolution 2D inundation model (JFLOW), a screening was undertaken to identify where modification of features in the landscape to slow and store surface water flows might make the most difference. These included Runoff Attenuation Features (RAFs), tree-planting, and soil structure improvements. Following a stakeholder workshop with catchment partners, these opportunities were refined and sub-catchments were prioritised for more detailed modelling using Dynamic TOPMODEL. The JFLOW models were re-run, and the benefits were re-computed and summarised in a suite of interactive maps that can be used, along with a User Guide, to help inform decisions at the wider catchment scale.

Dynamic TOPMODEL was then used to model the priority sub-catchments to help understand the effect of NFM on the total hydrograph, including contributions from overland flow and subsurface flow. The three detailed models were calibrated against real data collected during the period Nov - Dec 2015, in order to capture catchment wetting by Storms Abigail and Barney prior to Storm Desmond. A framework was designed to represent both the uncertainties in the model parameters, and the gaps in the scientific evidence on how much different NFM measures influence catchment processes. A large number of simulations were undertaken for each catchment, and a set of model parameterisations showing 'acceptable' performance on the basis of the evidence, were determined based on a range of measures including the ability of the models to reproduce the observed peak flow for Storm Desmond.

The Dynamic TOPMODEL findings demonstrated that the combined effects of enhanced wet-canopy evaporation, infiltration and surface roughness associated with the addition of deciduous trees to key locations in the landscape produced significant reductions to flood peaks even for an event as extreme as Desmond. Making changes to individual hydrological parameters in the Eden woodland scenario demonstrated that the evaporative changes gave rise to the largest reduction in flood peaks, but that there was an in-combination effect whereby the overall effect from modifying 3 parameters (overland flow velocity, transmissivity and we canopy evaporation) to represent tree-planting was greater than the sum of the individual effects.

The two modelling strategies have helped to increase our knowledge of how and where in each catchment NFM measures can be more effective to reduce flood risk based on available datasets. The models help shed more light on the complexities of the streamflow generation mechanisms at work in the upland headwaters, in more detail than before, adding to the existing body of information on these catchments.

Comparisons between the peak streamflow reduction predicted by Dynamic TOPMODEL for tree-planting, and the reduction in peak streamflow using JFLOW have been shown to be similar for the Eden when adjusted for the components of flow that each model simulates. The attenuation of the peak flows as modelled with Dynamic TOPMODEL will become more significant as more areas produce overland flow, which can then be slowed down by additional roughness. For areas of expected high overland flow production, tree planting (in areas that follows best practice) or gulley blocking, that also targets the smaller, dendritic and ephemeral channels and depressions that may channel water is therefore important.

Using Dynamic TOPMODEL, we have also modelled drain-down of RAFs successfully with different time constants, and shown that for the Kent, RAFs designed with an intermediate drain-down time of around 10 hours would be more effective for a series of flood events as we saw in November through December 2015, although longer duration drain-down would perform well in the Cocker and upper Eden where there are proportionately more RAFs. The JFLOW modelling only covers single design events and assumes the RAFs are designed to be initially drained-down. Nonetheless, JFLOW is fully distributed at 2m resolution for very large areas and can tell us much about the effect of the critical overland flow pathways and accumulations, and how modifying those pathways and stores can slow and retain fast flows.

The models have helped to quantify by how much working with natural processes can improve the flood regulation in terms of the relative reduction of peak streamflow or by changes to timing, although this study has not attempted to quantify the other multiple benefits from NFM such as carbon storage or reduction of the impacts of diffuse pollution.
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Abbreviations

BFIHOST ................. Base Flow Index Hydrology Of Soil Types
Cmax........................ Maximum soil moisture capacity
DTM ......................... Digital Terrain Model
EA .......................... Environment Agency
EU ........................ European Union
IFSAR ........................ Interferometric Synthetic Aperture Radar
IHM ........................ Integrated Height Model
JRAFF ........................ JBA Consulting’s Runoff Attenuation Feature Finder
NFM ........................ Natural Flood Management
NFRM ........................ Natural Flood Risk Management
PROPWET.................. Proportion of time soils are wet
ReFH ........................ Revitalised Flood Hydrograph
URBEXT1990 ................ Urban Extent in 1990
WFD ........................ Water Framework Directive
WW ........................ Woodlands for Water
WWNP ........................ Working With Natural Processes
1 Introduction

1.1 Purpose and Scope of Study

Natural Flood Management (NFM) or Working With Natural Processes (WWNP) has the potential to enhance the flood regulating capacity of a catchment, alongside the provision of a wide range of other services that are not associated with traditional hard defences, from pollution assimilation to habitat creation and carbon storage (Figure 1-1). JBA Consulting (in association with Lancaster University) were commissioned by the Rivers Trust to investigate the strategic potential for NFM at the whole catchment scale in a tiered approach driven by catchment partners. The study was designed to produce a set of strategic catchment scale maps to highlight the opportunities and benefits of NFM based on distributed modelling for the three Cumbrian catchments of the Kent, Eden and Derwent within the Life-IP project area. These will enable a high level understanding of how the catchment streamflow response changes with distributed NFM measures, in terms of modelled changes to the peak streamflow, and timings of peaks between sub-catchments. In addition, the intention was to engage catchment groups and provide an opportunity to discuss and refine the maps, to help prioritise the most effective places to target NFM measures, and then model these in more detail.

Figure 1-1 NFM and whole catchment flood risk management
1.2 Project Aims and Outputs

The project aimed to:

- Identify opportunities and benefits of NFM considering the whole catchment for the Eden, Kent and Derwent catchments in Cumbria that fall within the area covered by Life-IP in the NW England.
- Engage with catchment stakeholders to understand a range of issues from local flooding mechanisms to land-ownership and historical catchment knowledge.
- Prioritise a set of sub-catchments to model in more detail.
- Undertake more detailed hydrological modelling in areas prioritised by the local River Trusts and investigate some realistic NFM scenarios.

1.3 Study Area

The project spans three major catchments in Cumbria, those of the upper Eden, Derwent and Kent encompassing over 50 draining sub-catchments across an area in excess of 1,000km² as illustrated in Figure 1-2.

![Figure 1-2: Modelled Cumbrian catchments and contributing sub-catchments (shaded polygons modelled in detail with Dynamic TOPMODEL)](image-url)
1.4 Overview of Approach

Figure 1-3 summarises the overall approach that was taken for this investigation, and the different stages are reflected in the sections of this report.

- **Evidence**
  - Review knowledge of the 3 catchments and plans such as the Cumbria Flood Plan
  - Review Evidence Base for effectiveness of different NFM measures

- **Opportunities**
  - Screen distributed WWNP: storage, tree planting, soil structure
  - Data mine updated Flood Map for Surface Water for storage

- **Benefits**
  - Run fully distributed 2m whole catchment rainfall, losses and 2d runoff model
  - Visualise benefits of initial opportunities for workshop

- **Engage**
  - Catchment workshop with Rivers Trust and catchment partners (7th Oct, 2016)
  - Identify which measures are feasible and effective; prioritise detailed modelling

- **Re-Map**
  - Re-run model with realistic options and update visualisations
  - Produce interactive maps showing refined opportunities and benefits

- **Appraise**
  - Undertake more detailed modelling for priority sub-catchments
  - Understand where most people are at risk downstream

- **Evolve**
  - Provide User-Guidance for interactive maps
  - Provide capacity building and training in the longer term

Figure 1-3: Strategic approach to identification of opportunities for natural flood risk management

Following a review of plans and evidence on different NFM, opportunities for appropriate NFM measures were identified using techniques in Section 2. These were represented in a strategic overland flow modelling approach using JFLOW (Lamb et al., 2009), which is detailed in Section 3. JFLOW is extremely fast, enabling a 2m resolution solution of the full 2d flow equations for 500km² catchments. The model is run with and without NFM features in the landscape that slow and store surface water, and the impact is quantified in terms of the effect on the overlap surface flow hydrographs. Section 4 shows how these benefits of NFM were computed and visualised using a suite of interactive maps and spreadsheets.

These were presented at the engagement workshop, where catchment groups helped to modify opportunities in the light of land ownership issues, or knowledge of flow mechanisms or schemes in the pipeline. The opportunities were then re-mapped and re-modelled, and visualised in a suite of Interactive PDFs with a User Guide issued alongside this longer technical report. The catchment partners also helped to identify areas to focus the more detailed modelling using Dynamic TOPMODEL to help quantify the benefits of NFM in these locations more accurately (in part by incorporating subsurface flow routing).

There has been considerable recent development in testing the robustness of distributed NFM measures, including the JBA winning entry to the Defra Floods Modelling Competition (Hankin et al., 2017), which was based around applying similar approaches to those used here, but modelling a wider range of extreme rainfall scenarios based on new statistical techniques that capture the spatial correlations in long term rainfall records. This report should therefore be seen as part of the jigsaw in building confidence of the effectiveness of NFM measures.
2 Identifying Opportunities for NFM

2.1 Introduction

NFM represents a strategy for working with the processes, features and characteristics of the natural environment to regulate downstream flood risk and provide multiple benefits that can enhance natural capital. Traditional engineered flood defence strategies can disturb the natural environment and reduce ecosystem services from a whole catchment perspective, so an approach which supplements established risk reduction strategies with NFM where possible is desirable. The mechanisms to achieve these aims include storing water, increasing soil infiltration, slowing water movement and reducing water flow connectivity. Many of the approaches to NFM can also integrate improvements to the local landscape and ecology further contributing to meeting the objectives of the EU Water Framework Directive (WFD). There are many different opportunities\textsuperscript{1} for NFM across a catchment such as upland mire restoration, revised/modified land management and land use, woodland creation, sediment management, built water storage, river restoration and development of Runoff Attenuation Features (RAFs).

This project investigates three broad categories of NFM opportunities, those of:

- Increasing water storage and slowing water through development of RAFs (label 1 in Figure 1-1)
- Opportunities for soil structure improvement based around land use change (label 2 in Figure 1-1)
- Opportunities for woodland planting and increased vegetation density in slowing the flow (label 3 in Figure 1-1)

The method of representation for these NFM measures within the strategic whole catchment model are outlined in Section 3.4.

2.2 Identification of Runoff Attenuation Features

Research on RAFs (Wilkinson et al., 2010) such as storage ponds, bunds, in-stream storage through woody debris dams and disconnecting drain flow pathways has shown that these features have the potential to reduce flood peaks and increase the time to peak for overland flows and streamflows downstream. Applying RAFs within the headwaters of a catchment therefore has the potential to attenuate sudden short duration storm events and reduce the subsequent flood risk to more urbanised areas of the catchment downstream.

RAFs have been derived from areas predicted at surface water flood risk and which are predicted to accumulate flows or fill natural depressions within the landscape as shown in Figure 2-1. The JRAFF model (JBA Runoff Attenuation Feature Finder) typically identifies areas of isolated flow accumulation, such as ponds and small channels, which may be appropriate to excavate or bund, or disconnect from flow pathways through gulley or ditch blocking. The JRAFF model extracted predicted flood extents sized between 100m$^2$ and 5,000m$^2$, an area threshold considered suited for local land management alterations, and well below the threshold on capacity that would fall under the Reservoirs Act (assuming average depth is a few metres). These areas were further refined to remove urban areas defined within the CORINE land cover 2012 dataset, a 2m buffer of OS OpenData buildings and a 2m buffer of OS OpenData roads which are deemed unsuitable to runoff attenuation features. A 2m buffer of roads results in a 4m wide exclusion zone for feature identification. This threshold has been derived based on typical road widths and ensures that opportunity features within any potential adjacent ditches are retained.

The JRAFF model was then used to calculate the additional storage volume if these areas are deepened (or bunded) by a further 1m before summarising these volumes within user specified areas such as the sub-catchments defined earlier. Given that the baseline predicted surface water flood risk differs between modelled return periods, a separate set of RAFs were identified for the two return periods considered as part of each catchment study. Within the Kent catchment only, any runoff attenuation features identified within peat soils were excluded where hillslopes were greater than six degrees based on current peat restoration practices (Moors for the Future Partnership, 2005).

\textsuperscript{1} Houses of Parliament, Parliamentary Office of Science and Technology, 2011, Natural Flood Management POSTNOTE No.396.
2.3 **Identification of tree-planting opportunities**

Restoring the riparian zone and planting woodland within the floodplain has been simulated to provide the potential for significant flood attenuation (Thomas and Nisbet, 2007, Nisbet and Thomas, 2008). A combination of improvements in wet-canopy interception and evaporation, enhanced soil drying and soil infiltration together with increases in hydraulic roughness which arise from woodland creation can lead to reductions in flood peaks together with delaying and spreading of tributary hydrographs.

The Woodlands for Water (WfW) opportunity EA dataset\(^2\) was supplied by the Environment Agency for this project (see also Broadmeadow et al, 2014). The dataset typically comprises a set of woodland planting opportunity areas such as riparian zones and floodplain areas together with a number of constraints such as urban areas, existing woodland and inland water.

WfW opportunity areas for riparian, floodplain zones and soils with an expected naturally high percentage of overland flow were taken forward, excluding those areas pre-defined as constraints. Whilst the source dataset infers opportunities to plant and enhance woodland areas, this scenario rather reflects a more general improvement in planting density between scrubland and mature forest as it is understood that conversion to mature woodland would not be appropriate across all land covers.

2.4 **Identification of opportunities for soil structure improvement**

This scenario pertains to the fact that many soils have been compacted through more intensive farming practices over a long period of time, and if de-compacted, improved soil structure has potential to take in and store considerably more of the incident rainfall (Packman et al., 2004). This can help reduce overland flow and reduce downstream flood risk.

For the third type of opportunity, soil structure improvement, the modelling targeted a particular land cover (improved grassland) which was identified as one of the most common land covers within each catchment based on the Land Cover Map 2007. For these areas, the catchment descriptor BFHOST (Boorman et al., 1995) was increased by 10% resulting in an equivalent increase in maximum soil moisture storage and reduction in initial soil moisture storage capacity for these land cover areas across the catchment. Users can assess the improvement relative to that for this type of land cover by scaling up by relative area compared to improved grassland.

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2. http://www.forestry.gov.uk/fr/woodlandforwater
There is an approximately linear relationship between total soil moisture storage \( (C_{\text{max}}/2) \) and BFIHOST, in the ReFH losses model:

\[
C_{\text{max}} = 596.7 \ \text{BFIHOST}^{0.95} \ \text{PROPWET}^{-0.24} \tag{1}
\]

For a catchment with 20% improved grassland, and an improvement in BFIHOST of 10%, the increased storage would be estimated using (1) as about 1%, which can be significant depending on the catchment area.

2.5 Sub-Catchment delineation and monitoring lines

To understand the surface runoff (overland flow and streamflow) attenuation benefit of NFM across each catchment, it was necessary to divide each of the three project catchments into a number of sub-catchments (at channel confluences rather than stream gauging stations) as illustrated in Figure 1-2. The Environment Agency’s Water Framework Directive waterbody catchments provided the initial sub-catchment divisions. A minority of these sub-catchments were further split into separate tributaries where this was predicted to improve ‘monitoring’ clarity within the model.

The Kent, Eden and Derwent catchments were sub-divided into 10, 18 and 25 sub-catchment units respectively with an average area of 20km\(^2\) each. Sub-catchments which reside within the overall catchment headwaters (and are not influenced by another sub-catchment upstream) were identified and form priority target areas given that these areas are less likely to be susceptible to downstream tributary flow interference.

At the downstream of each sub-catchment, monitoring lines were added to the whole catchment surface water model. These permitted recording of the predicted surface runoff time series hydrograph which reached the outlet of each sub-catchment from each of the model simulations. These streamflow hydrographs (based on overland flows and in-channel routing of these flows) were then able to be compared between model scenarios to analyse the predicted attenuation benefits resulting from each NFM scenario in comparison with the baseline simulation. Appendix B comprises a spreadsheet where the user can examine the streamflow hydrographs for a range of NFM scenarios and compare to the baseline at distributed locations around the catchment.
3 Strategic Modelling with JFLOW

3.1 Introduction to the whole catchment approach

JBA Consulting have previously completed strategic surface water flood risk modelling using their in-house two-dimensional hydrodynamic modelling software JFLOW (Lamb et al., 2009). This was used to develop the national updated Flood Map for Surface Water (now called the Risk of Flooding from Surface Water - RoFSW) for the Environment Agency which provides information on predicted surface water flood risk and depths, at a 2m resolution for England and Wales (EA, 2013).

The RoFSW technique has now been advanced for modelling whole catchments to understand the distributed impact of NFM measures on predicted overland flow and resultant contribution to streamflow. A 2m resolution model spanning each of the three catchments of the Upper Eden, Derwent and Kent was constructed, in order to inform the baseline surface water flood risk from source to sink.

The characteristics of the strategic approach are:

- Fully distributed, 2m resolution
- Rainfall and Revitalised Flood Hydrograph (ReFH) losses approach
- Overland flow modelling using JFLOW, which solves the full 2d St Venant flow equations
- Focussed on NFM measures in headwaters
- Provides an understanding of the relative timing of peak streamflow around the catchment to help assess any tributary synchronisation issues

This last point is made since it is possible to make flood risk worse, if the flood peaks are synchronised from sub-catchments.

3.2 Rainfall, Losses and 2d Overland Flow Modelling

The model utilises JBA Consulting’s 2d hydrodynamic modelling software JFLOW (Lamb et al., 2009), which has been benchmarked against other 2d inundation models against a wide range of test-cases (Hunter et al., 2008). The approach builds on the blanket rainfall approach (see for example Hankin et al, 2008), which was developed further to include the ReFH losses model (Kjeldsen et al., 2005), and used to develop the RoFSW (EA, 2013).

The model integrates spatially varying gross rainfall, with representation of both rural infiltration using the ReFH rainfall to overland flow calculated losses model and urban sewer loss rates (Figure 3-1). Rural ReFH losses are controlled by the maximum soil moisture storage capacity (Cmax) which is estimated using the catchment descriptors BFIHOST and PROPWET whilst urban losses are based on estimated sewer capacity losses and percentage overland flow.

The floodplain has been represented using a 2m Digital Terrain Model (DTM) based on a combination of filtered LiDAR and interferometric synthetic aperture radar (IFSAR) with permission from the EA and Airbus. It is based on the EA’s 2012 composite DTM adopted for the national RoFSW project, which has had hydrological pathway checks applied to maximise hydrological flow pathway continuity. Spatially varying hydraulic roughness coefficients were adopted throughout based on land cover, using the same baseline roughness coefficients adopted in the RoFSW.

The baseline model was simulated for predicted rainfall depths associated with the 10-year and 30-year return periods over a 6-hour storm duration. For the Derwent catchment the 1 in 10 year RP was replaced with the 1 in 100-year event. A larger event magnitude was selected for the Derwent catchment as the numbers of significant waterbodies within the catchment were predicted to dampen intervention responses for smaller storm event magnitudes.
3.3 Monitoring lines and computing peak streamflow reduction

As previously discussed, a series of model monitoring lines were digitised across the 'pour point' (outflow) of each sub-catchment. These enabled a comparison of baseline and intervention scenario surface overland flow contribution to the streamflow hydrographs, and an analysis of predicted potential attenuation between the design events with and without NFM measures (Figure 3-2). The benefits were then measured in terms of the percentage reduction to the peak streamflow and the increase in absolute time of arrival of the peak. This latter is not an accurate computation of 'time to peak' but is time to peak from start of simulation.\footnote{In other words, time since simulation starts as opposed to centroid of storm}
• Runoff Attenuation Features (based on JRAFF approach)
  o In JFLOW, these are modelled as extra storage and once identified, artificially incised into the DTM by 1m, to force additional storage through lowering of localised ground elevations. This is agnostic to the type of RAF, whether it represented storage in small channels, off-line pond storage, overland flow interception RAFs or whether the feature is enhanced through shallow bunds and/or excavation.
• Enhanced Planting (based on Woodlands for Water).
  o In JFLOW these are represented using additional roughness for areas identified for potential tree-planting. The values used in the RoFSW maps were used for the baseline simulation, and this represented a lot of ‘rough upland’ areas as having a Manning's $n$ value of 0.1. This was increased based published values in Chow (1973) to:
    ▪ 0.15 for woodlands (0.15-0.2 corresponds to dense woodland)
    ▪ 0.125 for shrub, scrubland or peat
    ▪ Care should be taken if planting downstream of settlements, as ‘roughening up’ can create backwater effects that can increase flood extent upstream.
  o Opportunity areas defined as riparian or floodplain zones were modified to represent mature woodland. Opportunity areas defined as soils with naturally high percentage overland flow potential were modified to represent scrubland given that these typically resided within montane environments.
  o Within the Kent catchment, any opportunities which resided within peat soils were adjusted to the same roughness as for scrubland (0.125).
  o Within the Derwent catchment, opportunities designated as soils with naturally high percentage overland flow potential were proportionally reduced in area given their significant coverage within the opportunity dataset; the opportunities were reduced in area to meet European Union planting average of 44% across the catchment.
  o The ‘catchment descriptors’ that can influence soil infiltration or soil storage were not changed for the enhanced planting scenario, since the science behind quantifying the effect of tree planting on these ‘catchment descriptors’ is poorly developed.
• Soil Structure Improvement
  o In JFLOW this was introduced via a percentage change in the ReFH losses model to represent an improvement in the soil moisture storage and reduction in initial soil moisture storage capacity. For land cover types specified as 'improved grassland' as identified using LCM2007, the catchment descriptor BFIHOST was increased by 10% resulting in improved maximum soil moisture storage and reduction in initial soil moisture storage capacity for these land cover areas.

The whole catchment surface water model was re-simulated for each NFM scenario independently with changes in sub-catchment monitored streamflow hydrographs analysed to investigate the change in streamflow peak between baseline and storage adjusted scenarios.

3.5 Uncertainties and Assumptions with JFLOW Approach

There are a number of assumptions behind using this screening technique which stem from the basic model characteristics that were introduced in Section 3.1. That is to say, with this technique we are primarily interested in the changes to the overland flow based on the effect of the NFM measures that are designed to modify overland flow behaviour, primarily in headwaters, upstream from settlements, and the approach does not model the whole hydrograph. These measures and the assumptions behind each are:

• Runoff Attenuation Features
  o Assumed to have been designed to drain down between storms, so are modelled as extra capacity for the design storms. This is refined in the detailed modelling described in Section 6.
• Enhanced Planting (based on Woodlands for Water).
  o Assumed that the tree planting is sympathetic and follows Forestry Commission best practice, with management through time.
Planting needs to ensure fine scale streamflow generation routes are captured by planting.

- The roughness values used assume that the trees are mature or land cover has been converted to established scrubland.
- Assumes that caution is taken when planting downstream of communities at risk, such that the planting is sited downstream of any potential backwater effects.

- Soil Structure Improvements
  - Assumes that the soils are consequently able to store more water. Implemented in the model by increasing BFIHOST to modify the maximum soil moisture storage $C_{max}$ and initial soil moisture storage capacity $C_{ini}$.

Other major assumptions and consequences of the approach are explored in the following subsections.

### 3.5.1 Limitations of 'Design Storm'.

The use of a design storm profile (Design Hyetograph) stems from the FEH/FSR approach (IH, 1999), and it has been used uniformly here to help understand streamflow generation and relative timing of overland flow and streamflow around the catchment. The approach has the following limitations:

- The FEH rainfall parameters are statistical and provide estimates of average depth-duration-frequencies of typical storm events
- The storm profiles do not take into account spatial structure to the rainfall, something that can now be addressed using spatial joint probability events (Keef et al., 2013), and was included in the JBA and LEC winning Defra Floods Competition entry^4
- Flooding often arises from multiple-peaked rainfall events (see later in this report how this is addressed with Dynamic TOPMODEL)

### 3.5.2 Initial Conditions

The initial wetness has been modelled using the $C_{ini}$ parameter from the ReFH losses model, which depends on soil type (or at least the crude estimate of soil type portrayed in the national Soil Association map). The RAF measures that have been modelled, also assume that these are designed to drain down between events so are empty at the start of the strategic modelling. The approach therefore models an idealised situation, to allow a comparison of the relative effectiveness of NFM measures around the catchment. The detailed modelling (Sections 6, 7) overcomes this by modelling the whole period November to mid-December 2015, a period over which the catchments initially started dry, and wetted through time. Furthermore, the RAFs have been modelled with a simple drain-down function and a range of time constants or 'residence times of response' have been used to simulate different pipe diameters.

### 3.5.3 Missing Processes

The approach provides a virtual 'sandbox' for testing the effectiveness of highly distributed NFM measures on surface overland flow across large catchments. There are specific processes such as open water evaporation, soil evaporation, wet-canopy evaporation, transpiration and infiltration that have been lumped into a losses model, and fluxes of water from artificial influences such as abstraction, groundwater, sewage discharges, reservoir regulation that are not included. These are significant processes, but the intention with the strategic modelling is to test the response of the catchment under a known accumulation of rainfall with and without NFM measures and assess the relative magnitude of the difference, holding everything else constant. These processes are more completely represented in the detailed modelling using Dynamic TOPMODEL in Sections 6 and 7 of this report.

### 3.5.4 Physical representation

The JFLOW model solves the full 2d overland flow equations called the St Venant equations (Lamb et al., 2009) and has been benchmarked favourably (e.g. see Hunter et al., 2008), comparing well with a wide range of industrial modelling packages against a wide range of test-cases.

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3.5.5 Model performance

The strategic modelling approach used the same constants and losses that were used in the national RoFSW maps (EA, 2013). Confidence in these assumptions on losses and rates was gained in a national online exercise where Lead Local Flood Authorities fed back on the predicted surface water flooding. The predicted overland flow from the technique has also been compared against the ReFH streamflow hydrographs (with a 'baseflow' component, subtracted) for a similar scale catchment, the Irwell also in north west England. Here it has been shown that on average the absolute flows predicted for headwaters are similar to those predicted using the same duration (6 hour) ReFH hydrographs. Further downstream the approach becomes less accurate most likely due to urban interactions and artificial influences. The predicted flood extents were also compared with the RoFSW maps for the same return periods, and compared favourably higher in the catchment, but show greater extent further downstream as would be expected since here rainfall is being accumulated over whole catchments and not over tiles as per the RoFSW maps.

3.5.6 Overall Confidence in Approach

The above assumptions mean that we should use JFLOW outputs in relative or 'difference' mode, so it is good at identifying which sub-catchment will give us more benefit and the relative scale of that benefit in terms of reducing or slowing down overland flow and streamflow. It has opened up ways of modelling highly distributed measures in the 'upstream' headwaters at 2m resolution, that before were modelled using 'lumped' approaches. It is not useful for absolute predictions, in terms of which property will be flooded and how large the damages avoided might be at a detailed scale, but can be used to understand the relative change we might expect. For more detailed model calibration, a more detailed hydrological model (see Section 6) has been built for three priority sub-catchments identified for the Kent, Derwent and Eden in the stakeholder workshop.
4 JFLOW Predictions

The opportunities identified for NFM measures introduced in Section 2 and how these are represented is described in Section 3. The sub-catchment monitoring lines described in Section 2.5 were used to quantify the benefits of the NFM features in terms of peak streamflow reduction and changes to the timing of the flood peak (see Figure 3-2). A set of detailed opportunity maps were generated ready for the stakeholder workshop (Section 5) combined with benefits maps showing the potential for surface water flow attenuation. These used colour theming and labelling to illustrate three core aspects of the strategic modelling:

- The body of the sub-catchments was colour themed based on the size of the NFM intervention (e.g. area of woodland)
- The perimeter of the sub-catchments was colour-themed based on the percentage reduction to the predicted streamflow
- The with and without time to peak flow were labelled in the body of the sub-catchment

In this way, the workshop was informed by clear visualisations of both the opportunities that were assumed and the resulting potential benefits from the strategic modelling. Some of the final, post-workshop, refined maps are presented here, but complete copies are in electronic Appendix A.

In addition to this suite of maps for each catchment, an Excel workbook of hydrographs (Figure 4-1) for all monitoring cross sections was produced (Appendix B). This illustrated the relative impact of the different NFM measures on the monitored hydrographs, which essentially represent the quickflow component of streamflow (see for example, Ven Te Chow et al, 1988). The rapid rising limb is indicative of rapid overland flow, and some of the stranger looking hydrographs with double or negative peaks arise because of interactions with other tributaries.

![Figure 4-1: Spreadsheet of monitoring hydrographs](image)
4.1 Opportunity and predicted benefits for the Kent

Figure 4-2 provides an overview map for the strategic modelling of the Kent catchment for the impact of RAF NFM measures (other measures can be seen in Appendix 1). There are 3 key features of this interactive map (the drop-down in the right panel allows the user to toggle between scenarios). These maps follow the refinement following the workshop, and highlight:

- The body of the sub-catchments is colour shaded depending on the total potential (area for enhanced planting or area for extra RAF capacity) for the NFM features selected
- The perimeters of the sub-catchments are colour themed by the percentage reduction in streamflow that is predicted to occur by modelling with and without NFM measures in place
- The inset text in each sub-catchment shows how much the time of the peak surface overland flow changes between with and without NFM features

4.2 Detailed sub-catchment opportunity maps for the Kent

The user can also click on the sub-catchments in Appendix A, and open up a zoomed in map showing the different opportunities that have been modelled within each sub-catchment. The next three maps show the opportunities identified for RAfs (Figure 4-3), enhanced planting, or roughening up (Figure 4-4) and soil structure improvement (Figure 4-5).
Figure 4.3 Upper Kent RAF Opportunities for NFM

Figure 4.4 Upper Kent WIW and peat opportunities for NFM
Figure 4-5 Upper Kent Land Use Change Opportunities for NFM

The main messages from the Kent modelling are:

- **Tree Planting.** The Upper Kent catchment is the strategic priority for catchment roughening via woodland planting and peat restoration although there are issues with synchronisation discussed below.

- **RAFs.** The main opportunities appear to be in the Gowan catchment and to a lesser extent in the Flodder and Mint catchments. Synchronisation issues between the Gowan and Upper Kent are a key consideration.

- **Soil improvement.** The Gowan and Flodder catchments provide the most potential for soil improvement. The impact is modest compared to RAFs or WfW, however there are no real barriers to the implementation of soil improvement and it provides significant additional benefits for the wider water environment.

- **Peat restoration.** This is focused in the Upper Kent where it has significant potential to 'slow the flow' and de-synchronise the peak runoff from the Upper Kent and the Gowan.

- **Synchronisation.** Peak quickflow from the Gowan and Upper Kent are synchronised. WfW slows the flow and RAFs tend to reduce peak runoff. The modelling supports a strategic approach to focusing WIW and peat restoration in the Upper Kent and RAFs and soil improvement in the Gowan.
4.3 Opportunity and predicted benefits for the Eden

Figure 4-6 provides an overview map for the strategic modelling of the Eden catchment for the impact of RAF NFM measures, the equivalent maps for WIW and Soil Structure Improvement are in the electronic Appendix A.

![Eden Catchment](image)

Figure 4-6 Eden Opportunities and Benefits for NFM

4.4 Detailed sub-catchment opportunity maps for the Eden

The user can also click on the sub-catchments in Appendix A, and open up a zoomed in map showing the different opportunities that have been modelled within each sub-catchment. The next three maps show the opportunities identified for RAFs (Figure 4-7), enhanced planting, or roughening up (Figure 4-8) and soil structure improvement (Figure 4-9).
Figure 4-7 Eden RAF Opportunities for NFM

Figure 4-8 Upper Eden Woodlands and Shrub opportunities for NFM
The main messages from the Eden modelling are:

- **Tree Planting.** The Upper Eden, upstream of Kirby Stephens, has significant potential for on the Woodlands for Water maps, which will slow the flow and avoid synchronisation issues, see below.

- **RAFs.** Helm, Blind and Scandal Beck all appear to provide excellent opportunities for RAFs. This coupled with sediment and phosphorus issues in Helm Beck could significantly improve both water quality and flood risk. Hilton Beck also has significant potential for RAFs which should avoid synchronisation issues, see below.

- **Soil improvement.** Although the reductions in peak quickflow are modest Helm, Blind and Scandal Beck all appear to provide good opportunities for targeted soil improvement which will support WFD improvements in water quality.

- **Synchronisation.** The main risk is synchronising tributary inflows directly upstream of Appleby. To avoid this WfW above Kirby Stephens and RAF/Soil improvement in Helm, Blind, Scandal and Hilton Becks could be a strategic approach.
4.5 Opportunity and predicted benefits for the Derwent

Figure 4-10 provides an overview map for the strategic modelling of the Derwent catchment for the impact of RAF NFM measures, the equivalent maps for WfW and Soil Structure Improvement are in the electronic Appendix A.

Figure 4-10 Derwent: Opportunities and Benefits for NFM

4.6 Detailed sub-catchment opportunity maps for the Derwent

The user can also click on the sub-catchments in Appendix A, and open up a zoomed in map showing the different opportunities that have been modelled within each sub-catchment. The next three maps show the opportunities identified for RAFs (Figure 4-11), enhanced planting, or roughening up (Figure 4-12) and soil structure improvement (Figure 4-13).
Figure 4-11 Cocker Beck: RAF Opportunities for NFM

Figure 4-12 Cocker Beck: WfW and Shrub planting Opportunities for NFM
The main messages from the Derwent modelling are:

- **Tree Planting.** The catchment is already heavily forested. This means that the practical opportunity to increase woodland cover may be less than in other catchments and that RAFs and Soil improvement could be strategic priorities. Dash Beck and the Derwent downstream of Bassenthwaite lake represent the best opportunities for WfW however, there are potentially synchronisation issues with the river Cocker, see below.
- **RAFs.** The Cocker catchment provides good opportunities for RAFs which will reduce peak runoff into Cockermouth and keep the Derwent and the Cocker out of phase.
- **Soil improvement.** This provides modest reductions in peak runoff in locations as above for RAFs.
- **Lakes.** These provide a significant buffering capacity within this catchment which is significantly greater than that which could be achieved through use of NFM. The Derwent could be treated as a series of ‘independent’ catchments separated by lakes when developing a strategic approach to NFM in the catchment.
- **Synchronisation.** There is a risk that ‘slowing the flow’ in the Derwent downstream of Bassenthwaite will synchronise peak runoff between the Derwent and the Cocker, so RAF and soil structure improvements could be sought unless timings are more carefully assessed. It may be prudent to focus NFM interventions in the Cocker catchment to avoid this risk.
4.7 Wider impacts of NFM on People and Property

To understand the contribution NFM applied within upper catchments may have on downstream communities at flood risk and identify sub-catchments with the greatest predicted flood risk downstream, the following key metric was investigated:

- The cumulative number of residential properties downstream from each sub-catchment predicted to be at risk in Flood Zone 3.

This was used to provide an indication of how many people are predicted to be at flood risk from a 100-year magnitude design event and may benefit from the implementation of upstream NFM measures. A population count was derived from using the average household size of 2.3 people as identified within the 2011 national census (Office for National Statistics, 2013).

The following sub-sections provide interpretation of the maps showing downstream cumulative number of people at flood risk in Flood Zone 3. As a cumulative metric, each sub-catchment includes both the number of people predicted to be at risk within downstream sub-catchments as well as downstream from the modelled study catchment. This ensures that population counts are more comparable between the three study catchments.

The strategic modelling approach does produce predicted surface flow depth grids, for which the change in impacts to property could be computed between NFM scenarios. However, impacts and property benefits will be highly dependent on the number, area and siting of NFM measures, and it was therefore not deemed appropriate to highlight financial benefits without more detailed modelling of specific NFM measure adoption. For example, it is advised that NFM measures are focussed in the headwaters upstream of settlements, and that for example woodland is not planted downstream of the backwater distance of a settlement without more detailed modelling to show that risk does not increase.
4.7.1 Kent Catchment Communities at Risk

The cumulative numbers of people predicted to be at flood risk within Flood Zone 3 are illustrated for each sub-catchment in Figure 4-14. The most downstream sub-catchment in the south comprises the largest community at risk across Kendal from which upstream sub-catchments may assist in managing downstream flood risk. A number of tributaries within this downstream sub-catchment are predicted to pose a flood risk to Kendal but are not influenced by the modelled upstream sub-catchments; this explains why the cumulative count is greatest within the most downstream sub-catchment and not vice versa. The Gowan and Kent headwater sub-catchments are predicted to comprise the greatest cumulative number of people at flood risk downstream. There is not predicted to be a significant number of people at flood risk downstream of the modelled catchment area, with the majority of risk surrounding Kendal.

Figure 4-14 Cumulative count of people predicted at flood risk downstream across Kent catchment
4.7.2 Eden Catchment Communities at Risk

The cumulative numbers of people predicted to be at flood risk within Flood Zone 3 are illustrated for each sub-catchment in Figure 4-15. The upstream sub-catchments of the Eden at Kirkby Stephen and Scandal Beck comprise the greatest cumulative number of people predicted at flood risk downstream across the Eden catchment. Given the significant size of the whole Eden catchment in comparison with the Upper Eden area modelled as part of this study, a significant number of people are predicted to be at flood risk downstream from the modelled area such as communities surrounding Carlisle. To understand the more local flood risk, please subtract the count of people 3282 downstream of the study area.

Figure 4-15 Cumulative count of people predicted at flood risk downstream across Eden catchment.
4.7.3 Derwent Catchment Communities at Risk

The cumulative numbers of people predicted to be at flood risk within Flood Zone 3 are illustrated for each sub-catchment in Figure 4-15. The upstream sub-catchments of Trout Beck and Glenderamackin in the east of the catchment comprise the greatest cumulative number of people predicted at flood risk downstream across the Derwent catchment. These sub-catchments are upstream from both the large communities of Keswick and Cockermouth.

The numbers of people predicted to be at flood risk downstream from the modelled catchment area remain significant and comprise communities continuing within Cockermouth and down to Workington. To understand the more local food risk please subtract the count of 538 people further downstream.

Figure 4-16 Cumulative count of people predicted at flood risk downstream across the Derwent catchment
5 Workshop and feedback

A stakeholder workshop with an attendance of approximately 50 people from key organisations was held to engage with the mapping and provide a reality check on the opportunities at Newton Rigg College, Penrith, on 7th October, 2016. Based on our methodology (Figure 1-1), engagement is key to developing a common strategic understanding of the role that NFM can have within a catchment.

The aims of the workshop were to:

- Help identify where opportunities were feasible / not feasible and modify the assumptions in the modelling. This included adding in planned NFM measures.
- Use the benefits maps, knowledge of land ownership, understanding of existing land cover to prioritise a set of sub-catchments for more detailed modelling with Dynamic TOPMODEL.

A suite of large scale maps was printed for the workshops, similar to the figures in the preceding Section 4, for discussion in groups gathered around the tables.

It was clearly stated at the start of workshop that modelling was:

- Part of a weight of evidence (used with ‘communities at risk’, local knowledge/opportunity) and subject to uncertainties
- Good in relative mode, where we compare changes to runoff (quickflow) and timing with and without measures
- Good at identifying where best to focus and the scale of possible impact
- Good at identifying the relative impact of different NFM interventions
- More reliable in headwater catchments, and is unlikely to be so accurate further downstream for large channels and the influence of large lakes is not likely to be represented fully

Some draft detailed Dynamic TOPMODEL outputs were shown at the workshop, but it was always the intention to allow attendees to identify in more detail which priority sub-catchments (with an area of approximately 100km²) to model using this more complete hydrological model.

5.1 Workshop feedback

A range of feedback was provided and notes were taken, along with a post-workshop analysis of the comments written by delegates on the maps. Some key issues raised are given below, with some basic answers in sub-bullets:

- Don't make arbitrary changes to national datasets or lose opportunities, as we need to keep the long term goal in view.
  - Only one small change was made for the Derwent WiW layer, as it predicted a huge coverage that would be large on a European level. Other changes were made based on local knowledge and feedback.
- Don't plant excessively above national averages
  - See above, the Derwent was changed in response to this to ensure planting opportunities did not exceed the European average of 44%.
- Model the increase in roughness for other planting or restoration not just tree planting - e.g. interpret as scrub, heath, etc.
  - The interpretation of the maps was adjusted so that the WIW areas can more loosely represent areas of shrub or scrubland planting or roughening up for areas such as peat.
- Can some of the springs / smaller channels be deepened to store more water
  - Some of the RAFs are in these areas, and would need to be assessed on an individual basis.
- Think about soil structure improvement for other land covers, not just improved grassland
  - Yes, the idea was to use improved grassland as an example. The effects of doing this for other land use types can be assessed by area
• Change 'woodland' to hydraulic roughness and put anywhere above moorland line. Most land is acid grassland that can be restored to rougher habitats. See section 5.3.2.
• Can land behind levees be captured? Yes, see section 5.3.1.
• Sediment management also key and will impact behaviour of floodplains - needs to be considered alongside flows. Although it is technically possible to incorporate sediment transport into the detailed modelling approach the results would be highly speculative due to the lack of data. JFLOW does output velocity information, and shear stresses are proportional to the square of the velocity, so it may be realistic to map shear stresses.
• Can maintenance be designed out or into the measures that are put in place? If the measures are not maintained, then the effectiveness of interventions will decrease.
• Can Storm Desmond or real events be modelled? Storm durations are relatively short. This is investigated in the detailed modelling.
• Can EA communities at risk data be used? Yes, the model results are just part of the weight of evidence to be used when developing a strategic approach to NFM delivery.
• Communities at risk/impacted by flooding should be displayed and the catchments immediately connected to these are the highest priority. This is correct so long as NFM can make a difference, the modelling can help us understand the potential for NFM.
• Focus on areas where attenuation features result in floodplain reconnection. The reconnection of the floodplain is weakly represented in the initial screening of RAF opportunities for smaller tributaries, since JRAFF highlights in-channel storage opportunities < 5000m². The workshop was used to identify and incorporate these larger scale interventions, section 5.3.1.
• Soils - slowly permeable soils in the Upper Eden and sandy loams elsewhere can exhibit significant compaction in silage and in-by fields, especially in wet conditions. It is possible to scale the results from the soil permeability maps according to local understanding of the high risk area.

Changes were also made throughout the three catchments based on comments made on the maps and during the workshop, to alter areas of storage or enhanced planting where local knowledge and feedback was available.

5.2 Matrix to help identify priority sub-catchments
A matrix for each sub-catchment was completed, weighing up a number of issues including:

• Land ownership - are opportunities feasible?
• Observations based on local knowledge
• Observations from strategic maps
• Downstream risk
• Availability of good quality monitoring data
• Size of catchment
• Markers placed by workshop attendees on maps

Ultimately, it was concluded that a number of catchments could be addressed for each study area, and given time scales the three priorities chosen represented a compromise. These were:

• Kent: Upper and mid Kent and Gowan above the EA Bowston flow gauge (71km²)
• Eden: Upper Eden upstream of EA Great Musgrave flow gauge (223km²)
• Derwent: Cocker Beck between the EA Scalehill and Southwaite Bridge gauges (53km²)

5.3 Updating the JFLOW modelling
Following the workshop, feedback was collated and the JFLOW modelling was updated to reflect the changes across the three scenarios.

5.3.1 Runoff Attenuation Features
During the workshop, several additional potential storage opportunities were raised by local organisations in attendance. These included rural valleys which were identified as most suitable for improved floodplain reconnection and storage. To represent these within the updated
JFLOW modelling, additional RAFs were digitised as offline storage areas and incised into the DTM as previously discussed within the methodology.

5.3.2 Enhanced Planting Opportunities
Local organisations in attendance at the workshop identified several existing schemes and measures recently implemented across the study catchments. Furthermore, organisations with land ownership suggested expansion of existing opportunities where feasible within their own land boundary. These opportunities were updated within the JFLOW modelling through expansion of woodland or scrubland opportunities and increases in hydraulic roughness as previously discussed within the methodology.

As previously discussed, the Woodlands for Water dataset, specifically identifies opportunities for soils with an estimated high percentage overland flow, were observed to cover significant proportions of the study catchments. The representation of these areas within the JFLOW modelling were updated post-workshop to be representative of scrubland roughness rather than mature woodland, reducing the increase in hydraulic roughness for these opportunities in comparison with the modelling presented at the workshop which adopted woodland planting across all Woodlands for Water opportunities. Furthermore, opportunities for soils with an estimated naturally high percentage overland flow within the Derwent catchment were observed to cover a significant proportion of the catchment. Therefore, these specific opportunities within the Derwent catchment were reduced in area in order to better meet European averages for planting at 44% of the catchment area.

5.3.3 Soil Structure Improvements
Following the workshop, no significant updates were noted to the soil structure improvements scenario. As previously discussed, users may understand the relative benefit in overland flow attenuation through comparison with other land cover types by comparing their relative proportional area.

5.4 Updating the Maps and Creating Interactive Maps
Having updated the JFLOW modelling post-workshop, the modelling outputs were presented within a set of overview and detailed maps for each catchment (as shown in Section 4), similar to those presented at the workshop. As the map deliverables were intended to be shared digitally, this enabled each catchment map to be converted into a suite of interactive PDF maps rather than generating separate maps for printing.

The interactive PDF maps (Appendix A) include a single overview map per study catchment together with detailed maps representing each sub-catchment area. Guidance on accessing and toggling information within the maps is available within the User Guide supplied alongside this report. In summary, each overview map displays one of the catchments modelled and illustrates the opportunity areas and overland flow and runoff attenuation for each design event and intervention scenario modelled. Detailed maps can be accessed via clicking on a sub-catchment from the overview map and display the location of NFM interventions modelled together with other useful reference and potential additional constraint data layers.
6 Dynamic TOPMODEL

6.1 Introduction

This section introduces Dynamic TOPMODEL and how it has been set-up for the three priority sub-catchments which are identified in Figure 1-1:

- Kent: Upper and mid Kent and Gowan above the EA Bowston flow gauge (71km²)
- Eden: Upper Eden upstream of EA Great Musgrave flow gauge (223km²)
- Derwent: Cocker Beck between the EA Scalehill and Southwaite Bridge gauges (53km²)

Lancaster Environment Centre have developed an extended and flexible implementation of the distributed Dynamic TOPMODEL (Beven and Freer, 2001, Metcalfe et al., 2015), which has the following key characteristics:

- It is a distributed hydrological model, which uses areas of similar hydrological behaviour called HRUs (Hydrological Response Units), these can be divided to represent distributed NFM interventions in the landscape.
- The impacts of these NFM measures can be mapped back into the landscape.
- It has sufficient complexity to represent the key catchment processes, notably subsurface flow pathways in addition to overland flow pathways and there is evidence for how NFM measures can influence the parameters (e.g. transmissivity distribution) representing these processes.
- It enables efficient modelling, allowing thousands of model runs to be simulated to investigate uncertainties and sensitivities.

Detailed modelling means simulation of spatially-distributed catchment states (above-ground and sub-surface) through a period, and making use of spatially-distributed data such as tree-planting areas, and output of spatially and temporally distributed results.

6.1.1 Detailed model characteristics

There are a range of approaches and modelling packages⁵ that could have been used for this study, ranging from a lumped approach such as the Probability Distributed Moisture (PDM) model, or a model with a greater number of physical processes such as MIKE SHE, SHETRAN or the SWAT models, which make a large number of assumptions about effective parameter values controlling the different streamflow generation processes. Dynamic TOPMODEL represents an intermediate level of complexity that incorporates what we think are the key hydrological processes, but without imposing too many assumptions resulting in a large number of parameters (related to say soil properties), for which we do not have direct measurements.

Dynamic TOPMODEL was also selected for the detailed modelling because it:

- Makes use of standard data formats for catchment topography (elevations, channel network) and relevant spatial data such as land cover.
- Presents results back to the landscape as well as formats such as streamflow hydrographs that are easily understandable by partners.
- Uses real, spatially distributed rainfall data and can be rapidly calibrated against real event data allowing for data quality.
- Incorporates spatial data provided by Rivers Trust (RT) and catchment partners of NFM interventions, for example tree-planting, soil restoration and addition of offline storage area (RAFs) and simulate the effect of these changes on streamflow response.
- Simulates a wide range of catchment scales (up to 223 km² in this study) and hydrological regimes such as the extreme flood event arising from Storm Desmond in December 2015;
- Allows for relatively quick application to future RT study catchments and different configurations of sub-catchments within an existing project.
- Uses a framework that allows assimilation of meteorological and streamflow data supplied in standard formats, such as those collected by the Environment Agency.
- Allows for free-distribution of source or compiled code and, with suitable guidance and training, be operated by RT staff and catchment partners.

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In conjunction with a hydraulic-routing scheme, also developed at LEC, this has been applied to the 28km² Brompton, North Yorkshire, in order to simulate the impact of up to 60 in-channel NFM interventions (Metcalfe et al., in press). The model is written in the open source R language, which is distributed under the GNU Lesser Public Licence (GNU LGPL v2.1). It can be run on most common operating systems. The R implementation has been released as a package on the CRAN archive (Metcalfe et al., 2016), passing the rigorous quality assurance and testing required by the submission process.

### 6.2 Overview of Dynamic TOPMODEL

Dynamic TOPMODEL was first implemented in FORTRAN by Beven and Freer (2001). It is an extension of the popular TOPMODEL (Beven and Kirkby, 1979) applied in many studies (see Beven, 1997, and references cited within). Dynamic TOPMODEL employs the efficient parameterisation scheme of TOPMODEL, with all parameters shown in Table 6-1, along with typical ranges of values applied in this project.

Table 6-1: Parameter ranges and typical values within Dynamic TOPMODEL simulations (from Metcalfe et al., 2015)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Units</th>
<th>Lower</th>
<th>Upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vof</td>
<td>Overland flow velocity</td>
<td>m/hr</td>
<td>1</td>
<td>150</td>
</tr>
<tr>
<td>M</td>
<td>Form of exponential decline in conductivity</td>
<td>m</td>
<td>0.0011</td>
<td>0.033</td>
</tr>
<tr>
<td>Srzmax</td>
<td>Max root zone storage</td>
<td>m</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>srz0</td>
<td>Initial root zone storage</td>
<td>%</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>Vchan</td>
<td>Channel routing velocity</td>
<td>m/hr</td>
<td>500</td>
<td>5000</td>
</tr>
<tr>
<td>ln(T0)</td>
<td>Lateral saturated transmissivity</td>
<td>m²/hr</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>Sdmax</td>
<td>Max effective deficit of saturated zone</td>
<td>m</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Td</td>
<td>Unsaturated zone time delay</td>
<td>m/hr</td>
<td>1</td>
<td>10</td>
</tr>
</tbody>
</table>

Beven (1997), Beven and Freer (2001) and Metcalfe et al (2015) provide other examples of parameter values that have been applied in various catchments.

Overland flow velocity is fixed throughout each unit, and can be changed to reflect changes in surface roughness introduced by, for example, peat restoration or riparian tree-planting.

The limiting transmissivity $T_0$ \([L]^2[T]\) is a measure of the local maximum saturated downslope transmissivity per unit hydraulic gradient (where transmissivity is the product of the permeability and saturated depth). This is a key parameter in identifying the onset of saturation overland flow (SOF). It controls the rate at which the soil’s storage capacity can be replenished by downslope drainage. When downslope flows into lower slopes filling remaining storage capacity, return flow is produced. SOF is also generated when rain falls onto these areas of already saturated ground.

An exponential transmissivity profile is assumed. The use of such a form is supported by experimental evidence such as Davies et al. (2013) and Nyberg (1995), and replicates the typically higher values of permeability found near the ground surface. The recession parameter $m$ \([L]\) controls the rate of decline of transmissivity $T$ as water table depth reduces. Small values of $m$ lead to very rapid declines in transmissivity, suggesting shallower, faster responding streamflow generation systems. Deeper active hydrological systems are represented by a slower decline in transmissivity$^{6}$.

Dynamic TOPMODEL routes subsurface flow downslope between HRUs using a routing matrix derived from the local topography. It is assumed that the local slope is a reasonable approximation for the hydraulic gradient.

The root zone storage $Srzmax$ is a lumped component that must be filled before any water table recharge begins through incident rainfall. Transpiration (and soil evaporation) is removed from this zone at a rate proportional to the actual storage. Direct observations of soil moisture content are unavailable for the catchments in the periods simulated, so as an approximation all catchments are assumed to be saturated at the start of the simulations$^7$ ($srz0$).

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$^{6}$ Limiting Transmissivity $T_0$ is the integral of the saturated hydraulic conductivity from the surface to the bedrock. With an exponential profile assumed in DT, this can be calculated from the surface saturated $K$ and the $m$ recession parameter. If we assume our field values correspond to the values Nick or RT people supply and we are confident in calibrated value of $m$ then yes, we can relate the $T_0$ for the HRU as long as it is uniform over that area.

$^{7}$ The soil store is emptied by evapotranspiration between events, but not by any drainage into the unsaturated zone.
In the original version of TOPMODEL, definition of HRUs is restricted to the Topographic Wetness Index (TWI), which is a spatially-distributed indication of the likelihood of saturation TWI=$\ln(a)/\tan(\beta)$ with $a$ the upslope area (the region draining through this point) and $\beta$ the local slope. Areas of high TWI are more likely to become saturated and produce saturation overland flow (SOF).

In Dynamic TOPMODEL downslope subsurface routing between landscape units is undertaken with a kinematic formulation employing a “flow-distribution” matrix calculated from the catchment topography.

This allows some of the assumptions of the earlier model to be relaxed allowing distributed changes to the catchment properties to be simulated. The user may now bring in any reasonable strategy into the landscape classification (see Figure 6-1).

Figure 6-1. Catchment discretisation incorporating multiple landscape layers undertaken in Dynamic TOPMODEL pre-processing (Metcalfe et al., 2015)

The relevance to this project is that areas flagged for NFM interventions may now be incorporated as distinct units into the catchment classification. In unaltered catchments these units are assumed, for simplicity, to behave identically to the other landscape areas. To simulate the effect of applying one or more NFM interventions, the parameters in particular HRUs are altered to reflect their changed hydrological properties. Structural changes to the inter-group routing may also be applied to modify how subsurface flow and overland flow is routed through intervention areas. In section 6.10 we discuss the evidence for these changes to catchment properties associated with NFM measures.

A pre-processing module is supplied with the deliverable code. Catchment layers, including the location and width of the river channels, are supplied as geo-referenced raster datasets to this module. Given specification of how these layers should be combined, the code processes the data into a single “discretisation” raster and supporting data objects as shown in Figure 6-2. This allows rapid production of a discretisation (‘hypothesis’) of the catchment configuration and new layers to be brought in as they become available.
An example of a catchment discretisation process is given in Figure 6-3. This results from the combination of the local TWI split into 5 groups and two types of WIW tree planting areas where scrub or woodland levels of roughness will be applied. Areas marked as RAF 1 or 2 have been identified by the JBA JRAFF screening tool that identifies locations of natural accumulation along flow pathways that could be enhanced by adding bunds to store overland flow. The levels refer to the return period of event (10 or 30 year) that was applied to identify the feature. RAFs are treated as discrete units and “burned” into the discretisation raster. The other areas are combined so that, for example, there are three WIW areas of type 3, each with a different mean TWI. The restriction on the size of areas means that a number of potential classifications will be omitted in the final classification, although there is no restriction on the size of any individual feature or part of feature, but any the aggregated area of any landscape classification, in or without an intervention area, has to exceed a threshold size (0.5%) to avoid numerous very small HRUs that added computational load without benefit to the representation.
Once a discretisation has been produced the model may use it to run against rainfall data for a specified time period. For that period, it produces a time series of simulated streamflows at the EA monitored streamflow gauge and time series of the internal states (e.g., soil moisture deficit) of each of the HRUs. The internal states output is tabulated in Table 6-2.

Table 6-2: Internal states recorded for each Dynamic TOPMODEL HRU

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>suz</td>
<td>Unsaturated zone storage</td>
<td>m</td>
</tr>
<tr>
<td>srz</td>
<td>Root zone storage</td>
<td>m</td>
</tr>
<tr>
<td>ssurf</td>
<td>Surface excess storage</td>
<td>m</td>
</tr>
<tr>
<td>sd</td>
<td>Soil moisture deficit</td>
<td>m</td>
</tr>
<tr>
<td>quz</td>
<td>Gravity drainage from unsaturated zone into water table</td>
<td>m/hr</td>
</tr>
<tr>
<td>qb</td>
<td>Specific subsurface downslope flow</td>
<td>m/hr</td>
</tr>
<tr>
<td>Ea</td>
<td>Actual evapotranspiration</td>
<td>mm/hr</td>
</tr>
<tr>
<td>Qin</td>
<td>Upslope total input flux</td>
<td>m³/hr</td>
</tr>
</tbody>
</table>

Also recorded is the evapotranspiration, overland flow discharging into the channel and its contribution to the streamflow.
6.3 Calibration storm series

The size of the flood caused by Storm Desmond is in part dependant on the catchment wetting from the storm events that occurred over the preceding weeks. As a direct result, a 6-week period of rainfall and streamflow was selected in November – December 2015 (Figure 6-4) for the modelling, that included Storms Abigail (12th-13th November), Barney (17th-18th November), Clodagh (29th November) and Desmond (5th-6th December). The first and last of these events had the highest impact on the streamflow. Clodagh was primarily a “wind” storm and in Cumbria did not produce significant streamflow (Marsh et al., 2016). In November a south-westerly airflow described as an ‘atmospheric river’ became established bringing persistent warm moisture-laden air from subtropical regions resulting in persistent heavy rainfall. A three-day total of 138mm was recorded at the Shap automatic weather station in mid-November (Marsh et al., 2016), compared to the total of 145-180mm recorded at rain gauges around the Kent catchment in September and October.

Dynamic TOPMODEL requires as input a time series of potential (or actual) evapotranspiration. We used the Calder (1983) approximation of a diurnal sinusoidal variation in potential evapotranspiration.

![Figure 6-4. Simulation period showing specific discharges recorded at Bowston Mill, Middle Kent and rainfall data interpolated from the gauges around that catchment. Evapotranspiration estimated using the approach described in the text.](image)

Environment Agency rainfall and streamflow observations were used for the Monte Carlo calibration and GLUE analyses of the Dynamic TOMODEL simulations described in the sections below.

6.4 Spatial representation

Catchment topography data were supplied as 2m merged Digital Terrain Model (DTM) in GEOTiff format projected to the OSGB36 CRS. Detailed river networks (DRNs) were supplied as ESRI Shapefiles. The DTMs for each catchment were re-sampled to 10m resolution as higher resolution raster datasets led to very high computational demands.

Sub-catchment boundaries for first-order and higher streams to be modelled were supplied by JBA. A pre-processing module was developed that takes these definitions and masks to the boundaries of the individual sub-catchments the overall catchment DTM and DRN and any other landscape layers such as intervention areas (Figure 6-5).

The spatial positions of EA tipping-bucket raingauges (TBRs) and EA streamflow gauges are identified from meta-data (header rows) that were included in text files of time series data provided by the EA. Raingauges within a 5km radius may then be identified and their observations included. There were significant orographic effects on the rainfall in the study periods due to the high catchment relief, leading to a high rainfall gradient across the catchment. The available rainfall data (some sites were rejected in the absence of complete records) were
therefore Kridged using spatial location and altitude as predictor variables to give a basin-integrated value for each basin.

Figure 6-5. Subdivision of the Kent catchment draining to Bowston Mill after application to the pre-processing module described in the text. EA tipping-bucket raingauges are shown as black squares and EA streamflow gauging stations as circles.

WW and other intervention areas already described were supplied by the RT and JBA as ESRI Shapefiles. These were rasterised and incorporated into the catchment discretisation. The catchments areas are classified first by their TWI, then by their location within each of the intervention areas. A minimum areal contribution of 1% is applied to reduce the complexity of the resulting groupings.

6.5 Evidence base for parameters representing NFM

6.5.1 Introduction

The NFM interventions simulated using Dynamic TOPMODEL were those associated with planting trees (including evapotranspiration and resultant soil drying effects; reduced overland flow via enhanced soil permeability; and slowing overland flow via increased surface roughness), peatland restoration (slowing overland flow via increased surface roughness) and the addition of runoff attenuation features on hillslopes to capture and slow overland flow. Almost all tree planting for NFM in the UK has been associated with deciduous trees, so the tree effects reviewed focussed on deciduous woodland pertinent to the 6-week period of floods in Cumbria over the November – December 2015 period.

6.5.2 Deciduous woodland effects on wet-canopy evaporation in leafless winter periods in UK (and elsewhere in Europe) versus improved grasslands

Deciduous woodlands in the early winter (i.e., November-December) in Western Europe, when the overstory is leafless, exhibit only very small rates of transpiration (Vinke et al., 2005).
Potentially, these rates may be marginally higher than those for improved grasslands, if the woodland is open and accompanied by a leafed understory vegetation of shrubs and/or longer grasses (Rychnovská 1975; Black and Kelliher, 1989; Roberts and Rosier, 1994; Verón et al., 2011). This effect is, however, likely to be insignificant when compared with the contrasts in wet-canopy evaporation (also called ‘interception loss’ or EWC).

As Reynolds and Henderson (1967) noted ‘...although sometimes there is measureable reduction of interception losses in winter due to leaf fall, the effect is commonly surprisingly small...’ (p178). Combined EWC and transpiration losses from grasslands in the early winter are likely to be small, for example 5.6% of gross rainfall (100[16.3/289.5 mm] for months of December 1975-1985 in Table 10: Kirby et al., 1991). However, in some contrast, the wet-canopy evaporation rate for deciduous woodland when the overstory is leafless in winter is likely to be within the range 10-20% of the gross rainfall for the conditions prevailing in the UK or for similar situations in continental Europe (Table 6-3). The greatest contrasts are likely between these woodlands and short grasses (Thurow et al., 1987). A recent example study is that of Herbst et al. (2008) that undertook wet-canopy evaporation investigations in Grimsbury Wood (Berkshire, UK) during periods when the oak (Quercus robur L.) and birch (Betula pubescens L.) overstory was either leafed or leafless. Figure 6-6 shows the relationship between the net rainfall components received beneath the canopy (i.e., throughfall and stemflow pathways) versus the gross rainfall received by the woodland canopy. That component of gross rainfall that never reaches the ground beneath the woodland canopy, when measured over weekly (or longer) integration periods, equates to that returned to the atmosphere as wet canopy evaporation.

Table 6-3: Wet-canopy evaporation: rates for leafless deciduous trees plus shrubs in winter

<table>
<thead>
<tr>
<th>% P (by rank)</th>
<th>Dominant species</th>
<th>Reference</th>
<th>UK/Europe</th>
</tr>
</thead>
<tbody>
<tr>
<td>36%</td>
<td>oak/birch</td>
<td>Noirfalis (1959)</td>
<td>UK</td>
</tr>
<tr>
<td>29%</td>
<td>hornbeam</td>
<td>Leyton et al (1967)</td>
<td>Continental Europe</td>
</tr>
<tr>
<td>22.5%</td>
<td>oak</td>
<td>Vinke et al (2005)</td>
<td>Continental Europe</td>
</tr>
<tr>
<td>19.8%</td>
<td>oak/birch</td>
<td>Herbst et al (2008)</td>
<td>UK</td>
</tr>
<tr>
<td>15.1%</td>
<td>beech/hornbeam</td>
<td>Aussenac (1968)</td>
<td>Continental Europe</td>
</tr>
<tr>
<td>14%</td>
<td>beech</td>
<td>Reynolds &amp; Henderson (1967)</td>
<td>UK</td>
</tr>
<tr>
<td>12.1%</td>
<td>mixed</td>
<td>White and Carlisle (1967)</td>
<td>UK (Cumbria)</td>
</tr>
<tr>
<td>12%</td>
<td>oak coppice</td>
<td>Thompson (1972)</td>
<td>UK</td>
</tr>
<tr>
<td>11%</td>
<td>oak</td>
<td>Dolman (1987)</td>
<td>Continental Europe</td>
</tr>
<tr>
<td>10.5%</td>
<td>hornbeam/oak</td>
<td>Schnock (1969)</td>
<td>Continental Europe</td>
</tr>
<tr>
<td>10%</td>
<td>oak/beech</td>
<td>Staelens et al (2008)</td>
<td>Continental Europe</td>
</tr>
<tr>
<td>9.9%</td>
<td>oak</td>
<td>Carlisle et al (1965)</td>
<td>UK</td>
</tr>
<tr>
<td>7%</td>
<td>beech</td>
<td>Gerrits (2010)</td>
<td>Continental Europe</td>
</tr>
</tbody>
</table>

A wet-canopy evaporation range that also encompasses most of the extremes in observed behaviour of leafless vegetation canopies would be 5-50% of gross rainfall (Table 6-3). The maintenance of high wet-canopy evaporation rates from deciduous trees even after leaf fall has been attributed to minimal change in canopy capacity from leafy to leafless periods (see e.g., Table 5 in Rosier et al. 1990). This effect is likely to be magnified where a complex woody understorey is present within the woodland.
6.5.3 Deciduous woodland effects on antecedent moisture status in the early winter versus improved grasslands

The higher rate of wet-canopy evaporation during winter leafless periods, combined with the higher combined rates of wet-canopy evaporation and transpiration from leafed deciduous trees in the proceeding summer and autumn in comparison to grassland (Brown et al., 2005), means that woodland soils are likely to be drier during the winter. A drier subsurface condition will reduce the proportion of rainfall delivering fast streamflow responses thereby reducing peak flood flows (Chappell et al., 2006, 2017). Finch (2000) observed drier soil moisture profiles (by 250 mm) beneath sweet chestnut (Castanea sativa L.) and larch (Larix decidua L.) woodland and grasslands in Pang basin (Berkshire, UK) through December in 1997. Indeed, the profile did not reach its maximum saturation until April 1998 (Figure 6-7). Similarly, Calder et al. (2003) show soil moisture deficits through December 2000 that are drier by 30 mm in the soil (0-0.90 m) beneath oak (Quercus robur L.) of Clipstone Forest (Nottinghamshire, UK) than beneath adjacent grassland (Figure 6-8). A scenario of 80 mm of additional soil moisture deficit beneath deciduous woodland compared to grassland in the early winter is within the 30-250 mm range of the two UK studies noted, but is clearly associated with a highly uncertain range.

Figure 6-6. Net rainfall received beneath a woodland overstory of oak/beech trees versus gross rainfall received by the canopy for both leafed and leafless periods, where (a) shows the throughfall component and (b) the stemflow component of net rainfall (adapted from Herbst et al., 2008).
Figure 6-7. Profile water content (mm depth over 0-3.0 m depth) beneath sweet chestnut (Castanea sativa L.) and larch (Larix decidua L.) woodland and beneath grasslands in Pang basin (Berkshire, UK), adapted from Finch (2000).

(a)

Figure 6-8. Soil moisture deficit (mm depth over 0-0.90 m depth) beneath (a) oak (Quercus robur L.) of Clipstone Forest (Nottinghamshire, UK) than beneath (b) adjacent grassland adapted from Calder et al. (2003).

(b)

6.5.4 Deciduous woodland effects on slowly permeable, gleyed UK soils

Overland flow on hillslopes may be caused by rainfall intensities (mm/hr) exceeding the saturated hydraulic conductivity (mm/hr) of a topsoil or other surface horizon (equivalent to the ‘infiltration capacity’ or ‘coefficient of permeability of the topsoil’). This rapid pathway of rainfall towards stream channels is called ‘infiltration-excess overland flow’ (Horton, 1933). If rainfall is reaching the ground at a rate that is less than saturated hydraulic conductivity of the topsoil, but
cannot infiltrate because the topsoil is already saturated as a result of drainage from upslope areas, then the rainfall onto these saturated areas will move as overland flow across the surface. This pathway is called ‘saturation overland flow by direct precipitation’ or SOF by direct precipitation (Dunne and Black, 1970). If the downslope subsurface flows exceed the ability of the downstream soils to discharge them directly into a stream channel, then subsurface water may emerge from the topsoil onto the ground surface as ‘return flow’ (Cook, 1946). This return flow may then travel overland towards a stream as so called ‘saturation overland flow by return flow’ (SOF by return flow).

Soil types that typically have a lower saturated hydraulic conductivity have a greater likelihood of generating ‘infiltration-excess overland flow’, and where present in downslope areas, also a greater likelihood of generating surface flows by ‘saturation overland flow by direct precipitation’ and ‘saturation overland flow by return flow’. The soil type called a Gleysol using the international soil classification system (FAO-UNESCO, 1990) or gley within the Soil Survey of England and Wales (SSEW) soil classification system (Jarvis et al., 1984) typically exhibits lower saturated hydraulic conductivity values throughout UK soil profiles (Chappell and Ternan, 1991). Table 6-4 shows an example KS profile for a gley in the Lune Valley, Northwest England (UK). These measurements were undertaken in the field with a ring parameter (Chappell and Ternan, 1997), a technique demonstrated to give accurate values, even for disturbance-sensitive gley soils (Chappell and Lancaster, 2007).

Table 6-4: Horizon-specific saturated hydraulic conductivities (cm/hr) of a Humic Gleysol near Farleton, Lancashire (UK). Measurements undertaken using a ring permeameter by Richard Hartley and reported in Chappell and Ternan (1992)

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Mean Ks (cm/hr)</th>
<th>Range (n = 56)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.10</td>
<td>9.1</td>
<td>1.31–30.7</td>
</tr>
<tr>
<td>0.10-0.20</td>
<td>21.8</td>
<td>8.98–57.0</td>
</tr>
<tr>
<td>0.20-0.50</td>
<td>0.11</td>
<td>0.021–3.02</td>
</tr>
<tr>
<td>0.50-1.00</td>
<td>0.002</td>
<td>0.0007–0.21</td>
</tr>
</tbody>
</table>

Soils in England and Wales that are classified as gley include the SSEW Soil Associations of 713e-Brickfield-1, 713f-Brickfield-2, 713g-Brickfield-3, 721c-Wilcocks-1, and 721d-Wilcocks-2 (Jarvis et al., 1984). The 721d-Wilcocks-2 soil is mapped within the Upper Kent basin, 713e-Brickfield-1, 713g-Brickfield-3 and 721c-Wilcocks-1 in the Upper Eden basin, and 713f-Brickfield-2 in the Lower Cocker basin (Soil Survey of England and Wales, 1983). As a result of their greater likelihood for generating overland flow (by whichever of the three mechanisms), these gley soils are classified as having an SPRHOST value in excess of 50% (Boorman et al., 1995). Enhancing the permeability of such soils is considered to have the greatest impact on reducing overland flow across catchments and thereby have the greatest potential to reduce flood peaks in rivers (Nisbet et al., 2011). As a result, tree planting to increase soil permeability includes areas with such gley soils. It should be noted that the SPRHOST >50% classification also captures areas covered soil types such as Dystric Leptosol, Ferric Podzol, and Dystric Cambisol within the study basins in Cumbria. Chappell and Ternan (1992) provide an explanation of why these soil types are less likely to generate overland flow and so should not be lumped with gleys in the HOST soil classification.

Consequently, for NFM modelling a key need is to represent the permeability effects of planting deciduous trees on gley soils. Very few UK studies are available that quantify the difference in soil KS of gley soils beneath deciduous trees relative to that beneath adjacent grasslands (Chandler and Chappell, 2008). These few studies are summarised in Table 6-5, and give a range of 1.5 to 3.5 factor increase in permeability for deciduous tree planting on gley soils.
Table 6-5: Statistically significant ratio of KS between deciduous trees and grassland growing on gley soils in the UK.

<table>
<thead>
<tr>
<th>F/G</th>
<th>Tree age</th>
<th>Soil type2</th>
<th>Location</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.81</td>
<td>2 years</td>
<td>713e-Brickfield-1</td>
<td>Tebay Gill Cumbria</td>
<td>Mawdsley, Chappell &amp; Swallow (2016)</td>
</tr>
</tbody>
</table>

1  Factor difference in KS, i.e., (KS below deciduous trees / KS below grassland)
3  Results of related study of Carroll et al (2004) Soil Use Manage 20: 357-359 rejected on basic quality assurance criteria (i.e. absent sampling size per land-cover; absent information on frequency distribution etc)

This observed increase in permeability for gley is smaller than the factor of 5 difference between predominantly deciduous woodland (Fagus sylvatica L., Prunus spinose L., Quercus petraea L., Betula pendula L., Acer pseudoplatanus L.) and improved pasture recently observed on well drained Eutric Cambisol (SSEW Brown Earth) soils in Scotland by Archer et al (2012, 2013). The observed effect on gley is also smaller than the effects observed on other soil types across the globe (Table 6-6).  

Table 6-6: Ratio of topsoil permeability under trees to that under adjacent pasture. See Chandler and Chappell (2008) for those references not cited in this report.

<table>
<thead>
<tr>
<th>F/G</th>
<th>Soil typea</th>
<th>Tree typeb</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8</td>
<td>Gleysol</td>
<td>Crataegus monogyna</td>
<td>Mawdsley, Chappell &amp; Swallow (2016)</td>
</tr>
<tr>
<td>2.0</td>
<td>Luvisol</td>
<td>Eucalyptus spp.</td>
<td>Lorimer and Douglas (1995)</td>
</tr>
<tr>
<td>2.5</td>
<td>nk</td>
<td>Eucalyptus spp.</td>
<td>Burch et al. (1987)</td>
</tr>
<tr>
<td>3.4c</td>
<td>Gleysol</td>
<td>Quercus robur</td>
<td>Chandler and Chappell (2008)</td>
</tr>
<tr>
<td>4.8</td>
<td>nk</td>
<td>Pinus insularis</td>
<td>Costalles (1979)</td>
</tr>
<tr>
<td>5.2</td>
<td>Cambisol</td>
<td>mixed deciduous</td>
<td>Archer et al. (2013)</td>
</tr>
<tr>
<td>4.5–7.2</td>
<td>Cambisol</td>
<td>Quercus robur</td>
<td>Burt et al. (1983)</td>
</tr>
<tr>
<td>6</td>
<td>Cambisol</td>
<td>mixed</td>
<td>Archer et al. (2013)</td>
</tr>
<tr>
<td>8</td>
<td>Cambisol</td>
<td>mixed</td>
<td>Archer et al. (2013)</td>
</tr>
<tr>
<td>2.3–12</td>
<td>Ferralsol</td>
<td>Eucalyptus/Gravillea spp.</td>
<td>Wood (1977)</td>
</tr>
<tr>
<td>14</td>
<td>Nitisol</td>
<td>Hibiscus elatus</td>
<td>Ternan et al. (1987)</td>
</tr>
<tr>
<td>20</td>
<td>Andosol</td>
<td>Podocarp</td>
<td>Jackson (1973)</td>
</tr>
<tr>
<td>23–41</td>
<td>Nkd</td>
<td>Quercus spp.</td>
<td>Molchanov (1960)</td>
</tr>
<tr>
<td>50e</td>
<td>Ultisol</td>
<td>Quercus spp.</td>
<td>Hoover (1949)</td>
</tr>
<tr>
<td>17–140</td>
<td>Cambisol</td>
<td>Eucalyptus spp.</td>
<td>Wood (1977)</td>
</tr>
</tbody>
</table>

F/G = ratio of the topsoil saturated hydraulic conductivity under trees to that under pasture (ranked by magnitude)
(nk) not known

a  FAO-UNESCO classification
b  Dominant or representative tree species
c  At 3 m from Tree No. 1
d  Reported as ‘dark grey soils’
e  0.1 m depth
Critically, it should be remembered that most of the stream hydrograph during floods comprises of water that has primarily travelled to the stream via subsurface pathways. Even within very flashy, but undisturbed tropical streams, only small proportions of flow within the basin have been directly measured as overland flow (e.g., < 10% streamflow: Chappell et al. 1999, 2006). Therefore, while the overland flow pathways are important given their speed and sediment transport aspects, simulated flow pathways should be dominated by subsurface pathways either close to the surface in soils or deeper within the surficial or solid geology (Ockenden and Chappell, 2011; Jones et al., 2014).

6.5.5 Deciduous woodland impacts on surface roughness regulating overland flow on slopes versus improved grasslands
Once generated, the passage of overland flow down slopes towards streams is regulated by slope angle, degree of topographic contour convergence-divergence, the roughness of the surface and the opportunities for re-infiltration (also called ‘runon’). The surface roughness is often characterised with Manning’s roughness coefficient, n or Darcy-Weisbach friction factor, f, where increasing surface roughness reduces overland flow speeds. Considering the roughness of the ground covered by improved pasture, heathland or deciduous woodland, many different elements combine to produce an effective roughness for a whole hillslope. For example, within a deciduous woodland, roughness contributions would come from: (2) micro-scale roughness of the litter layer, (2) structural roots at the ground surface running across the slope, (3) obstructions to flow caused by tree stems (or the understory vegetation), (4) presence of paths and tracks, (5) the presence of fence lines or walls, and (6) meso-scale topographic irregularities of the slope. All components need to be characterised and summed by linear superposition to provide an accurate measurement of the effective roughness of a whole hillslope (Medeiros et al., 2012). Direct measurements of the roughness components across a range of surface vegetation conditions at floodplain sites in Florida (USA) by Medeiros et al. (2012) produced Manning’s (dimensionless) n values that ranged from 0.030 to 0.061 for forest areas against a range of 0.013 to 0.050 for other surfaces including barren land and grasslands.

Chow (1959) states that floodplains covered by pasture should be ascribed a roughness value of 0.035, while those covered by light brush and weeds 0.050, dense brush 0.070 and dense forest 0.1-0.2. Thus in direct comparison with the direct measurements of roughness undertaken by Medeiros et al. (2012), the differences between woody vegetation and pasture-cum-barren land are much less than those reported in Chow (1959). Thus Chow (1959) shows a reduction in roughness by a factor of 0.35 from forest to grassland, while even taking the most extreme values from Medeiros et al. (2012) a reduction of only 0.21 (i.e., 0.013/0.061). Given: (1) the limited number of studies directly measuring hillslope roughness, as in Medeiros et al. (2012), (2) the discrepancies between the field-measured and tabulated (or estimated) values, combined with (3) the large variability in roughness values measured even within the same vegetation types, a large uncertainty should be placed on the range of possible roughness values used in models.

6.5.6 Effects of peatland management on surface roughness regulating overland flow
Similar issues arise when estimating the effects of peatland management on the effective roughness of hillslopes as with the comparisons between the effects of forest versus pasturelands illustrated in section 6.5.5. For example peatland restoration may involve replacing patches of bare peat with Sphagnum spp. moss, changing micro-scale roughness, but also adding small obstructions within the artificial drains, thereby changing meso-scale roughness of hillslopes. Holden et al (2008) used 256 bounded overland flow plots (0.5 m x 6 m) in the Upper Wharfe catchment (UK) and found that the Darcy-Weisbach friction factor (i.e. roughness) was greater when Sphagnum spp. moss rather than bare ground was present, resulting in a reduction of overland flow speeds by a factor of 3.3 (0.04959/0.0149 in Table 1). However, the quantification of peatland improvements is complicated by the fact that at the meso-scale, the effectiveness of blocking drains on overland flow (and hence effectiveness roughness) can be strongly dependent on the orientation of the drains, i.e., whether they run across slope or downslope (Holden et al., 2006), and blocking downslope drains will have the most effect.

6.5.7 Characteristics of downslope ‘overland flow interception RAFs’ used to store and slow overland flow on slopes
Small ponds to capture and temporarily store overland flow (see Section 6.5.4) on its way to stream channels have been described as ‘overland flow interception RAFs’ or ‘overland flow
disconnection ponds’, where RAFs are ‘runoff attenuation features’. If the overland flow is generated at the same time as the peak discharge in the stream channel, then temporary storage of the overland flow on slopes could delay this component of the flow so that it is added to the less critical recession in the stream behaviour. If the overland flow is primarily generated on the rising stage of stream hydrograph (see e.g., Chappell et al., 2006), delaying the overland flow could have the negative effect of adding the overland flow to the channel at the time of the peak in the streamflow! Clearly understanding precisely when overland flow is being added to stream channels is critical for understanding how it should be managed. Few direct measurements of overland flow using plot studies are available in the UK to help quantify the timing of this process. Figure 6-9 shows how one such feature at the Belford Catchment Solutions Project in Northumberland is able to retain and hence damp the initial phase of overland flow generation.

![RAF-11 Impact](RAF-11-Impact.png)

Figure 6-9. Inflow and outflow to the 500 m³ overland flow interception RAF number 11 in late June 2012 at the Belford Catchment Solutions Project in Northumberland (UK), adapted from Nicholson (2013).

Overland flow interception RAFs have been constructed at many locations in the UK and individually range from 20 to 1000 m³ in overland flow holding capacity (Deasy et al., 2010; Nicholson et al., 2012; Nicholson, 2013). RAFs added into the simulations for this study are 100-5,000 m³ in area and so are broadly similar in capacity.

### 6.6 Capture of key features of catchment and NFM measures

A set of HRUs were developed based on local hydrological characteristics, the most important of which is the topographic wetness index (TWI). These were then split further so that individual NFM measures could be represented in the landscape. For example, the HRU representing the saturated area adjacent to the watercourse in the upper catchment becomes split into two, one where there is no change to the landscape, and another where there is tree planting.

- **HRU1** – high SPR areas – Mimicking tree planting effects.
  - Modification of T0 (implemented as a 1.5 to 2.5 multiplicative factor of the unlogged value)
  - Decreased SOF velocity (reduced by between 0.5 and 0.75 of the present value to represent a similar change in roughness implemented for the JFLOW simulations).
  - Wet-canopy evaporation increases implemented as a loss to the gross rainfall input (using a similar strategy to Buytaert and Beven, 2009).
  - Modification of the initial root zone storage to mimic drier antecedent soil moisture conditions as a result of additional soil drying by enhanced wet-copy evaporation (and enhanced transpiration in previous months).

- **HRU2** – RAF features
  - Increased storage by introduction of RAFs is based upon modified JFLOW RAF opportunity maps
  - Implemented by a modification to the root zone storage to 1m, making use of the existing store represented in the model
  - RAFs drain via a “pipe” (Leaky RAFs)
Assume all RAFs are all the same and drain is directly to water course.

- Implemented as a sensitivity of 3 "pipe" sizes to see differences in ‘effective’ pipe size in terms of peak reduction.

- **HRU3 – Peat**
  - Decreased SOF velocity (reduced by between 0.65 and 0.8 of the present value to represent a similar change in roughness implemented for the JFLOW simulations).

### 6.7 Calibration approach using Monte-Carlo framework

The rainfall-streamflow time-series presented in Section 6.1 was simulated using Dynamic TOPMODEL within a framework that provides a sensitivity and uncertainty analysis of these baseline simulations and subsequently provides more representative simulations of NFM interventions.

The overall aim of the approach is to define a set of models that are acceptable on the basis of the observed data and knowledge of catchment processes, and vary the parameters for these models by factors that are justifiable on the basis of the evidence (Section 6.5).

A schematic of the framework is presented in Figure 6-10 where the following interconnected steps are shown:

- Initial varied parameter ranges were specified and sampled using random, Monte-Carlo sampling of values between sensible ranges (Table 6-1).
- Each of the sampled parameter sets (for each catchment) was used for one model simulation.
- Uncertainty analysis using the GLUE approach: each simulation output was evaluated based upon pre-defined acceptance criteria to provide a subset of acceptable simulations. Each acceptable simulation was assigned a weighting (score) based on fit to these criteria.
- A weighted combination of all acceptable simulated discharges was used to represent the pre-intervention baseline catchment streamflow (Figure 6-10).
- The evidence base relating to intervention effects was mapped onto each of the acceptable parameter sets using a “fuzzy mapping” methodology (see Section 6.7.5; c.f. Buytaert and Beven, 2009); this provided the modified parameter sets for each intervention scenario.
- Each modified acceptable parameter set was used when simulating interventions within the HRU of interest (the acceptable parameter set of 3. above was used outside this HRU).
- Intervention results: the best estimate of changes and associated uncertainty estimates derived from acceptable simulations, the weighting from 3. above and intervention scenario weighting.

---

8 The Manning’s equation was used to approximate the changes to flow rates based on changes to the manning coefficient, so the changes represent evidence based on engineering tables.
The figure shows a generic approach, which would be equally applicable to other modelling software if we remove the reference to Dynamic TOPMODEL.

### 6.7.1 Model parameters and sampling

The relevant model parameters are described in Section 6.1 along with those included within the uncertainty analysis. To some degree, model parameters are model-specific, potentially scale-dependent and inherently uncertain. Given this, and the uncertainties associated with the model and boundary condition data, an uncertainty framework helps us to be more honest about the conclusions that can be drawn, and these will ultimately be more robust. The initial phase of the uncertainty analysis is to sample the chosen parameters within a physically-plausible range (Table 6-1) and make a large number of simulations using random permutations of parameters. These parameter sets were randomly sampled from the specified ranges: using Monte Carlo sampling from uniform distributions.

### 6.7.2 Simulations

The sampling strategy was used to generate 5,000 parameter sets for each catchment and each parameter set was used to simulate each catchment using the same rainfall inputs. Simulation output was saved for all simulation runs for evaluation as described below.

### 6.7.3 Identifying acceptable parameter sets using Generalised Likelihood Uncertainty Estimation

Each simulation was compared to the criteria defined below to determine whether or not it was representative of the observed behaviour. Within the Generalised Likelihood Uncertainty Estimation framework (GLUE; Beven, 2006, 2012; Blazkova and Beven, 2009; Liu et al., 2009; Beven and Binley, 2014), the degree of acceptance of any simulation is weighted (or scored) quantitatively and is associated with the simulation during the entire analysis. Any simulations which are deemed physically unacceptable play no further part in the analysis and do not form part of the results. The acceptance criteria are given in Table 6-7, based on overall performance measure over the whole modelled period (NSE), the accuracy of the model prediction for the peak flow during Storm Desmond, and the maximum percentage of the catchment areas generating overland flow (by infiltration-excess or saturation processes).
### Table 6-7: Limits of acceptability used in the GLUE analysis

<table>
<thead>
<tr>
<th></th>
<th>Nash Sutcliffe Efficiency (NSE)</th>
<th>Max. Discharge Desmond (m³ s⁻¹)</th>
<th>SOF max area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eden</td>
<td>&gt; 0.85</td>
<td>&gt; 5.5 and &lt; 8.5</td>
<td>&gt; 0.1 and &lt; 0.95</td>
</tr>
<tr>
<td>Kent</td>
<td>&gt; 0.85</td>
<td>&gt; 6.9 and &lt; 10.2</td>
<td>&gt; 0.1 and &lt; 0.95</td>
</tr>
<tr>
<td>Derwent</td>
<td>&gt; 0.85</td>
<td>&gt; 7.8 and &lt; 13.0</td>
<td>&gt; 0.2 and &lt; 0.95</td>
</tr>
</tbody>
</table>

#### 6.7.4 Baseline streamflow results

All of the acceptable time-series of streamflow are used to represent the baseline streamflow results, not just one “best” simulation. Each simulation is associated with its weighting (based on fit to criteria) and this weighting is used to determine how much influence each simulation has on the final results. This means that at each time-step there is a distribution of streamflow estimates, where each estimate has a different level of confidence and a most likely value can be determined as can an uncertainty range (see Figure 6-11) and which when applied to all time-steps for the simulation gives an envelope of simulated streamflow.

![Figure 6-11](image-url)

Figure 6-11. Distribution of simulated streamflow for example time-steps showing the weighted uncertainty estimates as orange circles.
6.7.5 Mapping of interventions onto model parameters

The estimates of parameter modifications outlined in Section 6.6 are mapped onto all of the physically-acceptable parameter sets. A schematic representation of how this is done is given in Figure 6-12 which shows how the evidence of the effect of a given intervention includes the uncertainty associated with the expected intervention effect. This is mapped via a number of weighted scenarios onto the acceptable parameter sets; this mapping results in a number of weighted scenarios (modified parameter sets) which are used in the model to simulate the effect of an intervention. So, we have taken into account parameter uncertainty and the uncertainty in the changes that NFM are thought to have on key catchment processes.

However, for space limitations we have shown the more optimistic intervention case scenarios (5 on a scale of 1 to 5) and the other scenarios are placed in Appendix C.

![Schematic diagram of the mapping of literature-derived evidence of the effect of interventions onto acceptable model parameter sets.](image)

6.7.6 Producing intervention results

For each intervention, and for each scenario from the mapping in the previous section, all modified acceptable parameter sets were run and result in a large number of simulations, in a similar way to the baseline simulations (Section 6.7.4). Each scenario is associated with its weighting from the GLUE analysis described above combined with a weighting assigned to each scenario from the fuzzy mapping exercise (Section 6.7.5 and Figure 6-12). Each set of simulations associated with each scenario allow some insight into the sensitivity of the model to degree of effect of intervention and can be combined to give an overall estimate of intervention effect, including an estimate of the uncertainty associated with the likely magnitude of effect.

We identified the 'Distribution of acceptable parameters' in Figure 6-12 using 'dotty plots' for each catchment, which show how well each model structure performed for each Monte-Carlo simulation, in terms of a performance measure labelled as 'WTG' in Figure 6-12. The red dots in Figure 6-13 are the sets of parameters for which observed model behaviours were considered acceptable based on expert judgement. This might be in terms of the peak flow during Desmond (qmax), or the proportion of land contributing to overland flow. Parameters showing little vertical variation in terms of WTG show there is an insensitivity (in combination with the other parameters) across the range of values simulated. Where there are several groups of red dots (horizontally) this suggests that the parameter is sensitive but there are several potential 'states' for the variable.

Figure 6-14, Figure 6-15 show the simulations that were considered acceptable based on constraints in Table 6-7. These plots can be difficult to interpret for the non-expert; they show the
part of the parameter ranges where acceptable simulations are found (and hence also parameter sensitivity) and they also result in the envelope of 'acceptable' model predictions in Section 7.

Figure 6.13. Acceptable simulations for the Kent in red, with all other simulations in blue. See Table 6.1 for definitions of model parameters.

Figure 6.13. Acceptable simulations for the Eden in red, with all other simulations in blue. See Table 6.1 for definitions of model parameters.
6.8 Representing NFM measures with Dynamic TOPMODEL parameters

NFM interventions were mapped onto Dynamic TOPMODEL parameters as outlined in Section 6.7.5 using the evidence for each intervention effect (see Section 6.5) and the mapping methodology. The modifications to specific parameters are implemented within three HRUs identified on the basis of intervention scenarios:

- **HRU1** – high SPR areas – low infiltration priority areas for tree planting.
  - Modification of wet canopy evaporation (Ew)
  - Modification of the SOF velocity (VSOF)
  - Modification of the soil surface transmissivity (T0)
  - Modification of the initial root zone storage deficit (Srzo)

- **HRU2** – RAF features
  - Increased storage by introduction of RAFs is based upon modified JFLOW RAF opportunity maps
  - Implemented by a modification to the Root zone storage to 1m
  - RAFs can drain via a “pipe” (Leaky RAFs)
  - Assume all RAFs are all the same and drain is directly to water course

- **HRU3** – Peat
  - Modification of the SOF velocity (VSOF)

Following the combined modification simulations representing tree-planting, some additional individual parameter change simulations were undertaken to see which of the individual modifications made the greatest difference.

6.8.1 Modification of wet canopy evaporation (HRU1)

The effect of deciduous woodland on wet canopy evaporation (in the winter period) was implemented based upon the evidence presented in Section 6.5.2. It was assumed that the existing model formulation for transpiration remained unchanged as its representation was implicit in the acceptable parameter sets identified. Wet-canopy evaporation was implemented
as a percentage of the rainfall that was lost to wet-canopy evaporation on an individual “wet” time-step basis (see Table 6-3).

6.8.2 Modification of surface overland flow velocity (HRUs 1 and 3)
The modification of overland flow velocity (VSOF) was modified to represent increased surface roughness associated with tree planting (HRU1: see section 6.5.4) and peatland restoration (HRU3: see section 6.5.5). This was implemented by back-calculating an effective change in velocity using Manning’s equation such that Dynamic TOPMODEL parameterisations were consistent with the JFLOW simulations.

6.8.3 Modification of the soil surface transmissivity (HRU1)
The transmissivity of the soil at the surface was modified to represent the increase in saturated hydraulic conductivity (‘infiltration capacity’) associated with tree planting (see Section 6.5.3). It was assumed that tree planting only modified this surface value and that the decrease in transmissivity with depth described by the exponential decline parameter (m) did not change significantly. It was also assumed that the likely change in surface transmissivity was assumed to equate to the observed changes in near-surface saturated hydraulic conductivity associated with tree growth (Section 6.5.4) This approach maintains consistency in representing the real system in model space.

6.8.4 Modification of the initial root zone storage deficit (HRU1)
The effects of increased evapotranspiration resulting from a land cover change to deciduous woodland includes drier initial conditions in the model. This was represented by changes to the initial root zone storage deficit (Srz0: see Sections 6.5.2 and 6.5.3).

6.9 Visualising changes to predicted flow distributions
Given the uncertainty framework, and the range of acceptable model predictions, we have devised a way to highlight differences to the predicted flow distributions with and without NFM measures in place. Figure 6-16 shows how the uncertainty in the model predictions means that we cannot just compare the peak flows predicted with and without NFM measures because a whole set of parameter combinations are acceptable on the basis of the observation data. Instead we make a histogram of predicted flows between dates centred on the storm Desmond peak and look at changes to the distribution. These figures are used to illustrate changes to behaviour due to NFM interventions in the face of uncertainty.
6.10 Quality Assurance of Dynamic TOPMODEL parameters

In terms of the parameter ranges used during calibration and the ranges of parameters that were used to represent NFM features, a number of steps were taken. These were set by experts at LEC and checked through:

- Literature review
- Discussion with Dynamic TOPMODEL model creator, Prof K. Beven
- Discussion with independent woodland expert, Tom Nisbet
7 Dynamic TOPMODEL Predictions

7.1 Introduction
This section summarises outputs from the calibration approach that was introduced in Section 6, and visualises the results following the generic approach in Figure 7-1.

Run Monte-Carlo simulations with a range of feasible parameters

Decide which parameters are acceptable based on a set of constraints

Show envelope of acceptable model predictions compared to observations

Define changes to parameters to represent NFM based on evidence

Model combinations of acceptable models and NFM changes to parameters

Visualise the impacts of different degrees of NFM compared to baseline

Visualise the changes to predicted flow distributions for different storms

Summarise how the modelling can inform implementation of NFM

Figure 7-1. Generic modelling procedure

The following sub-sections provide key outputs from the steps in this approach. The Dynamic TOPMODEL domains are the hashed areas shown in Figure 1-2, which are shown in more detail in the figures below.

For the Derwent catchment, we have also shown the results with and without the effects of the upstream influence of the flows coming from Crummock Water and the rest of the catchment. This is because the outflow for this prioritised sub-catchment is so strongly influenced by the upstream flows.

In the next sub-sections, the more optimistic scenarios are presented, with simulations across the range of assumptions shown in Figure 6-12 placed in Appendix C. The five histograms on the left hand side of this figure represent different bands of model performance depending on parameter uncertainty and uncertainty in the change of parameters to represent NFM.
7.2 Detailed modelling of the Kent priority sub-catchment

Figure 7-2 shows the detailed modelling domain for the Kent catchment, comprising 71km² upstream of the Bowston gauge and covering the Gowan, Upper and Mid Kent.

Figure 7-2 Dynamic TOPMODEL domain for the Kent catchment

Figure 7-3 shows the 5th and 95th percentiles of the acceptable model predictions (turquoise) based on the parameter combinations that meet the criteria in Table 6-7, compared with the observed data at the gauge (red). There were a greater range of simulations with different trajectories through time before these criteria were applied.

Figure 7-3 Range of acceptable model predictions for calibrated model of the Kent (mm of rainfall per unit area plotted against date)
The acceptable ranges of baseline model parameters were then used to run the modified NFM interventions. For the NFM scenario using RAFs, different time constants or ‘residence times of response’ for drain-down between events were experimented with (1 hour, 10 hour and 100 hours). The results for the 10 hour time constant showed the most significant change, reported in Figure 7-4 and compared with the baseline (see also Appendix C). For the 1 hour time constant, it is thought that the RAFs are draining too quickly without much attenuation when compared to the observed streamflow response, and for the 100 year time constant, they are draining down too slowly between storms, to be useful for the next storm.

![Figure 7-4 Kent: Comparison of RAFs with 10 hour time constants and baseline (mm of rainfall per unit area plotted against time step - Range of dates 2/11/2015 to 17/12/2015)](image)

For the NFM scenario representing tree-planting, the sensitivity of the streamflow hydrograph was investigated with respect to the level of impact that tree-planting is thought to have on different catchment processes based on the literature (Table 6-7). The median change based on the same scenario is given in Figure 7-6, which represents an easier to visualise summary without showing the uncertainties in the modelling.
Figure 7-5 Kent: Most optimistic representation of tree-planting NFM (mm of rainfall per unit area, plotted against time step - Range of dates 2/11/2015 to 17/12/2015)

Figure 7-6 Kent: Median representation of optimistic tree-planting NFM. (mm of rainfall per unit area, plotted against time step - Range of dates 2/11/2015 to 17/12/2015)
The changes to the **distribution of flows** for each type of intervention tells us more about how the interventions are shaping the runoff characteristics. Figure 7-7 shows how the NFM distributions are altered in response to the parameters that are changed to reflect NFM.

![Figure 7-7 Kent: Influence of NFM on flow predictions for each storm for tree-planting (blue)](image)

Depending on the weight of evidence for the impact of NFM interventions on the modelled parameters, our approach allows us to understand the expected percentage reduction in peak flows for different storms (Figure 7-8).

![Figure 7-8 Kent: Confidence in modelled percentage reduction in median flood peaks for different storms.](image)

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\(^9\) That is to say the range of flows predicted over a window covering each storm. We cannot compare individual peaks for given times due to the uncertainty.
7.3 Detailed modelling of the Eden priority sub-catchment

A detailed Dynamic TOPMODEL was set up for the Eden catchment upstream of the EA streamflow gauge at Great Musgrave (Figure 7-9).

Figure 7-9 Dynamic TOPMODEL Domain for the Eden

Figure 7-10 show the 5th and 95th percentiles of the acceptable model predictions (turquoise) based on the parameter combinations that meet the criteria in Table 6-7, compared with the observed data at the gauge.
The acceptable ranges of baseline model parameters were then used to run the modified NFM interventions. For the NFM scenario using RAFs, different time constants for drain-down between events were experimented with (1 hour, 10 hour and 100 hours). The results for the 100 hour time constant showed the most significant change, reported in Appendix C, here Figure 7-11 shows the intermediate 10 hour drain-down time compared with the baseline. For the 1 hour time constant, it is though that the RAFs are simply performing like overland flow pathways.
For the NFM scenario representing tree-planting, the sensitivity of the hydrograph (Figure 7-12) was investigated with respect to the level of local impact that tree-planting on different catchment processes based on the literature. The median change based on the same scenario is given in Figure 7-13 and Figure 7-12, which represents an easier to visualise summary without showing the uncertainties in the modelling.

Some additional individual parameter changes were simulated to see which of the 3 core parameter shifts gave rise to the modelled changes to the hydrograph. This is reported for the Eden in an additional section following reporting on all three catchments.
Figure 7-12 Eden: Most optimistic representation of tree-planting NFM (mm per unit area of catchment plotted against time step. Range of dates 2/11/2015 to 17/12/2015)

Figure 7-13 Eden: Median representation of optimistic tree-planting NFM. (mm per unit area of catchment plotted against time step. Range of dates 2/11/2015 to 17/12/2015)
The changes to the distribution of flows for each type of intervention tells us more about how the interventions are shaping the streamflow hydrograph characteristics. Figure 7-14 shows how the NFM distributions are altered in response to the parameters that are changed to reflect NFM.

Figure 7-14 Eden: Influence of NFM on flow predictions for each storm for tree-planting (blue)

Depending on the weight of evidence for the impact of NFM interventions on the modelled parameters, our approach allows us to understand the expected percentage reduction in peak flows for different storms (Figure 7-15).
Figure 7-15 Eden: Confidence in modelled percentage reduction in median flood peaks for different storms
7.4 Detailed modelling of the Derwent priority sub-catchment

Following the workshop, the 53km² Cocker catchment between the EA Scalehill and Southwaite Bridge streamflow gauges was prioritised for detailed modelling (Figure 7-16). Here the hydrographs are strongly influenced by the signal from the outflow of Crummock Water, and this has been separated in some of the figures later in this section.

Figure 7-16 Cocker (Derwent) Dynamic TOPMODEL Model Domain

Figure 7-17 shows the 5th and 95th percentiles of the acceptable model predictions (turquoise) based on the parameter combinations that meet the criteria in Table 6-7, compared with the observed data at the gauge.
The acceptable ranges of baseline model parameters were then used to run the modified NFM interventions. For the NFM scenario using RAFs, different time constants for drain-down between events were experimented with (1 hour, 10 hour and 100 hours). The results for the 10 hour time constant showed the most significant change, reported in Figure 7-18 and compared with the baseline. For the 1 hour time constant, it is though that the RAFs hardly modifying the overland flow pathways, and for the 100 year time constant, they are draining down too slowly between storms, to be useful for the next storm for the whole catchment. However, for the localised hydrograph with the influence of the upstream removed, the 100 hour drain-down rate is more effective still (Appendix C).

Figure 7-19 shows the same scenario, but for the 'local' Cocker flow production, in other words, the influence of the inflow from Crummock Water has been removed. This might therefore be the expected runoff attenuation at locations away from the main stem of the Cocker, for instance at Lower Lorton.
Figure 7-18 Cocker: Comparison of RAFs with 10 hour time constants and baseline

Figure 7-19 Local Cocker: Comparison of RAFs with 10 hour time constants and baseline with Crummock signal removed
For the NFM scenario representing tree-planting, the sensitivity of the hydrograph (Figure 7-20) was investigated with respect to the level of impact that tree-planting is thought to have on different catchment processes based on the literature. The median change based on the same scenario is given in Figure 7-21, which represents an easier to visualise summary without showing the uncertainties in the modelling. This has then been compared once again to the median for the localised hydrograph, removing the influence of Crummock Water in Figure 7-22, which acts to mask the effect of NFM.

![Figure 7-20 Cocker: Most optimistic representation of tree-planting NFM](image)
Figure 7-21 Cocker: Representation of optimistic tree-planting NFM - median

Figure 7-22 Localised Cocker: Representation of optimistic tree-planting NFM interventions (median)
The changes to the distribution of flows for each type of intervention tells us more about how the interventions are shaping the streamflow hydrograph characteristics. Figure 7-23 shows how the NFM distributions are altered in response to the parameters that are changed to reflect NFM.

Depending on the weight of evidence for the impact of NFM interventions on the modelled parameters, our approach allows us to understand the expected percentage reduction in peak flows for different storms (Figure 7-22). This is relatively small as the influence from Crummock Water has not been removed.

Figure 7-24 Cocker (includes lake influence) Confidence in modelled percentage reduction in median flood peaks for different storms
7.5 Modification of individual parameters representing tree-planting

Three core model parameter changes were made to represent additional tree-planting, those controlling the limiting transmissivity (T0), the surface overland flow velocity (SOF vel.) and the wet canopy evaporation (WC Evap). Some additional simulations were undertaken for the Eden catchment, to identify which parameter is giving rise to greater changes to the hydrograph response. Figure 7-25 shows that whilst the changes based on the wet canopy evaporation are most significant for the Eden, the in-combination effects of changing all three parameters (labelled ALL) are significantly greater. This can be as a result of the non-linear interactions - for instance reduced source of overland flow in one location due to heightened evaporation, combined with reduced flow velocities may well change key synchronisations between peaks on key tributaries.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Eden</th>
<th>Changes to the peak flow distributions around storm Desmond as a result of combined and individual parameter changes representing tree-planting.</th>
</tr>
</thead>
</table>

**Wet canopy evaporation:** As expected removes a consistent proportion of flow for most timesteps through the primary events. To a lesser extent there is some extent of a delayed flow response (but only for acceptable runs which give lower flow magnitudes). The overall effect of the wet canopy evaporation intervention is large but is not as high as with all 3 parameters changed. This wet-canopy evaporation effect from leafless deciduous trees is coming from a change to 21% of the Upper Eden. A greater effect would be expected for the Upper Kent due to the greater extent (34%) of WfW soils, and a smaller effect for the Lower Cocker with only 10% such soils.

**SOF velocity:** Delays the peak on most events and in some cases this also helps to reduce the peak – both of these are very small magnitude effects. These SOF velocity effects are small as the proportion of the storm-water reaching the channels by this pathway is small in the Upper Eden.

**T0:** Removes a small flow magnitude for smaller events but does little for larger events (in the odd case there is a very small increase in peak) – as with SOF velocity the magnitude of effect is very small. The effect of enhancing infiltration and permeability by the addition of trees is small, because their rates are already high in Upper Eden, giving little overland flow and so little opportunity to remove large volumes of water by this fast pathway.

**Overall:** We can say that the overall effect from modifying 3 parameters is greater than the sum of the individual effects.
7.6 Summary of Findings from Detailed Modelling

The detailed modelling in an uncertainty framework has generated many findings, and this report has only presented the key outputs to highlight the main conclusions. These are:

- Large scale NFM interventions have been shown to have a significant effect for a range of catchment conditions including and up to the streamflows experienced for the extreme Storm Desmond event in December 2015, based on the more optimistic assessment of the weight of evidence on how NFM changes the effective model parameters.
- The modelling suggests that the existing ‘natural capital’ in each catchment is already providing a great deal of benefit both for typical and extreme storm events. Augmenting this existing forestry and RAFs is a coherent long term aim for catchment management which is supported by the evidence.
- It is possible to take into account uncertainties in parameter values for hydrological models and constrain these to a set of acceptable combinations based on a set of sensible constraints. Here we have used an overall measure of performance across the storms of November through December 2015, how well the peak streamflow associated with Storm Desmond is predicted and a physically-acceptable range of percentage of the catchment generating significant volumes of overland flow.
- It is also possible to translate NFM interventions into a range of sensible changes to parameters representing catchment streamflow generation processes. These include the effects of tree-planting on initial soil moisture storage and transmissivity rates that map onto those changes that have been observed.
- Depending on the weight of evidence for the impact of NFM interventions on the modelled parameters, our approach allows us to understand the expected percentage reduction in peak flows for different storms (Figure 7-24).
- The combined effects of RAFs plus tree-planting were not simulated, although it is likely that these will be additive, we have seen from the modelling of individual parameter changes in Section 7.5 that combined changes can lead to effects that are more than the sum of their parts.
- Dynamic TOPMODEL has been used, along with a subset of acceptable parameter sets, to sample a combination of the acceptable models with a combination of the changes that NFM are thought to have on these parameters. These have been weighted according to our confidence in the literature, and we have been able to classify the predictions based on different levels of optimism for tree-planting. Here we have presented the more optimistic (in terms of planting extent, rather than local effect) scenarios, but these also incorporate model parameter uncertainty.
- The tree-planting scenario was investigated in more detail for the Eden, and it was found that whilst modifications (based on evidence in the literature) to wet canopy evaporation give the largest effect when changed individually, the in-combination effect of modifying wet canopy evaporation, transmissivity and surface overland flow velocity is significantly greater.
- We have been able to represent the drain-down of water from RAFs using a range of time constants from 1 hour to 10 hours to 100 hours. We have found that the short drain down time would not change the streamflow hydrograph characteristics much, with overland flow not attenuated significantly. For the longer, 100 hour time constant, the RAFs were similarly not very effective in the Kent for the sequence of storms that were modelled, as they do not drain down in time to be useful for following rain-events. These were more effective in the Cocker (local) and Eden, possibly because there are relatively a lot more RAF opportunities identified.
- Given that the Kent and Eden RAF modelling shows that the strongest results (and the modelling here is not influenced by large upstream catchments with large volumes of lake storage, as with the Cocker), it is recommended that RAFs are designed to drain down over approximately 10 hours, and there are methods available to design RAF outflows (e.g. as pipe diameters) to achieve this depending on storage volume.
- Peat restoration has been simulated within the modelling work and is predicted to make a contribution but the size of the contribution may have been underestimated as specific details of areas to be ponded are not known precisely, and whilst there is good evidence for increase in roughness for restored peat, it is more difficult to simulate other subsurface effects explicitly.
- Tree-planting was more effective at slowing the flow in the Eden compared to the other catchments where there modelled opportunities represent a greater proportional area,
and there are more riparian opportunities for planting. It is concluded from the distributed Dynamic TOPMODEL results that these riparian areas are saturated more of the time than for the high SPRHOST areas represented in the Kent. They are therefore more often generating overland flows, and these can be attenuated by tree-planting - which acts to slow overland flows in the same way that it is represented in JFLOW.

- There are a greater proportion of RAFs (4% of area) in the upper Eden compared to the Kent (2%) and the effects of these, scale approximately proportionally. If it is assumed that all RAFs are designed with similar drain-down time constants, then their impact scales with area. Those opportunities identified in this modelling are not the only opportunities and depending on land availability, it may be possible to include more.

- The synchronisation issue has not been investigated in detail with Dynamic TOPMODEL, but could be assessed with more simulations. It is considered likely that it is one of the non-linear effects that could give rise to the sensitivity of the predicted peak flow distributions when modelling hydrological parameter changes individually and combined.

### 7.7 Comparison of the Dynamic TOPMODEL predictions to the strategic modelling

It is difficult to compare the JFLOW modelling and Dynamic TOPMODEL predictions precisely as they model different aspects of the flow processes. Whilst JFLOW is fully distributed at 2m, and characterises how overland flow pathways can be modified by NFM in a lot of spatial detail, Dynamic TOPMODEL provides a more complete picture of the overall hydrograph response by (1) incorporating the role of distributed subsurface flow routing in overland flow and streamflow generation, and incorporating changes to wet-canopy evaporation. Dynamic TOPMODEL does simplify the spatial domain, but this leads to efficiencies in the computation domain, in terms of fewer Hydrological Response Units (HRUs). This has allowed many thousands of simulations to be run, to help explore model uncertainties and sensitivities. This is important for NFM as there are substantial gaps in our knowledge of the magnitude change in hydrological model parameters to reflect incomplete experimental evidence for changes in catchment properties (Section 6.5). There has been significant effort devoted to trying to separate land use change signals from climatological and natural variability for large catchments.

- Both JFLOW and Dynamic TOPMODEL show significant changes to the predicted hydrographs and timings in response to NFM tree-planting and RAF measures. Dynamic TOPMODEL shows up to half the reduction that JFLOW indicates for the surface overland flow based on the more optimistic weight of evidence scenarios.

- For JFLOW overland flow, single peaked design events were modelled for different return periods and it was assumed that the RAFs were empty (or that they had been designed to empty). The detailed modelling has helped quantify an appropriate drain-down rate that would on average provide the best performance in the face of a sequence of flood events as in Cumbria in the winter of 2015.

- The percentage change to the median predictions of peak streamflow reduction for Dynamic TOPMODEL have been compared to those predicted by JFLOW for an event that is comparable to the design events modelled. The Storm Abigail event was compared with the 30 year RP design event given that initial conditions would be more typical than for the other storms later in November or December. For this event on the Eden, Dynamic TOPMODEL suggests a 22% reduction in the overall stream hydrograph. JFLOW predicts a 44% reduction for the overland flow component, which for this smaller event might represent 50% of the overall hydrograph (there are many areas with SPRHOST>50% in the upper Eden). On a like for like basis these changes of around 20% are therefore compatible, although because all catchments are different, scaling the JFLOW changes using for example a SPRHOST is likely to be uncertain.

- For the RAF simulations on the KENT (at cross-section 100, Appendix B), JFLOW predicts an 8% peak flow reduction. The DT model predicts a reduction of up to 20%, but this also includes a drain-down function that is not included in JFLOW, so there is potential to store more water through the event.

- For the Cocker, the percentage changes are less pronounced, largely due to the influence of Crummock Water. Nonetheless, Dynamic TOPMODEL does predict some significant changes when this signal is removed, if RAFs are implemented (there are relatively large number of these identified in this catchment). The JFLOW modelling predicts relatively less impact of RAFs if a local tributary is chosen, but this may just be
as a result of having only one monitoring point at a location where the opportunities are not as dense.

- In terms of changes to the timing, JFLOW predicts a lot of attenuation to overland flow of approximately 13 hours near the base of the catchment (Cross section 100 was used to remove interference from Appleby town and from other tributaries). This is for the surface water component, and although the median flow for Abigail is predicted to be delayed, the overall hydrograph response is not changed by as much as JFLOW. However, for Storm Desmond, the Dynamic TOPMODEL peak streamflow does show considerable attenuation, which could be due to large amounts of saturation overland flow produced by emerging subsurface flow in the riparian areas (HRU), which, if 'roughened up', would be expected to slow the overland flow. The additional modelling of individual parameter changes for the Eden, illustrates just how complex this response is, and how the effects of combined parameter changes can be significantly greater than individual ones.

- The JFLOW changes to timings are based on surface overland flow being slowed down by increased roughness and modelling the full 2d shallow water equations, but the subsurface flows are not modelled explicitly, so the effects on the whole hydrograph may not be as significant. Further research is required, but the changes to the timings predicted by JFLOW are based on robust physical principles, it is just the extent of overland flow is uncertain.
8 Conclusions

8.1 Summary of Findings

The study has investigated Natural Flood Management in a tiered approach across the Eden, Kent and Derwent catchments in Cumbria, to help prioritise where different measures are more likely to be effective. Commencing with a rapid 2d overland flow modelling approach, a screening was undertaken at 2m resolution, to identify where modification of features in the landscape to slow and store surface water flows might make the most difference. Following a stakeholder workshop at Newton Rigg College, Penrith on the 7th October, 2016, these opportunities were refined based on feedback from local groups, who also helped prioritise sub-catchments for more detailed modelling. The models were re-run and the benefits were re-computed and summarised in a suite of interactive maps to help inform decisions in the wider catchments. A User Guide which lists assumptions and how to use the maps has also been produced.

Dynamic TOPMODEL was then used to model the priority sub-catchments to help understand the effect of tree-planting and runoff attenuation features on the total streamflow hydrograph (including contributions from overland flow and subsurface flow) in more detail. The three detailed models for were calibrated against real data collected during the period Nov - Dec 2015, in order to capture catchment wetting by Storms Abigail and Barney prior to Storm Desmond. We used a fuzzy calibration that results in not just one, but multiple model parameterisations having different combinations of parameters. The successful model parameterisations all met a set of constraints that we imposed based on: ‘goodness of fit’ over the whole series of storms in winter 2015, culminating in Storm Desmond; how well they reproduced the peak Desmond flow; and whether they resulted in a physically-acceptably proportion of overland flow.

The Dynamic TOPMODEL findings demonstrated that the combined effects of enhanced wet-canopy evaporation, infiltration and surface roughness associated with the addition of deciduous trees to key locations in the landscape produced reductions to flood peaks. The changes to the catchment parameters required to simulate these beneficial changes were based on a process-based analysis of pertinent values from published studies. Given that our data synthesis shows that few pertinent studies are available in the literature, obtaining new observational datasets of enhanced wet-canopy evaporation, infiltration and surface roughness associated with deciduous woodland (ideally within priority catchments) must be a new research priority to underpin future NFM modelling. Modelling changes to these parameters individually in the upper Eden, showed that wet canopy evaporation has the greatest individual effect, but that when the changes are made in combination, the effects are significantly greater than through making individual changes.

We undertook a detailed literature review to understand the likely differences in catchment processes such as wet-canopy evaporation and soil moisture deficit between deciduous woodland and grassland, and represented these as changes to the parameters we are using to control the catchment processes in a similar fuzzy way. We then took our set of physically-acceptable models and ran these in combination with this fuzzy set of ‘changes’ to represent NFM measures. This resulted in a set of predictions that vary in the degree of optimism that NFM works on the basis of the current evidence base. We then showed the predictions for some of these combinations, but further outputs can be made available.

The two modelling strategies help to increase our knowledge of how and where in each catchment NFM measures can be more effective to reduce flood risk based on available datasets. The models help shed more light on the complexities of the streamflow generation mechanisms at work in the upland headwaters, in more detail than before, adding to the existing body of information on these catchments. Comparisons between the peak streamflow reduction predicted by Dynamic TOPMODEL for tree-planting, and the reduction in peak runoff using JFLOW, have been shown to be similar for the Eden when corrected assuming the full hydrograph is made up of at least 50% ‘fast flow’. The attenuation of the peak flows as modelled with Dynamic TOPMODEL becomes more significant as more areas produce overland flow, which can then be slowed down by additional roughness. For areas of expected high overland flow production, tree planting (in areas that follows best practice) and gulley blocking that targets the smaller, dendritic and ephemeral channels and depressions that may channel water is therefore important.

Using Dynamic TOPMODEL, we have also modelled drain-down of RAFs successfully with different time constants, and shown that for the Kent, RAFs designed with an intermediate drain-down time of around 10 hours would be more effective for a series of flood events as we saw in November through December 2015, although longer duration drain-down would perform well in
the Cocker and upper Eden where there are proportionately more RAFs. The JFLOW modelling only represented these stores as initially drained-down, assuming that they are designed well, and modelled as single peaks. Nonetheless, JFLOW is fully distributed at 2m resolution for very large areas and can tell us much about the effect of the critical overland flow pathway and locations of high water accumulation, and how modifying those pathways and stores can slow and retain the fast 'quickflow' element of the hydrograph.

The models have helped to quantify by how much working with natural processes can improve the flood regulation in terms of the relative reduction of peak streamflow or by changes to timing, although this study has not attempted to quantify the other multiple benefits from NFM, such as carbon storage or reduction of the impacts of diffuse pollution. The changes have been shown to be significant even for extreme storms like Desmond, although further research is needed to qualify the changes made to hydrological parameters for tree-planting.

8.2 Recommendations

- The overall methodology of strategic modelling (JFLOW), engagement, refined modelling and detailed modelling (Dynamic TOPMODEL) has provided a robust framework for the three Cumbrian catchments, and numerous insights into how the catchments work.
- The strategic modelling has been used to produce a suite of interactive maps which should be used in combination with the user guide, which lists the different assumptions and limitations and highlight relative changes to the runoff hydrographs.
- The RAF NFM measures identified using JRAFF and JFLOW have been useful for identifying locations to model in more detail, and provide a starting point for more detailed modelling studies.
- The detailed modelling informs us that there is an optimum, 'intermediate' retention time for RAFs of around 10 hours where storage is more limited but that longer drain-down times may be acceptable where opportunities are more widespread.
- The detailed modelling has been compared with the strategic modelling, and whilst there are obvious differences in terms of JFLOW focussing on overland flow and DT modelling the whole hydrograph, there are similarities in terms of the potential for NFM to help regulate flooding. The peak flow reduction, when adjusted for baseflow with JFLOW, and using the optimistic Dynamic TOPMODEL scenario, compares reasonably well for the tree-planting and RAF scenarios for those cases reviewed. More scenarios should be compared for different initial conditions.
- JFLOW appears to over-predict the changes to the timing of the whole hydrograph flood peak, apart from for very extreme events such as Desmond, where it is thought large areas could be generating fast flow pathways which can then be attenuated with increased roughness.
- It is recommended that more comparisons are undertaken, and that the individual sensitivity of the four different parameters in Dynamic TOPMODEL that are thought to be influenced by NFM interventions are investigated
- All of the modelled NFM scenarios have used realistic changes to effective parameter values based on the scientific literature, but there are large gaps in our knowledge. The EA 'Evidence Base' project is seeking to address this, along with a NERC funded call (December 2016) to fill more of the evidence gaps. This needs to be done with new monitoring and in tandem with modelling of the kind reported here to help model scale effects. We strongly recommend that if any of the RAFs and tree-planting opportunities identified in this investigation are implemented, then an appropriate level of monitoring is put in place to assess the accuracy of the modelling assumptions.
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Appendices

A Interactive Maps

See attached electronic appendices:
B Spreadsheet of hydrographs

See attached electronic appendices:
C Full Suite of Dynamic TOPMODEL predictions for NFM interventions

This appendix includes more of the scenarios representing different weights of evidence for modelled changes to parameters to represent the influence of NFM, and correspond to the five histograms of behaviour shown on the bottom right hand side of Figure 9-1 (reproduction of Figure 6-7). 5 sets of model outputs in response to tree-planting were generated similar to the diagram, and here we show sets 1, 3 and 5, whereas in the main text we showed the most optimistic scenario, 5 for brevity. We also show the results for the 3 time constants associated with RAF drain-down.

![Diagram](image)

Figure 9.1. Schematic diagram of the mapping of literature-derived evidence of the effect of interventions onto acceptable model parameter sets. Note the schematic only depicts an example modification to one model parameter but intervention scenarios may include modification to multiple parameters.
### 9.1 Variation of RAF drain-down rates for the Kent

The results for the 1, 10 and 100 hour time constant are reported in the next 3 figures and compared with the baseline. For the 1 hour time constant, it is though that the RAFs are draining too quickly without much attenuation when compared to the observed streamflow response, and for the 100 year time constant, they are draining down too slowly between storms, to be useful for the next storm.

![Kent: Comparison of RAFs with 1 hour time constants and baseline](image-url)

Figure 9-2 Kent: Comparison of RAFs with 1 hour time constants and baseline
Figure 9-3 Kent: Comparison of RAFs with 10 hour time constants and baseline

Figure 9-4 Kent: Comparison of RAFs with 100 hour time constants and baseline
9.2 Tree-planting the Kent

For the NFM scenario representing tree-planting, the sensitivity of the streamflow hydrograph was investigated with respect to the level of impact that tree-planting is thought to have on different catchment processes based on the literature (Table 6-7). The range of models with different levels of optimism in the effects of NFM are shown for scenarios 1, 3 and 5 depicted in Figure 9-1.

Figure 9-5 Kent: Representation 1 for tree-planting NFM
Figure 9-6 Kent: Representation 3 for tree-planting NFM

Figure 9-7 Kent: Representation 5 for tree-planting NFM
9.3 Variation of RAF drain-down rates for the Eden

The results for the 1, 10 and 100 hour time constant are reported in the next 3 figures and compared with the baseline. For the 1 hour time constant, it is though that the RAFs are draining too quickly without much attenuation when compared to the observed streamflow response, and for the 100 year time constant, they are draining down slowly between storms, but possibly due to the capacity or when they are used for different events, the 100 hour drain-down rate is quite effective here.

![Figure 9-8 Eden: Comparison of RAFs with 1 hour time constants and baseline](image)
Figure 9-9 Eden: Comparison of RAFs with 10 hour time constants and baseline

Figure 9-10 Eden: Comparison of RAFs with 100 hour time constants and baseline
9.4 Tree-planting the Eden

For the NFM scenario representing tree-planting, the sensitivity of the streamflow hydrograph was investigated with respect to the level of impact that tree-planting is thought to have on different catchment processes based on the literature (Table 6-7). The range of models with different levels of optimism in the effects of NFM are shown for scenarios 1, 3 and 5 depicted in Figure 9-1.

![Graph showing streamflow hydrograph for tree-planting NFM]
Figure 9-12 Eden: Representation 3 for tree-planting NFM

Figure 9-13 Eden: Representation 5 for tree-planting NFM
9.5 Variation of RAF drain-down rates for the Cocker (Crummock signal removed)

The results for the 1, 10 and 100 hour time constant are reported in the next 3 figures and compared with the baseline. For the 1 hour time constant, it is though that the RAFs are draining too quickly without much attenuation when compared to the observed streamflow response, and for the 100 year time constant, they are draining down slowly between storms, but possibly due to the capacity or when they are used for different events, the 100 hour drain-down rate is also quite effective here.

Figure 9-14 Cocker: Comparison of RAFs with 1 hour time constants and baseline
Figure 9-15 Cocker: Comparison of RAFs with 10 hour time constants and baseline

Figure 9-16 Cocker: Comparison of RAFs with 100 hour time constants and baseline
9.6 Tree-planting the Cocker

For the NFM scenario representing tree-planting, the sensitivity of the streamflow hydrograph was investigated with respect to the level of impact that tree-planting is thought to have on different catchment processes based on the literature (Table 6-7). The range of models with different levels of optimism in the effects of NFM are shown for scenarios 1, 3 and 5 depicted in Figure 9-1.

Figure 9-17 Eden: Representation 1 for tree-planting NFM
Figure 9-18 Cocker: Representation 3 for tree-planting NFM

Figure 9-19 Cocker: Representation 5 for tree-planting NFM