We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900
Open access books available

185,000
International authors and editors

200M
Downloads

Our authors are among the

154
Countries delivered to

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



Chapter 1

Strategies for Testing the Impact of Natural Flood Risk Management Measures

Barry Hankin, Peter Metcalfe, David Johnson, Nick A. Chappell, Trevor Page, Iain Craigen, Rob Lamb and Keith Beven

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.68677

Abstract

Natural Flood Management (NFM) is an approach that seeks to work with natural processes to enhance the flood regulating capacity of a catchment, whilst delivering a wide range of ecosystem services, from pollution assimilation to habitat creation and carbon storage. This chapter describes a tiered approach to NFM, commencing with strategic modelling to identify a range of NFM opportunities (tree-planting, distributed runoff attenuation features, and soil structure improvements), and their potential benefits, before engagement with catchment partners, and prioritisation of areas for more detailed hydrological modelling and uncertainty analysis. NFM measures pose some fundamental challenges in modelling their contribution to flood risk management because they are often highly distributed, can influence multiple catchment processes, and evidence for their effectiveness at the large scale is uncertain. This demands we model the 'upstream' in more detail so that we can assess the effectiveness of many small-scale changes at the large-scale. We demonstrate an approach to address these challenges employing the fast, high resolution, fully-distributed inundation model JFLOW, and visualisation of potential benefits in map form. These are used to engage catchment managers who can prioritise areas for potential deployment of NFM measures, where more detailed modelling may be targeted. We then demonstrate a framework applying the semi-distributed Dynamic TOPMODEL in which uncertainty plays an integral role in the decision-making process.

Keywords: natural flood risk management, uncertainty

INTECH
open science | open minds

© 2017 The Author(s). Licensee InTech. This chapter is distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. CC BY

1. Introduction

Natural Flood Management (NFM), commonly referred to in the UK as Working with Natural Processes (WWNP), has been defined as taking action to manage flood risk by protecting, restoring and emulating the natural regulating function of catchments, rivers, floodplains and coasts [1]. NFM can integrate improvements to the local landscape and ecology, thereby contributing to meeting environmental goals (such as European Water Framework Directive objectives). Compared to hard-engineered Flood Risk Management (FRM), NFM is becoming attractive to policy makers and catchment managers due to lower upfront costs, the potential to create multiple ecosystem benefits (e.g. carbon storage, diffuse pollution and sediment risk regulation), and for its flexible scale of deployment, which may also help to stimulate or encourage community involvement. The mechanisms to achieve such aims include run-off storage, increasing soil infiltration, slowing surface water movement and reducing flow connectivity.

Across a catchment, there can be many different opportunities for NFM 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) to intercept overland flow. The key characteristics shared by these measures are that they are typically small-scale and highly distributed, and potentially alter a wide range of catchment processes. As a consequence of their small scale and local impact, they are mostly likely to be effective in reducing downstream flooding when implemented widely in the headwaters of catchments to reduce streamflow reaching downstream floodplains.

Catchment models routinely applied by regulatory agencies and water authorities for flood risk assessments, forecasting, water resources planning or water quality management, tend to represent upstream areas as discrete sub-catchments with uniform inputs. This can be very effective for simulating flows in the river further downstream near urban settlements, but averages over the effects of small-scale interventions and thus loses information into their impacts on the various hydrological processes of interest. For highly distributed, smaller scale measures and interventions, it will be vital to consider new approaches that not only scale their impact up more accurately but also consider the uncertainty in the representation of how catchment processes might change. There are still large evidence gaps and a need to test the effectiveness of these distributed measures against observational data. This will require detailed monitoring of catchment processes. A recent survey [2], however, showed that as few as 6% of NFM schemes in the UK have intensive hydrological monitoring.

The approaches demonstrated here aim to address the scaling-up problem in a way that reflects the uncertainty in the representation of small-scale hydrological processes and flood mitigation methods. In doing so we meet the challenge that was put to environmental modellers by Beven in 2009 [3], to give decision makers:

> *'…a realistic evaluation of uncertainty since this might actually change the decision that is made'*

By means of an example, we examine here a tiered approach taken to planning NFM strategies within the headwaters of the Eden, Kent and Derwent catchments in Cumbria, UK (**Figure 1**), that aimed to prioritise where different measures are likely to be most effective.

http://dx.doi.org/10.5772/intechopen.68677

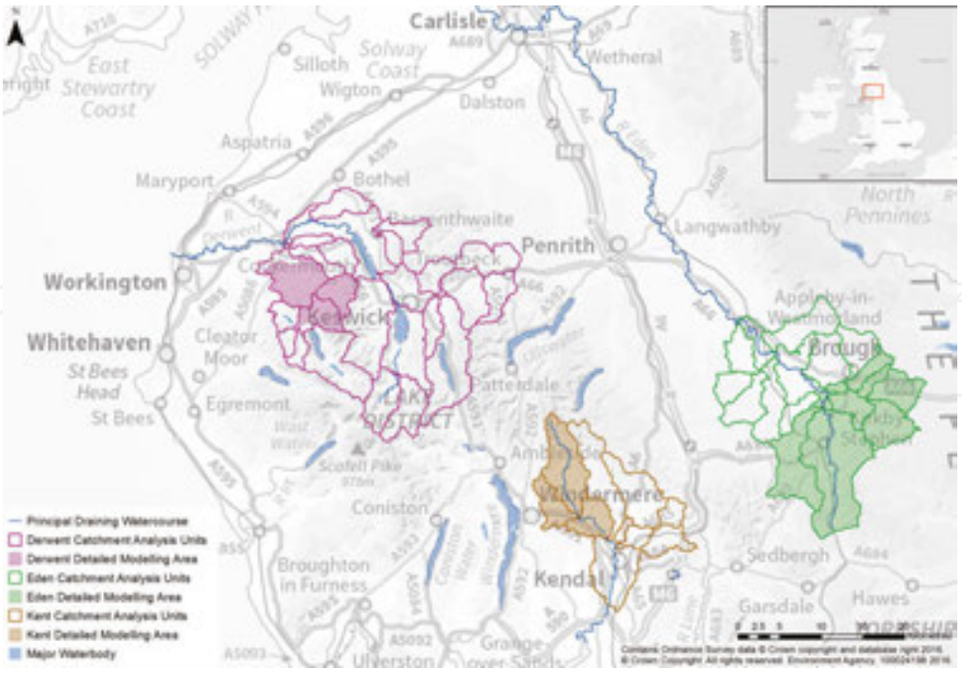


Figure 1. Overview of the study area.

This was followed by an analysis of uncertainty in the environmental model parameters and of the fuzziness in the evidence behind the changes applied to these models to represent effects of NFM measures.

We show how the effectiveness of very distributed NFM measures such as tree planting and enhanced storage in the headwater catchments can be appraised in a framework similar to established FRM practice. Advances in high-resolution modelling (here we explicitly model runoff on a 2 × 2m resolution grid within a 100-million-cell model [4]), have unlocked the potential to model 'upstream' at high resolution, and enable us to *test the aggregated impacts of very small scale measures at the larger scale*. This delivers a deeper understanding of the effectiveness of potential NFM plans in reducing peak runoff, but requires new strategies to consider 'synchronisation' issues [5], whereby flooding can be made worse by slowing the time of arrival of a flood peak in one tributary such that it interferes constructively with that of the receiving watercourse. It also opens up the ability to undertake continuous modelling through sequences of events, such that the antecedent wetness is taken into account.

Since NFM measures could be deployed in very many spatial configurations, it follows we should test for synchronisation effects against a wide range of plausible extreme loading conditions. The authors demonstrated such an approach in a recent UK government Flood Modelling Competition, where their winning entry [6], combined high resolution modelling of NFM with advancements in spatial joint probability analysis of extremes [7, 8], whereby multiple extreme rainfall scenarios were simulated, with realistic spatial patterns based on the long-term records at rainfall gauges around the catchment. The 'average' effectiveness of NFM across the upper part of the 2,300km^2 Eden catchment was then tested against 30 simulated extreme rainfall events selected to span a range of spatial patterns.

2. A risk management framework for NFM

Figure 2 highlights a pathway through the risk management cycle that attempts to integrate core elements needed for modern flood risk management, adapted for NFM with its distinguishing features of highly distributed interventions and uncertain impacts. This framework was developed and applied in the course of the Cumbrian project for identification of the types of NFM opportunities introduced earlier, with whole catchment modelling being applied to map potential risk reduction benefits.

This first step was undertaken for the Cumbrian project using rapid overland flow modelling approach using a 2 m resolution 2d JFLOW model to identify where modification of features in the landscape to slow and store surface water flows might make the most difference. These included the use of RAFs at locations of high flow accumulation, tree-planting, and soil structure improvements. The speed of set-up, very high resolution and rapid run times of JFLOW meant we were able to rapidly assess the effectiveness of these very distributed NFM measures, before sharing with catchment partners.

Our work in Cumbria has involved a wide range of catchment partners including landowners, flood management agencies, voluntary groups and farming groups, who used the whole-catchment mapping to refine potential opportunities for NFM deployments and also prioritise areas for more detailed modelling. The sub-catchments containing the most promising opportunities

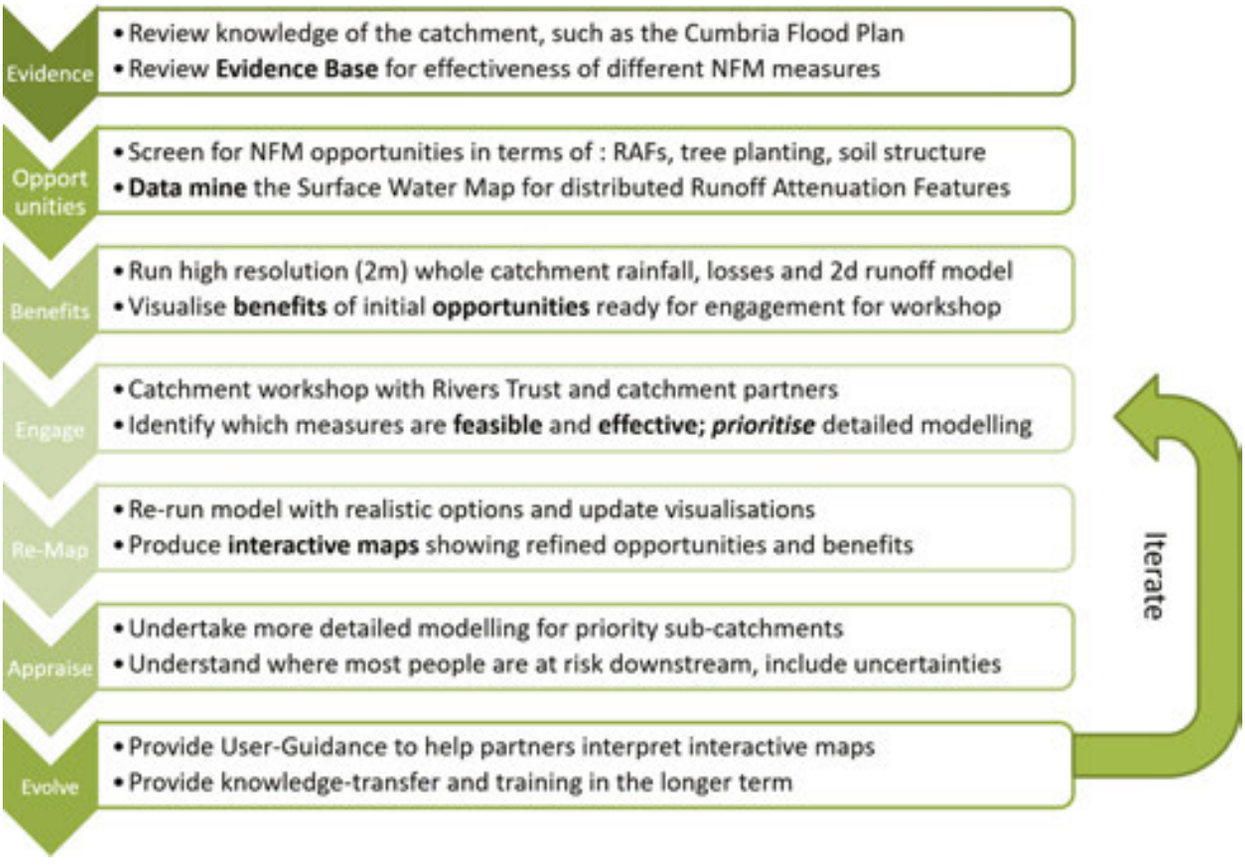


Figure 2. The risk management cycle for NFM.

http://dx.doi.org/10.5772/intechopen.68677

based on the JFLOW modelling were prioritised for more detailed uncertainty investigation using Dynamic TOPMODEL [9, 10] to compute the projected benefits of NFM.

Dynamic TOPMODEL provides a tool to help understand the effects of NFM on the total hydrograph, including contributions from overland flow and subsurface flow. The detailed models were calibrated against observed data collected during the period November–December 2015, in order to capture the flows arising from a sequence of prolonged and intense rainfall events associated with Storms Abigail and Barney prior to the most severe storm, Desmond (4–6 December 2015), which led to extreme rainfall and flooding in Cumbria [11, 12].

An uncertainty framework was used to represent not only the uncertainties in the parameters used in the model but also the gaps in the scientific evidence on how different NFM measures influence catchment processes (**Figure 3**). A large number of simulations were undertaken for each catchment, and a set of model parameterizations showing 'acceptable' performance on

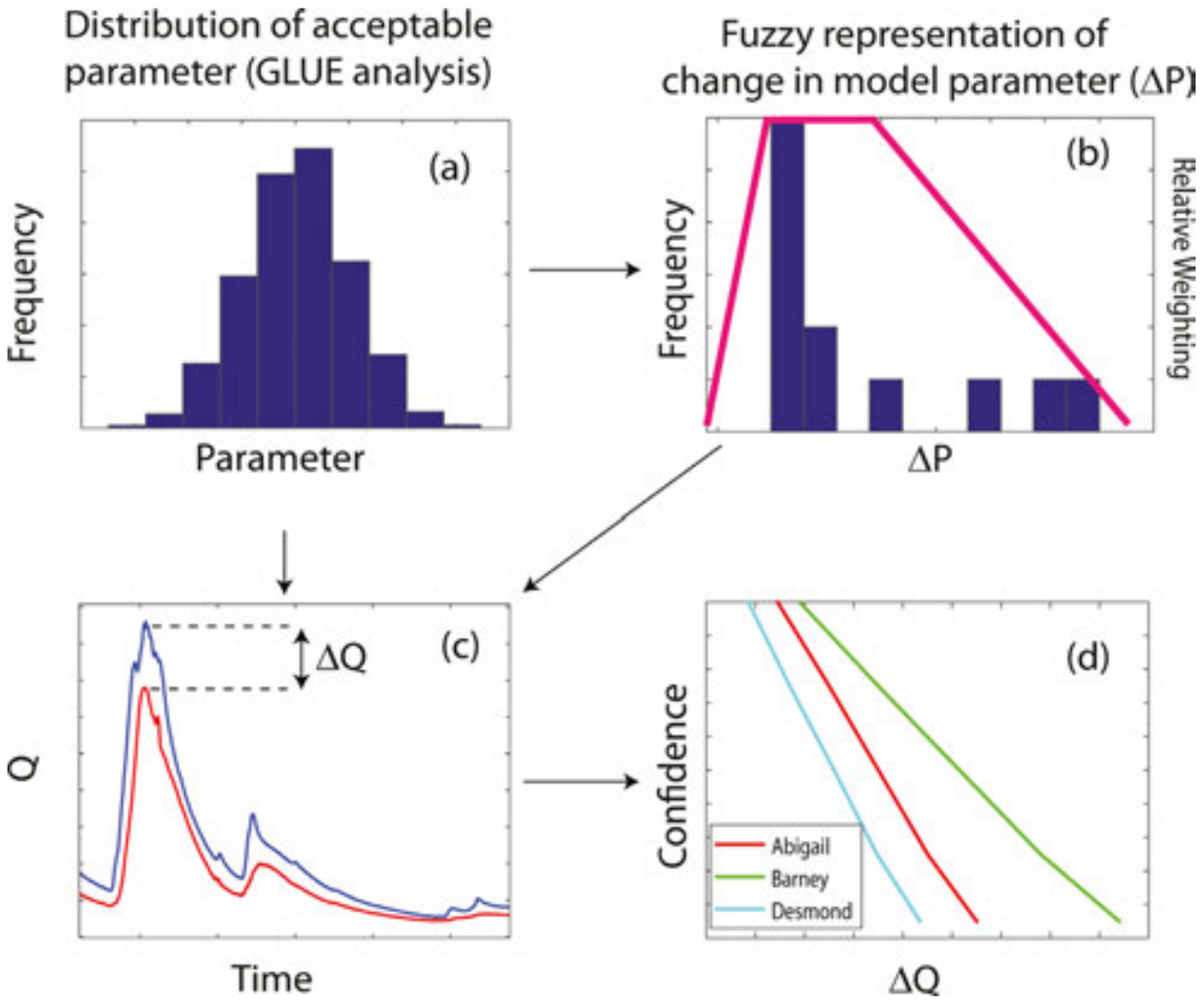


Figure 3. Stratified sampling of parameter uncertainty and fuzziness in evidence parameter changes to reflect NFM interventions. (a) Weight of evidence for effective parameter values (b) Weight of evidence for change in effective parameter values to reflect NFM intervention (c) Resulting change to peak flow in hydrograph response as a result of NFM (d) Confidence in magnitude of peak flow change based on combined weightings.

the basis of the evidence, were identified based on a range of measures including the ability of the models to reproduce the observed peak flow for Storm Desmond.

The next sections cover the broad steps in this flow chart.

3. Evidence for effectiveness of NFM

This section reviews evidence of the effects of NFM on catchment processes, and how this evidence was mapped onto the effective parameters that are used in the different modelling strategies adopted in the Cumbrian opportunity mapping project. This section gives a flavour of how we gathered evidence of *changes* to physical processes in the UK and tried to map these changes onto already uncertainly modelled processes.

For the JFLOW overland flow modelling, the physical influences considered were:

- Increasing roughness through land cover changes: grasses and mosses to shrubs and trees
- Increasing localised depression storage through construction of RAFs
- Increasing infiltration through improvements in soil structure

For Dynamic TOPMODEL, we consider the above processes and also those influencing subsurface flow, for example:

- Reducing surface overland flow velocities through woodland planting.
- Increasing surface storage associated with RAFs using modified surface routing and a maximum storage parameter.
- Increasing soil transmissivity through woodland planting.
- Increasing wet canopy evaporation through woodland planting.

The evidence for the above changes linked to tree-planting was considered with respect to deciduous woodland, which brings the most habitat and biodiversity benefits in this environment, and is in line with current activity within NFM schemes across the UK.

3.1. Surface roughness

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. Within a deciduous woodland, roughness contributions come from: (1) roughness of the litter layer, (2) roots at the ground surface running across the slope, (3) obstructions to flow caused by tree stems/understory, (4) paths and tracks, (5) fence lines or walls, and (6) subgrid topographic irregularities in slope. All components need to be characterised to provide an accurate measurement of the effective roughness of a whole hillslope. Direct measurements of the roughness components across a range of surface vegetation conditions at floodplain sites in Florida (USA) [13] produced Manning's n [14] values that ranged from 0.030 to 0.061 for forest areas against a range of 0.013–0.050 for other surfaces including barren land and grasslands.

Chow 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 [14]. Thus in direct comparison with the direct measurements of roughness undertaken in Ref. [13], the differences between woody vegetation and pasture-cum-barren land are considerably less. Given: (1) the limited number of studies directly measuring hillslope roughness [13], (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.

In this study, a comparison is made between with and without woodland, that amounts to a maximum increase of 50% in Manning's roughness, over the broad-scale 'upland' roughness value of 0.1 used to provide national flood maps in the UK. *Thus a maximum of 0.15 was used compatible with the engineering tables of Chow, but which requires more research to resolve the underlying physical processes contributing to frictional losses*.

3.2. Peatland management

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. 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. Holden et al. [15] used 256 bounded overland flow plots (0.5 m x 6 m) in the Upper Wharfe catchment (UK) and found that the 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. *This equates to an increased roughness of ~0.3, which was used in the JFLOW modelling and the reduced wave speed in Dynamic TOPMLODEL*, albeit starting from the relatively high generic roughness factor used in the national mapping, of 0.1 and increasing it to 0.13. Here we have used the roughness increase only, as the effect of drain blockage is not as clear and can be strongly dependent on the orientation of the drains, i.e. whether they run across slope or down slope [16].

3.3. Runoff attenuation features (RAFs)

Small ponds to capture and temporarily store overland flow 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'. Temporary storage of the overland flow on slopes could delay this component of the flow so that it reaches streams after the peak of the hydrograph has passed. However, if overland flow on a particular slope is generated on the rising stage of a stream hydrograph [17], delaying it could have the unwanted effect of adding the overland flow contribution to the channel at the time of the peak in the streamflow. Clearly understanding precisely when the overland flow is being added to stream channels, and doing so within a spatial frame of reference, is critical for understanding how it should be managed. Only a few direct measurements of overland flow using plot studies are available in the UK (e.g. Ref. [18]) to help quantify the timing of this process. The Belford Catchment Solutions Project in Northumberland has demonstrated how such features are able to retain and hence attenuate the initial phase of overland flow generation. Overland flow interception RAFs have

been constructed at many locations in the UK and individually range from 20 to 1000 m^3 in capacity (see Refs. [19–21]). *RAFs added into the simulations for this study are 100–5000 m^3 in area* and so are broadly similar in capacity.

3.4. Wet-canopy evaporation

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 [22]. 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 [23–26]. 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 [27] noted *'…although sometimes there is a measurable reduction of interception losses in winter due to leaf fall, the effect is commonly surprisingly small…'* 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 [28]). 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 1**), but perhaps less (as a percentage) for high magnitude events. *The first column of*

% P (by rank)	Dominant species	Reference	UK/Europe
40–50	Hawthorn (hedge)	Herbst et al. [82]	UK
36	Oak/birch	Noifalise [83]	Continental Europe
29	Hornbeam	Leyton et al. [84]	UK
22.5	Oak	Vincke et al. [22]	Continental Europe
19.8	Oak/birch	Herbst et al. [30]	UK
15.1	Beech/hornbeam	Aussenac [85]	Continental Europe
14	Beech	Reynolds and Henderson [27]	UK
12.1	Mixed	White and Carlisle [86]	UK (Cumbria)
12	Oak coppice	Thompson [87]	UK
11	Oak	Dolman [88]	Continental Europe
10.5	Hornbeam/oak	Schnock [89]	Continental Europe
10	Oak/beech	Staelens et al. [90]	Continental Europe
9.9	Oak	Carlisle et al. [91]	UK
7	Beech	Gerrits [92]	Continental Europe

Table 1. A wet canopy evaporation range (over 1–3 months) that also encompasses most of the extremes in observed behaviour of leafless vegetation canopies would be 7–50% of gross rainfall through winter storms for deciduous trees, although likely to be at the lower for an extreme event so a range of 4–20% was used in the modelling.

Table 1 was used to define the fuzzy set of wet canopy evaporation rates (top right panel of **Figure 3***) used in the Dynamic TOPMODEL but constrained to the smaller range of 4–20% considering the extreme nature of Desmond.*

3.5. Antecedent moisture status

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 [29–31], means that UK 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 [32, 33]. Finch [34] observed drier soil moisture profiles (by 250 mm) beneath sweet chestnut and larch woodland and grasslands in Pang basin (Berkshire, UK) through December in 1997. Indeed, the profile did not reach its maximum saturation until April 1998. Similarly, Calder et al. [35] 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. 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.

NFM might feasibly give wetter antecedent conditions in a sequence of winter events if the increased infiltration effects of tree planting on soil moisture are larger than those of enhanced wet canopy evaporation ('infiltration trade-off hypothesis'). *Here we attempted to account for this through detailed modelling of several consecutive storms, and although the drier antecedent soil moisture was taken into account, the deficit was reduced considerably after the first storm in the series.*

3.6. Woodland on slowly permeable, gleyed UK soils

Overland flow on hillslopes may be caused by rainfall intensities (mm/hr) exceeding the saturated hydraulic conductivity (K_S; 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' [36]. If rainfall is reaching the ground at a rate less than the 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 [37]. 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' [38]. 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 were 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 [39] or gley within the Soil Survey of England and Wales (SSEW) soil classification system [40] typically exhibits lower saturated hydraulic conductivity values throughout UK soil profiles [41]. **Table 2** shows an example K_S profile for a gley in the Lune Valley, Northwest England (UK). These measurements were undertaken in the field with a ring permeameter [42], a technique demonstrated to give accurate values, even for disturbance-sensitive gley soils [43].

Depth (m)	Mean K_S (cm/hr)	Range (n = 56)
-0.10	9.1	1.31–30.7
0.10–0.20	21.8	8.98–57.0
0.20–0.50	0.11	0.021–3.02
0.50–1.00	0.002	0.0007–0.21

Table 2. Horizon-specific saturated hydraulic conductivities (cm/hr) of a Humic Gleysol near Farleton, Lancashire (UK) after [39, 40].

Soils in England and Wales that are classified as gley cover a range of soil associations based on the SSEW [44]. As a result of their greater likelihood of generating overland flow, these gley soils are classified as having an SPRHOST[1] value in excess of 50% [45]. Enhancing the permeability of such soils could have the greatest impact on reducing overland flow across catchments and thereby have the greatest potential to reduce flood peaks in rivers [46]. As a result, tree planting to increase soil permeability includes areas with such gley soils.

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 [47].

These few studies are summarised in **Table 3** and give a range of 1.5–3.5 factor increase in permeability for deciduous tree planting on gley soils. *The Ks factors in the first column of* **Table 3** *were then used to provide the fuzzy set of parameter changes in the Dynamic TOPMODEL scenarios*.

This observed increase in permeability for gley is smaller than the factor of five difference between predominantly deciduous woodland and improved pasture recently observed on well drained Eutric Cambisol (SSEW Brown Earth) soils in Scotland by Archer et al. [48, 49]. The observed effect on gley is also smaller than the effects observed on other soil types across the globe, the majority of which are between 2 and 20, with some outliers much greater than this, which is likely to be due to macropores along root channels. In any event, if the roughness of these high runoff areas can be increased through roughening up, then it may be possible to attenuate quick-flow from these soils until they become saturated by deficit filling.

[1] *Standard percentage runoff based on hydrology of soils types*

F/G[1]	Tree age	Soil type[2]	Location	Reference
1.81	2 years	713e-Brickfield-1	Tebay Gill Cumbria	Mawdsley, Chappell & Swallow [93]
2.43	10 years	721d-Wilcocks-2	Pontbren Mid-Wales	Marshall et al. [94][3]
3.40	107 years	713f-Brickfield-2	Lancaster Lancashire	Chandler and Chappell [47]

[1]Factor difference in KS, i.e. KS below deciduous trees/KS below grassland.

[2]SSEW Soil Association from Soil Survey of England and Wales [44].

[3]Results of related study of Carroll et al. [81] rejected on basic quality assurance criteria (i.e. absent sampling size per land-cover; absent information on frequency distribution, etc.).

Table 3. Ratio of Ks measured for deciduous trees to that grassland growing on gley soils in the UK.

Critically, it should be remembered that most of the stream hydrograph during floods comprises water that has primarily travelled to the stream via subsurface pathways (effects of trees on Ks might not be isotropic–but we have even less information on downslope Ks). 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 [50]). Therefore, while the overland flow pathways are important given their speed and sediment transport aspects, especially during flood events, simulated flow pathways are likely to be dominated by subsurface responses (which can also be fast–subsurface celerities in wet soils can even exceed overland flow velocities [51]), pathways either close to the surface in soils or deeper within the surficial or solid geology [52, 53].

4. Opportunity mapping of NFM

Opportunity maps can be developed from local knowledge, land cover maps, flood modelling outputs, or a combination of all three, as described here. In this chapter, opportunities for three core types of NFM (tree-planting, RAFs and soil structure improvements) were developed from different national strategic maps, and then through consultation at an engagement event. Ideally, engagement would be a continuous process of refinement where more local knowledge of the landscape and opportunities are built in through time, and evidence is co-produced [54]. The following sections explain how these opportunities were identified and refined.

4.1. Runoff attenuation features

Research on RAFs [55–57] 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. 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.

Opportunities to deploy RAFs can be identified from areas of high flow accumulation in surface water flood maps, and comprise small areas such as natural depressions within the landscape, or small in-channel storage as shown in **Figure 4**. The JRAFF model identifies the

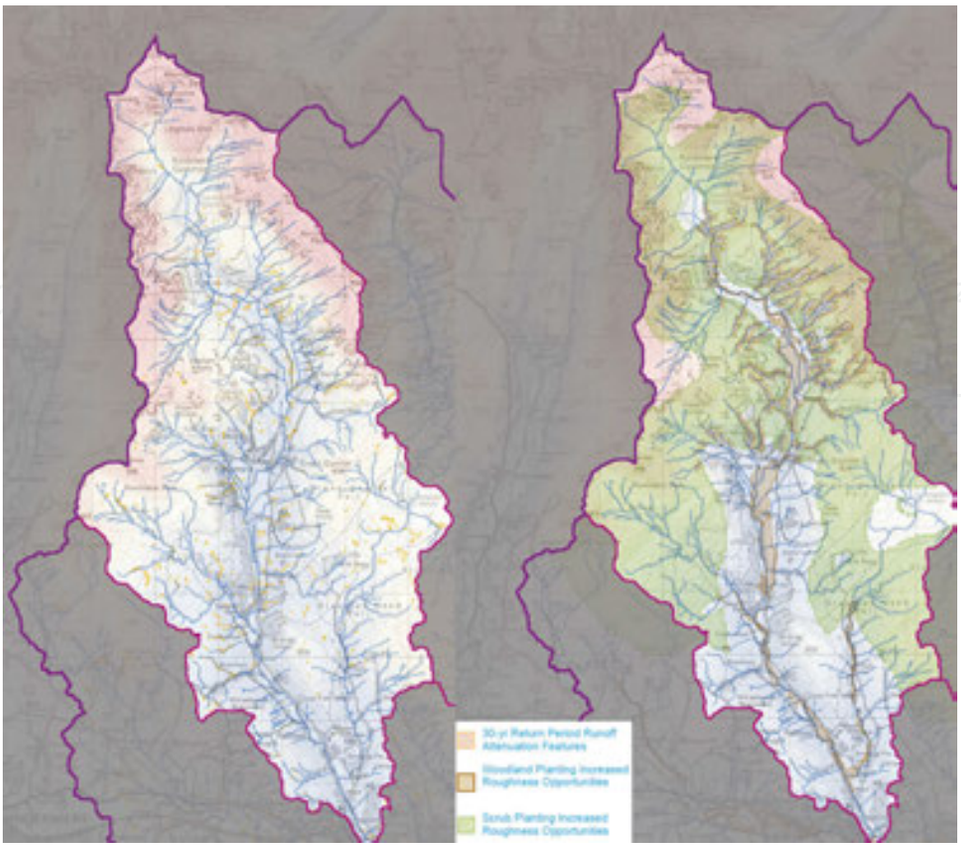


Figure 4. Runoff Attenuation Features (RAFs) and shrub and approximate woodland planting opportunities in the upper Kent (for illustration).

orange 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 gully or ditch blocking. An additional storage of 1 m in depth at these locations is represented through burning the Digital Terrain Model (DTM) deeper by 1 m in the RAF model scenario.

The JRAFF tool places a set of constraints on the size and location of these accumulations:

- Area threshold between 100 and 5000 m^2
  - This was considered suitable for local land management alterations, and well below the threshold of capacity that would fall under the UK Reservoirs Act (10,000 m^3).
- CORINE land cover 2012 dataset and a 2 m buffer of OS OpenData buildings and roads deemed unsuitable to runoff attenuation features.
  - A 2 m buffer of roads results in a 4 m wide exclusion zone. This threshold has been derived based on typical road widths and ensures that opportunity features within any potential adjacent ditches are retained.

In the application to Cumbrian catchments, the JRAFF model was used to calculate the additional storage volume if such areas were to be deepened[2] by a further 1 m before summarising

[2]*Equally representing a bund around an existing flow accumulation area*

these volumes within priority sub-catchments defined earlier. Within the Kent catchment only, any RAFs identified within peat soils were excluded where hillslopes were greater than six degrees. This constraint is based on current peat restoration practices [58]. This process identifies a very large number of opportunities which can be incorporated into a model. These opportunities represent large scale, long term NFM delivery and provide the evidence required to take a strategic approach to optimising the benefits of providing additional distributes storage within the catchment.

4.2. 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 (see Refs. [59, 60]). A combination of improvements in wet canopy evaporation and transpiration 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 was supplied by the Environment Agency for this project [61] and it was modified with the local knowledge and through inspecting soil series maps to give potential tree-planting opportunities (**Figure 4**). The dataset typically comprises a set of woodland plantings opportunity areas such as riparian zones and floodplain areas together with a number of constraints such as urban areas, existing woodland and inland water. 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.

The modified WfW opportunity maps represent large, long-term NFM delivery within each catchment. The incorporation of this opportunity into the model provides the evidence required to take a strategic approach to optimising the benefits of providing additional 'natural roughness' within the catchment.

4.3. 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 [62]. This can help reduce overland flow and reduce downstream flood risk, although could potentially have limited benefits in wet winters.

For the third type of opportunity, soil structure improvement, the JFLOW 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 BFIHOST [45], which influences amount of runoff routed over the landscape in the modelling (see below), was increased by 10% resulting in an approximately 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 then assess the improvement relative to that for this type of land cover by scaling up by relative area compared to improved grassland.

This more targeted approach to improving soil permeability avoids overestimating the impact of soil improvement by applying an unrealistic blanket improvement across the catchment. Soils can only be improved if they are damaged. Palmer and Smith, 2013 [63] estimated that approximately 38% of soils were structurally damaged, the percentage was higher under arable and lower under pasture, in a survey in the SW of England.

4.4. Strategic modelling and estimating benefits

The strategic modelling was undertaken using a fast 2d hydrodynamic modelling software JFLOW [4], which has been benchmarked against other 2d inundation models against a wide range of test cases [64]. The approach illustrated in **Figure 5**, builds on the blanket rainfall approach (e.g. Ref. [65]), which was developed further to include the ReFH losses model [66], and used to develop a national SW flood map RoFSW [67]).

The model integrates spatially varying rainfall, with the representation of both rural infiltrations using the ReFH rainfall to overland flow calculated losses (i.e. infiltration) model and urban sewer loss rates (a national average of 12 mm/hour was used). 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.

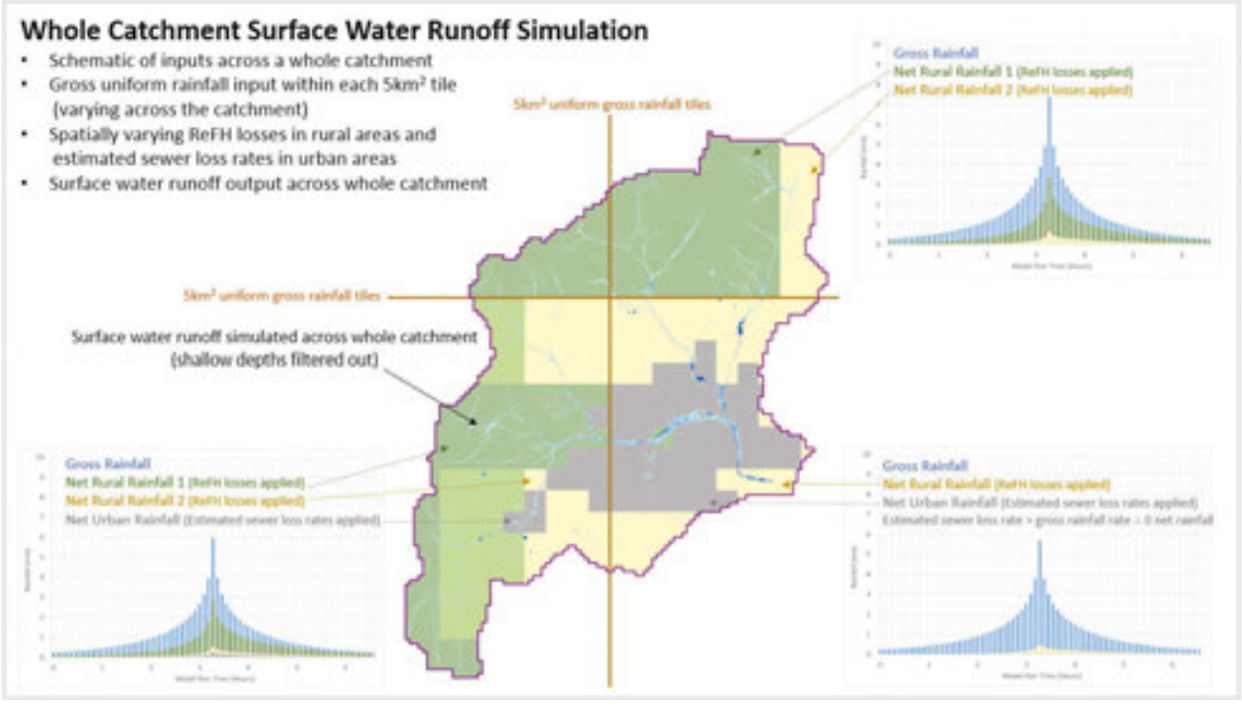


Figure 5. The rainfall and losses approach to whole catchment modelling.

http://dx.doi.org/10.5772/intechopen.68677

The floodplain is represented using a 2 m Digital Terrain Model (DTM) based on a combination of filtered LiDAR, filled in with coarser scale photogrammetry or SAR data. Sinks and dams are removed in order to maximise hydrological flow pathway continuity. Spatially varying hydraulic roughness coefficients were adopted throughout, based on land cover and the same roughness coefficients adopted in national maps. The baseline scenarios were for the 10-year and 30-year return periods with a 6-hour storm duration.

Much consideration is given to the placement of virtual monitoring locations around the catchment that monitor the hydrographs for different sub-catchments and their modelled response to NFM interventions (**Figure 6**). For urban areas, culverts and 'cut-throughs' can be added to allow the passage of water downstream more realistically.

The percentage change in the peak runoff response for each sub-catchment was then visualised in a second set of 'benefit maps' (**Figure 7**), for use at the engagement workshops. These were colour themed in different ways, with the perimeters shaded to reflect the magnitude of the modelled peak runoff reduction and the fill based on the extent of the opportunity. Benefits are cumulative, in that every opportunity must be implemented within upstream sub-catchments in order to obtain the visualised benefits.

These maps represent the potential benefits of large-scale, long term NFM delivery across a catchment. They are most appropriately used in relative mode, allowing the user to identify particular sub-catchments which provide greater benefit than other sub-catchments and the different interventions that should be targeted to provide these benefits.

Other approaches to showing benefits or damages avoided have been developed, whereby the average property damages [68] per 1 km tile are shown with and without NFM, and this

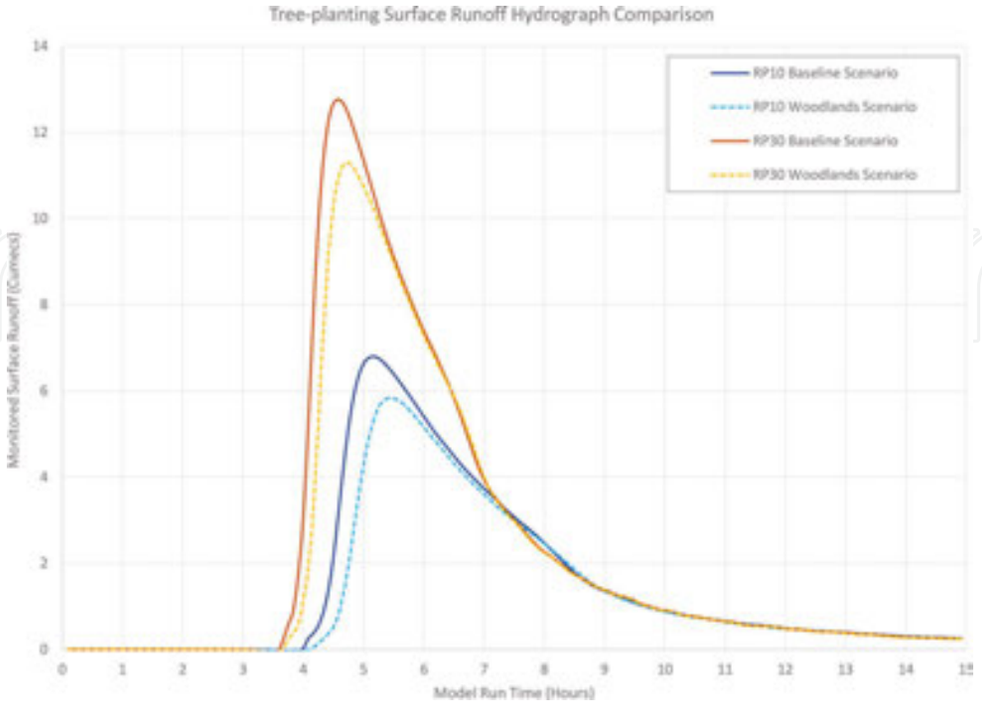


Figure 6. Example peak fast-flow reduction based on modelling NFM.

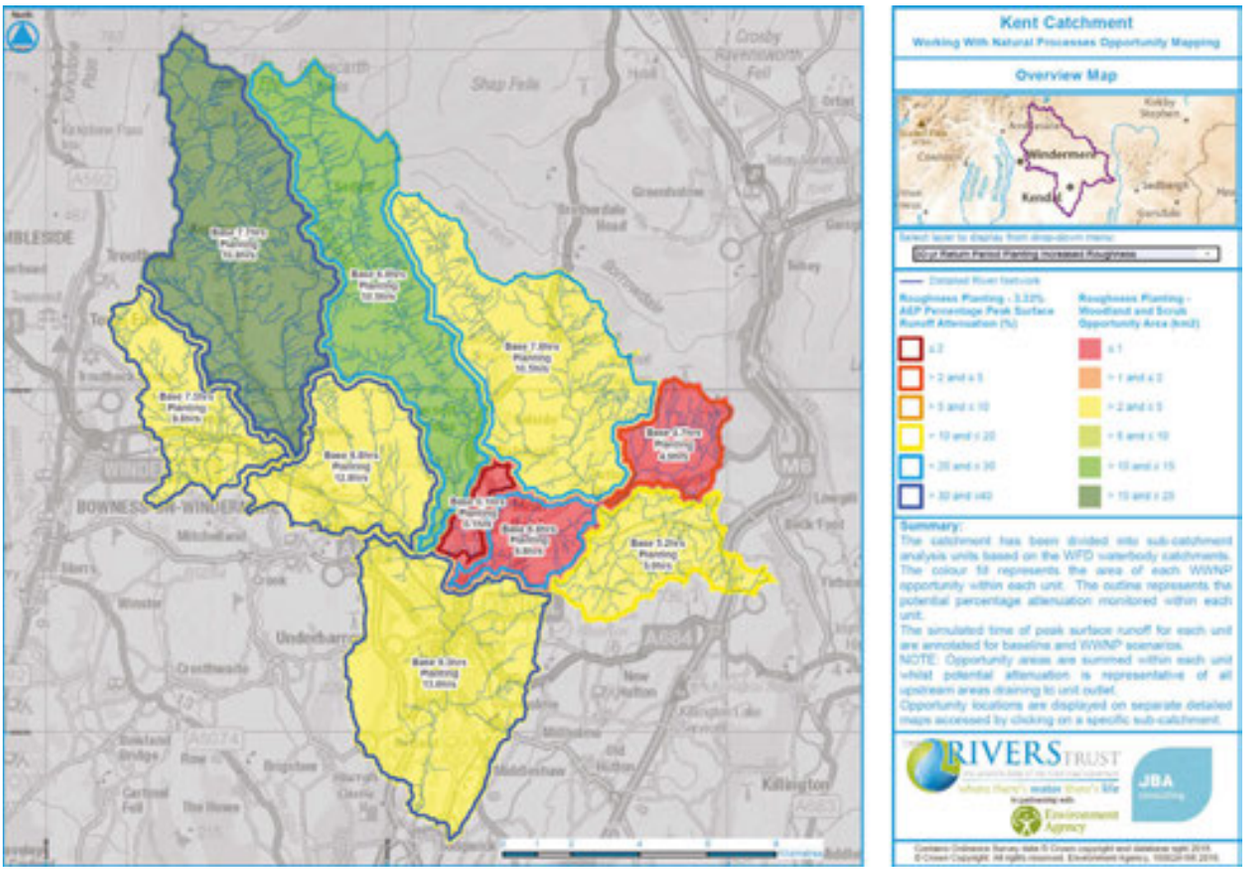


Figure 7. Visualisation of potential runoff reduction if all NFM opportunities taken up.

helps put appraisal of NFM on a footing with more established methods and identify potential dis-benefits due to, for example, backwater effects causing upstream flooding.

5. Engagement and refinement

Visualisations such as **Figures 4**, **7** and **8** have been found useful at engagement events, whereby catchment partners can mark the maps and alter the opportunities based on their local knowledge, then see the potential benefits based on the broad-scale modelling. Many of the identified opportunities will not be feasible due to land ownership and access issues. There may already be interventions planned which can also be added to the maps. Following the engagement, the models were re-run and the maps and interactive PDFs regenerated for the whole catchment.

One key benefit of the engagement approach is the development of a shared understanding of flood generation, routing and accumulation within a catchment. The opportunity for planners, water company engineers, land managers, FCRM, water quality and biodiversity specialists to elicit hydrological understanding from modellers including issues of synchronisation is of enormous value. The engagement process also enables the modelling team to appreciate and incorporate a more credible set of opportunities and parameters back into the model. This

http://dx.doi.org/10.5772/intechopen.68677

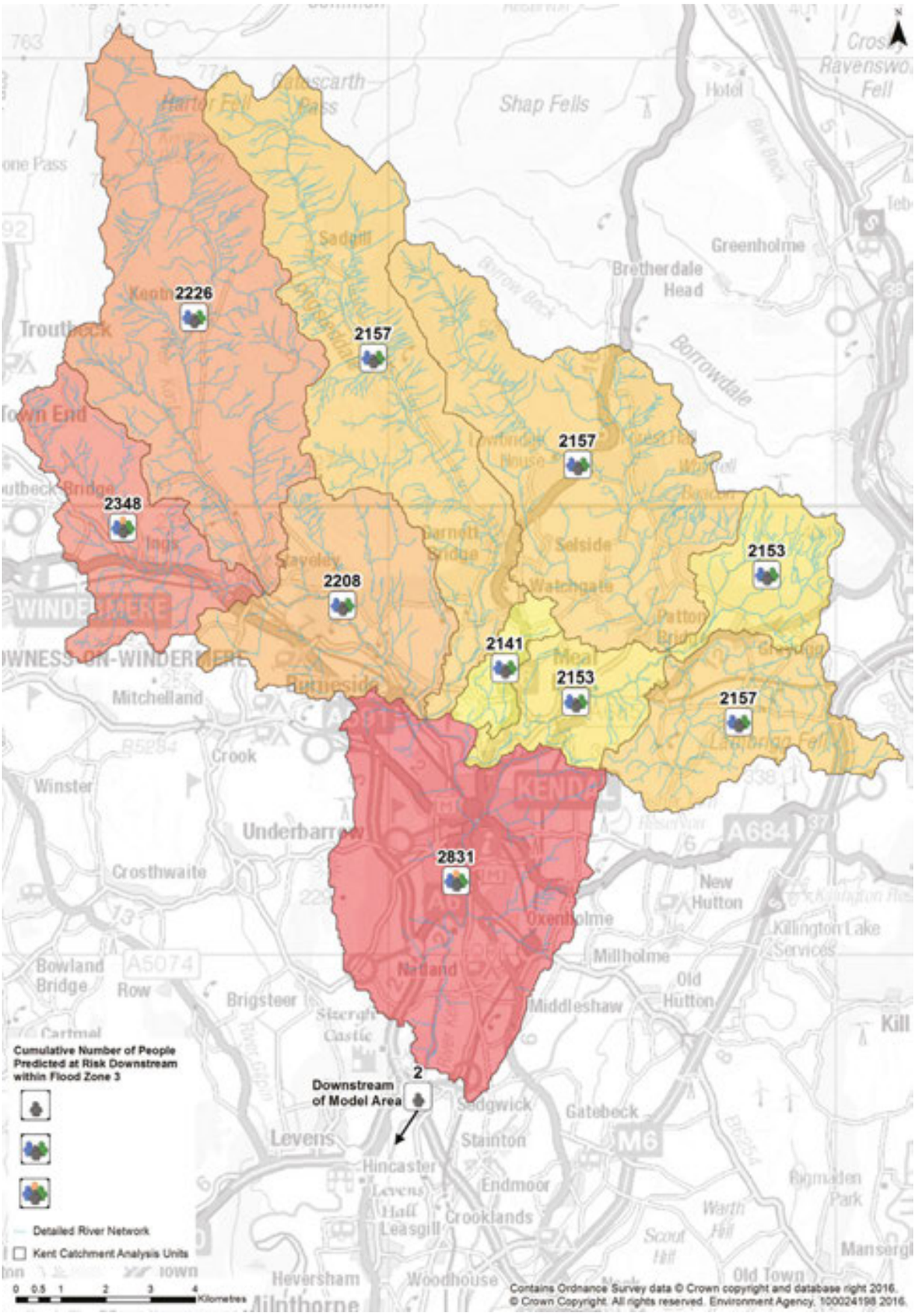


Figure 8. Downstream risk visualised for the Kent.

two-way process builds confidence in the model outputs, allowing delivery organisations to make appropriate use of the modelling, based on improved understanding, as part of the weight of evidence required to develop a more strategic approach to NFM delivery.

In addition to the refinement of the opportunities, and through remodelling the benefits, the catchment partners were asked to prioritise sub-catchments for more detailed modelling to build confidence and implement NFM. A matrix was developed, based on the following criteria:

- Land ownership and access—are opportunities feasible?
- Observations based on local knowledge
- Observations from strategic maps
- Scale of downstream risk
- Existence and location of monitoring
- Catchment size
- Preferences counted in the workshop

The upper and mid-Kent and Gowan sub-catchments were prioritised, and it can be seen in **Figure 8** that there are different centres of risk and strong reason to supplement any established FRM measures with NFM if possible. The catchments were also identified in the Cumbria Flood Plan for NFM-type interventions, largely for peat or bog restoration in the upper Kent.

5.1. Modelling of NFM with dynamic TOPMODEL

Given limited observational evidence effectiveness of NFM at scales >10 km^2, the prioritisation of areas to model in more detail and through using Monte-Carlo simulations was considered essential to understand more about uncertainty and build on the screening-level modelling with JFLOW (despite its high resolution). The detailed modelling was therefore calibrated against an observed series of extreme events, Nov-Dec 2015, within three severely-impacted catchments up to 223 km^2 in the area within Cumbria, UK. The results from one of these catchments, the upper Kent (90 km^2) are used in the following sections to illustrate the approach that was taken for all three catchments.

Lancaster University has recently developed an extended and flexible implementation of the Dynamic TOPMODEL model [9, 10], first implemented in FORTRAN by Beven and Freer [9]. It is an extension of the popular TOPMODEL [69] applied in many studies [70]. Dynamic TOPMODEL employs the efficient parameterisation scheme of TOPMODEL, but allows a more general approach to a grouping of points in a catchment for calculation purposes, based on overlays of characteristics rather than simply the map of the topographic index. All the model parameters needed to run the model are shown in **Table 4**, along with typical ranges of values applied in this project. **Figure 9** provides a perceptual overview of Dynamic TOPMODEL.

http://dx.doi.org/10.5772/intechopen.68677

Parameter	Description	Units	Lower	Upper
V_{of}	Overland flow velocity	m/hr	1	150
m	Form of exponential decline in conductivity	m	0.0011	0.033
SRZ_{max}	Max root zone storage	m	0.1	0.3
SRZ_0	Initial root zone storage	%	20	100
V_{chan}	Channel routing velocity	m/hr	500	5000
$ln(T_0)$	Lateral saturated transmissivity	m^2/hr	3	12
$Sdmax$	Max effective deficit of saturated zone	m	0.5	0.5
T_d	Unsaturated zone time delay	m/hr	1	10

Table 4. Parameter ranges/typical values within dynamic TOMODEL (after Ref. [10]).

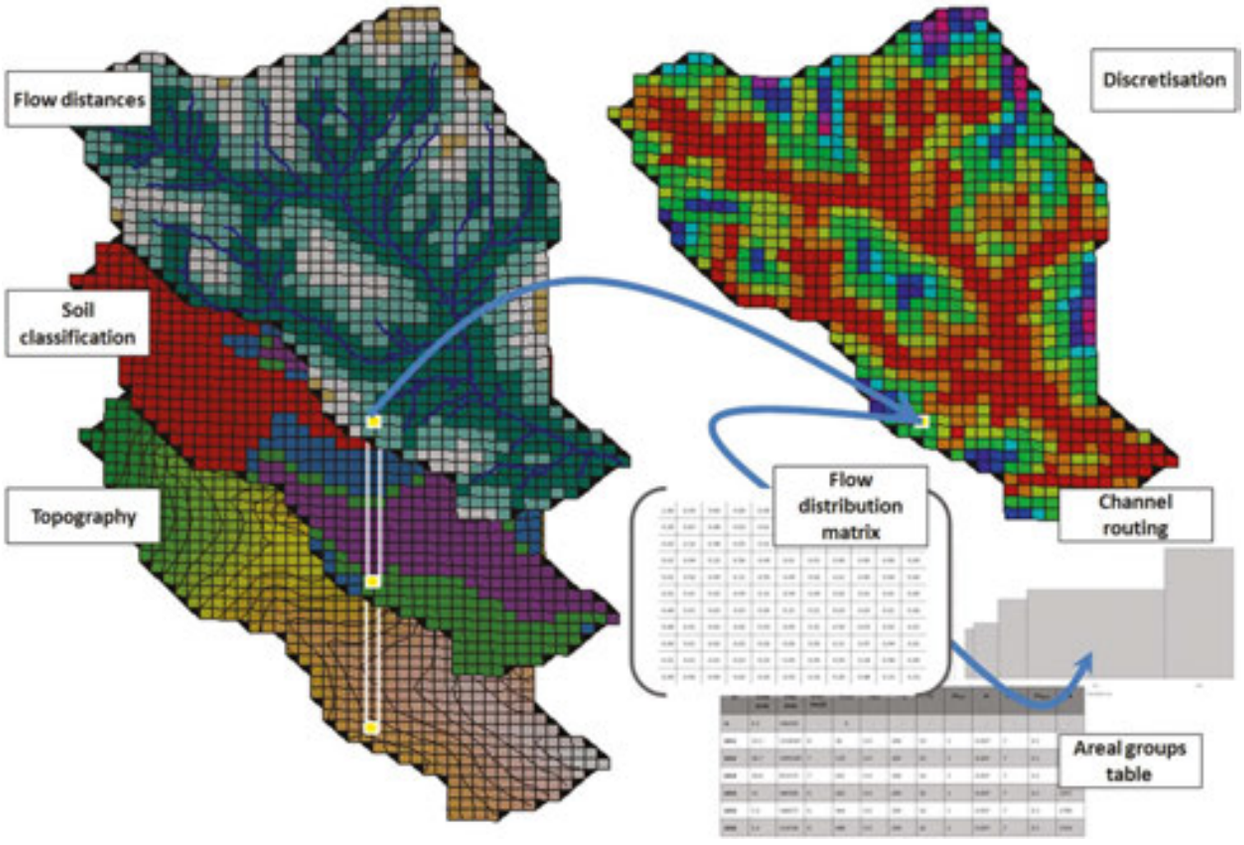


Figure 9. Schematic of dynamic TOPMODEL.

It is a semi-distributed hydrological model that utilises areas of similar hydrological behaviour called HRUs (Hydrological Response Units). These units may be in the evaluation of NFM divided to represent distributed interventions within the landscape. It has sufficient complexity to represent the key catchment processes, notably subsurface and overland flow pathways, and there is some evidence to link NFM measures to alteration of the parameters (e.g. transmissivity

distribution) representing these processes. Its simple structure allows efficient operation, allowing thousands of model runs to be simulated to investigate uncertainties and sensitivities.

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 maximum transmissivity at complete saturation T_0 $[L]^2/[T]$ is a measure of the local maximum saturated downslope transmissivity per unit hydraulic gradient (where transmissivity is the integral of the permeability to the saturated depth). This is a key parameter in identifying the onset of saturation overland flow (SOF). 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 [71] and reproduces 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 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.

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 SRZ_{max} 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 a reasonable initial value was applied ($SRZ_0 = 95\%$).

Dynamic TOPMODEL represents an intermediate level of complexity that incorporates 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. The model was also selected because of 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 overlays provided by the Rivers Trust (RT) and catchment partners of NFM interventions, for example, tree-planting, soil restoration and the 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 km^2 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 the source or compiled the code and, with suitable guidance and training, be operated by RT staff and catchment partners.

In conjunction with a hydraulic-routing scheme, also developed at Lancaster University, Dynamic TOPMODEL has been applied to the 28 km^2 Brompton, North Yorkshire, catchment in order to simulate the impact of up to 60 in-channel NFM interventions [5]. The model is written in the open source R language, distributed under the GNU Lesser Public Licence (GNU LGPL v2.1) and can be run on most common operating systems. The R implementation has been released as a package on the CRAN archive [72], passing the rigorous quality assurance and testing required by the submission process.

5.1.1. Representing NFM opportunities within HRUs for Dynamic TOPMODEL

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 T_0 (1.5–2.5 multiplicative factor of the un-logged value).
  - Decreased SOF velocity (reduced by 0.5 and 0.75–equivalent to a change in roughness for JFLOW).
  - Wet-canopy evaporation increases implemented as a loss to the gross rainfall input (using a similar strategy to Ref. [73]).
  - 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.
- 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 1 m, making use of the existing store represented in the model
  - RAFs are 'leaky', draining at a rate q_{drain} [L]/[T] proportional to their specific storage S [L]: $q_{drain} = S/T$, where the constant of proportionality T [T] is the residence time

- Assume all RAFs drain with the same time constant and 'piped' directly to a watercourse.
- Implemented as the sensitivity of three pipe sizes to see differences in 'effective' size based on peak reduction.

- HRU3–Peat
  - Decreased SOF velocity (reduced by between 0.65 and 0.8–equivalent to a change in roughness implemented for JFLOW).

6. Uncertainty framework

The scale of the flooding caused by Storm Desmond is in part dependent on the catchment wetting from the storm events that occurred over the preceding weeks. In consequence, a 6-week period of rainfall and streamflow was selected in Nov-Dec 2015 (**Figures 4–6**) for the modelling, that included Storms Abigail (12–13th November), Barney (17–18th November), Clodagh (29th November) and Desmond (5–6th 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 [11]. 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 3-day total of 138 mm was recorded at the Shap automatic weather station in mid-November [11], compared to the total of 145–180 mm recorded at rain gauges around the Kent catchment in September and October. Two gauges lying within the Derwent catchment recorded new UK record rainfall totals: at Honister Pass, 341 mm fell within 24 h and 405 mm within 48 h at Thirlmere [11]. Dynamic TOPMODEL requires as input a time series of potential (or actual) evapotranspiration. We used the Calder et al. [74] approximation of a diurnal sinusoidal variation in potential evapotranspiration.

5000 Monte-Carlo simulations were undertaken before applying an acceptability criterion which sorts behavioural simulations, from those that are not. Within the Generalised Likelihood Uncertainty Estimation framework (GLUE [75–78]), 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 were based on an overall performance measure over the whole modelled period (the Nash-Sutcliffe Efficiency statistic, NSE), the accuracy of the model prediction for the peak flow Q_{max} during Storm Desmond, and the maximum percentage of the catchment areas generating overland flow (by saturation through either of the processes described), SOF_{amax}. **Figure 10** illustrates the spread in model uncertainties through the calibration time series based on the resulting 'acceptable' parameter combinations.

Given the range of acceptable model predictions for each storm the problem arises of comparing the NFM interventions for all acceptable models. To compare the respective hydrographs contemporaneously is likely to be misleading, since each series' maxima may occur

http://dx.doi.org/10.5772/intechopen.68677

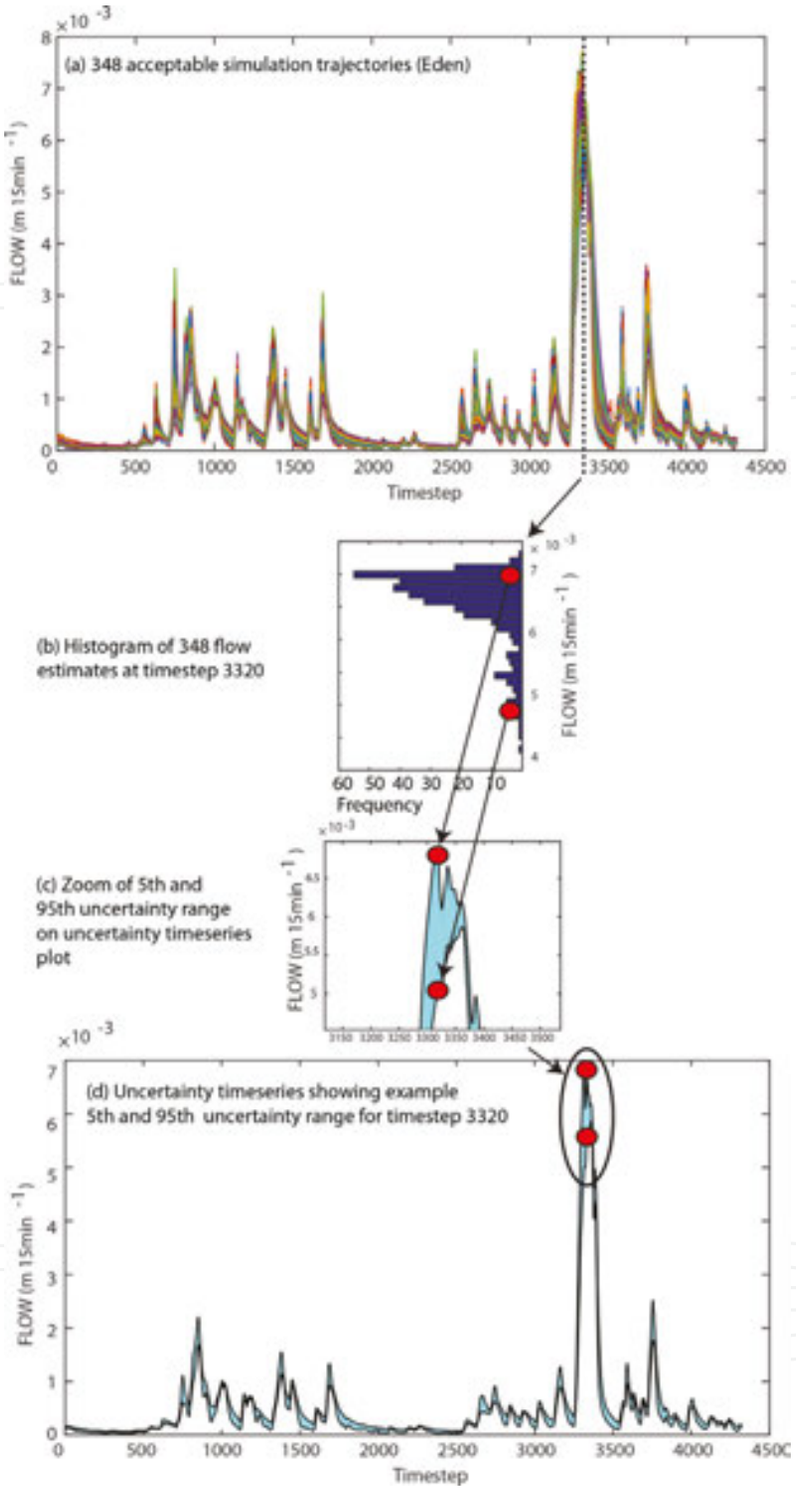


Figure 10. Translating uncertainty to model predictions (GLUE).

at different absolute times due, for example, to the retardation of the flood peak by the NFM measures. The distribution of flows for a window of time-steps around the peak has therefore been generated so that the shift in the distribution can be compared. This is illustrated in **Figure 11**.

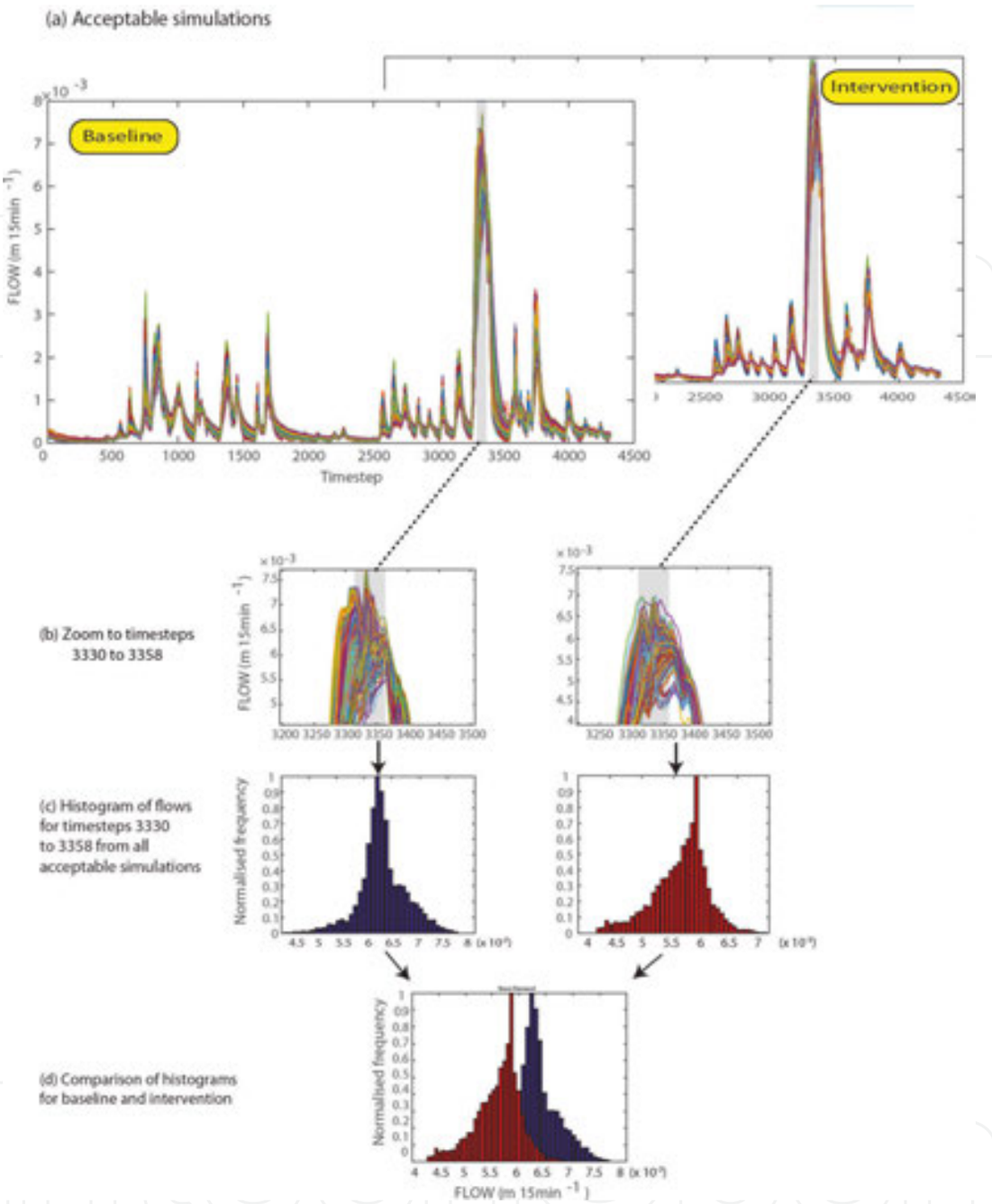


Figure 11. The change to predicted flow frequency distributions.

7. Results and discussion: comparison of models

We present here mainly the results for the Kent catchment, where the acceptance criteria discussed above were: NSE > 0.85; 6.9 < Q_{max} < 10.2; 0.1< SOF_{amax} <0.95, where Q_{max} is the peak flow per unit area for storm Desmond and SOF_{amax} was the very fuzzy range of acceptable fractional catchment areas producing SOF. This lead to 348 'acceptable' parameterisations, giving a range of predictions shown in **Figure 12**, for the RAF measures, designed to have a 1, 10 and 100 h retention time.

http://dx.doi.org/10.5772/intechopen.68677

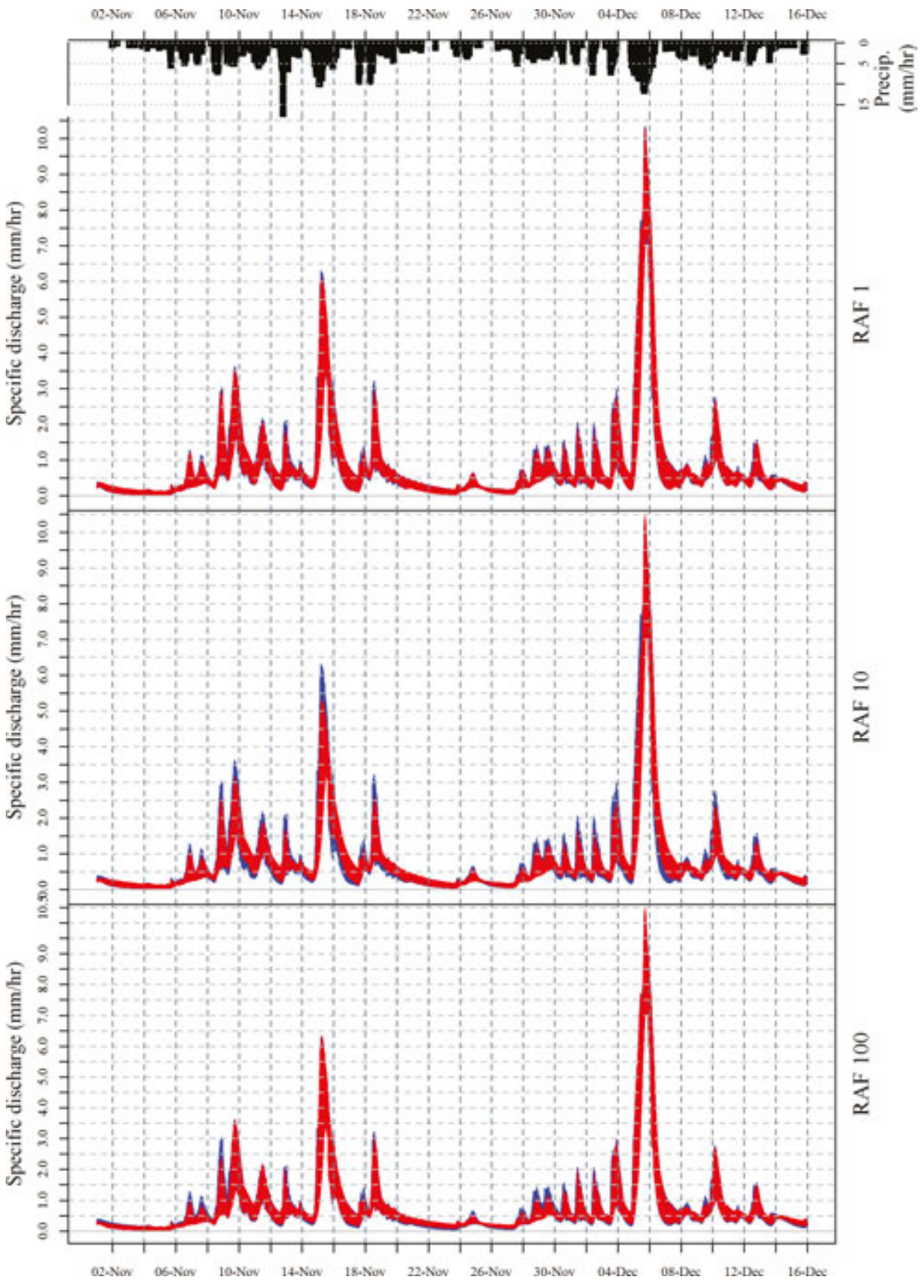


Figure 12. Range of predictions using acceptable combinations plus RAFs with a 1, 10 and 100 h retention time.

Figure 13 shows the range of potential changes to the storm profile when we apply two different levels of confidence (1 and 5, with 5 the least confident) in the evidence for the effect that tree-planting has on the different catchment processes.

It easier to consider the range of predicted peak flow reductions for each storm as a function of the confidence we place in the evidence (**Figure 14**) than by plotting the five different levels of confidence.

We can also make use of the generic approach from **Figure 11**, and plot the matrix of changes to the predicted peak flow distributions for a window around each named storm as a function of confidence (rows) in **Figure 15**, with a statistical significance of the changes highlighted in

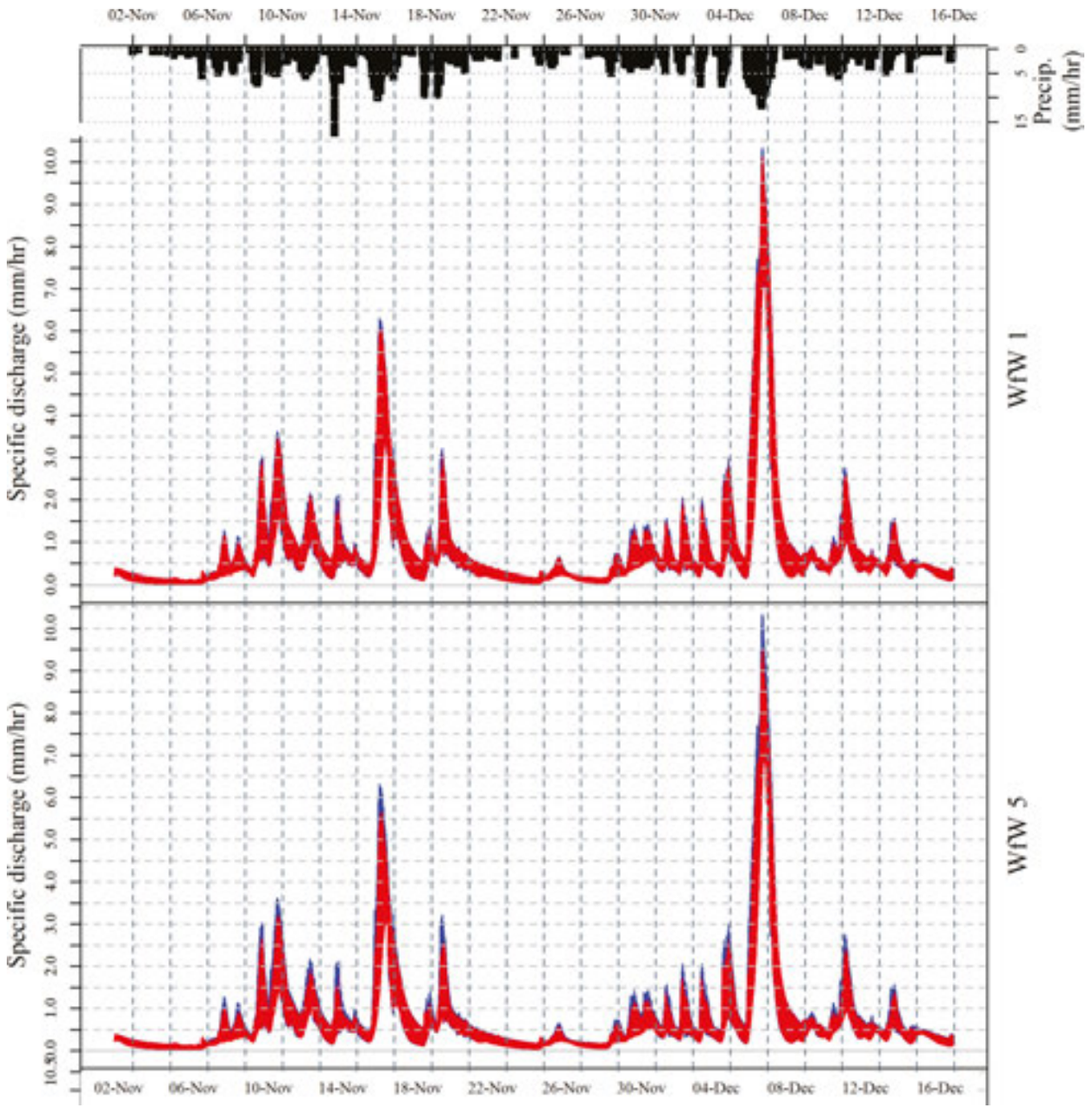


Figure 13. Effect of tree-planting opportunities with two levels of confidence in parameter changes.

http://dx.doi.org/10.5772/intechopen.68677

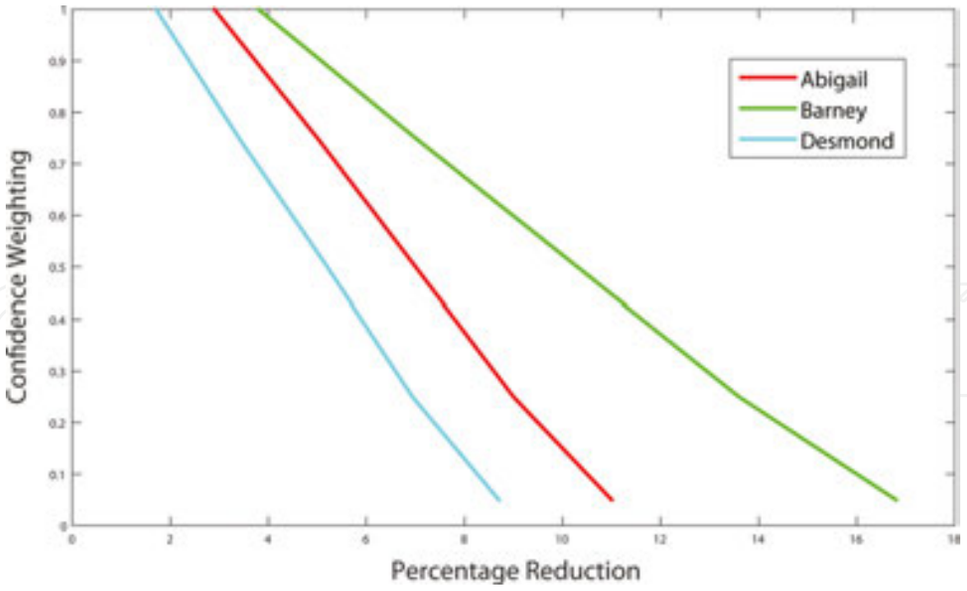


Figure 14. Confidence as a function of the percentage reduction for 3 of the named storms for tree-planting and roughening up.

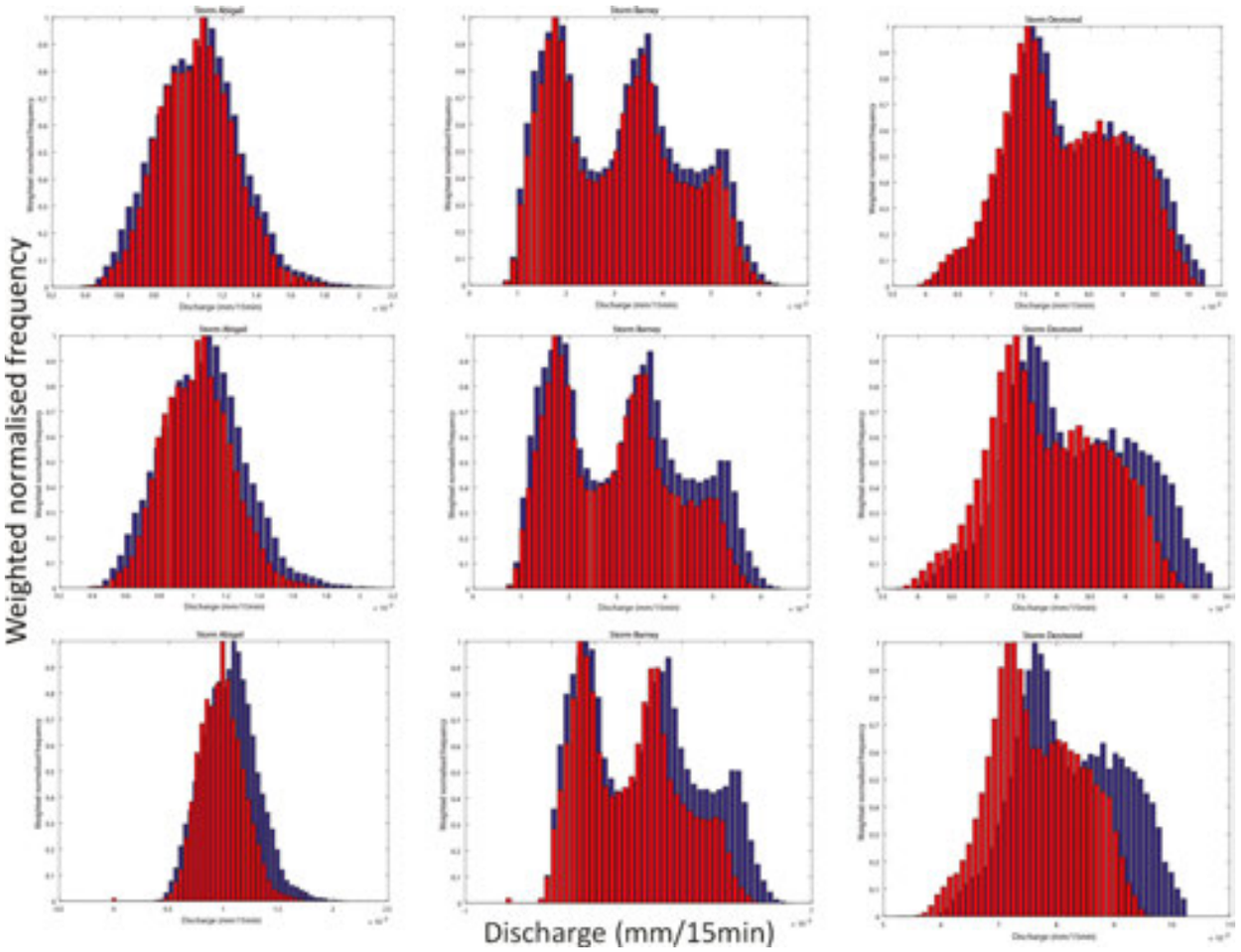


Figure 15. Matrix of shifts to the distribution of flows predicted around peaks for 3 storms (columns) for three confidence levels (rows).

Table 5. The WfW scenarios 1–5 were simulated, where there is more confidence in the evidence for scenario 1, and scenario 5 is the least confident. All the changes are more significant for storm Desmond, and the changes due to the RAF measures are generally more significant than the WfW.

Using Dynamic TOPMODEL, we have modelled drain-down of RAFs successfully with different time constants, and shown that for the Kent, RAFs designed with an intermediate residence time of around 10 h would be more effective for a series of flood events such as those in the period November through December 2015. The percentage reductions in peak flows are similar to the 2–5% peak runoff reduction predicted by JFLOW (30 year event) for the upper Kent for most of the period of modelling, apart from storm Desmond where **Figure 12** shows less reduction, potentially because the RAFs have not emptied.

It is less straightforward to compare the results for tree-planting between the modelling approaches, but for the Upper Kent, JFLOW predicts peak *streamflow* (without baseflow) reductions up to 30–40% for a 1 in 30 year design event (**Figure 7**), and based on **Figure 14**, the maximum reduction in *total flow* was half this, of the order 17% for storm Barney, but for simulations with the least confidence. However, these changes stem from very different physical processes, and further modelling has shown that although the perturbations applied to the wet canopy evaporation have the predominant impact, the *combined effect* was greater than the sum of the individual changes for evaporation, velocities and transmissivity.

The potential impact of large-scale NFM delivery on peak flow during extreme events such as storm Desmond is an important result. The evaluation of uncertainty enables us to use this finding appropriately and with greater confidence. The modelling allows us to see both the long-term potential of NFM and, critically, the model parameters and processes to which this prediction is most sensitive. These findings not only improve our understanding of the benefits of NFM but also guide future monitoring strategies that will be required to refine the modelling and adaptively manage NFM, and therefore flood risk, within a catchment. A consistent theme within the engagement was that it would be unlikely that advantage could be taken of every single potential opportunity, and so the results can seem overly optimistic but could be used in a relative sense.

	Abigail			**Barney**			**Desmond**		
	Δq_{max}	$\overline{\Delta q}$	**K-S**	Δq_{max}	$\overline{\Delta q}$	**K-S**	Δq_{max}	$\overline{\Delta q}$	**K-S**
WfW1	20.5	3.1	0.027	11.5	3.3	0.025	4.9	1.7	0.019
WfW5	30.9	9.6	0.139	26.9	12.9	0.124	14.2	7.9	0.076
RAF1	25.3	2.3	0.006	15.3	2.1	0.01	5.8	1.2	0.005
RAF10	28.6	7	0.067	22.5	13.7	0.118	4.5	0.1	0.055
RAF100	22.9	0.9	0.014	14.1	0.4	0.006	4.5	0.1	0.005

Δq_{max} = maximum relative reduction in peak (%); $\overline{\Delta q}$ = mean relative reduction in peak (%); K-S = Kolmogorov-Smirnov Statistic. The suffix to RAF corresponds to a retention time of 1, 10 and 100 h.

Table 5. Statistics for WfW and RAF interventions for each of the named storms in the simulation period.

http://dx.doi.org/10.5772/intechopen.68677

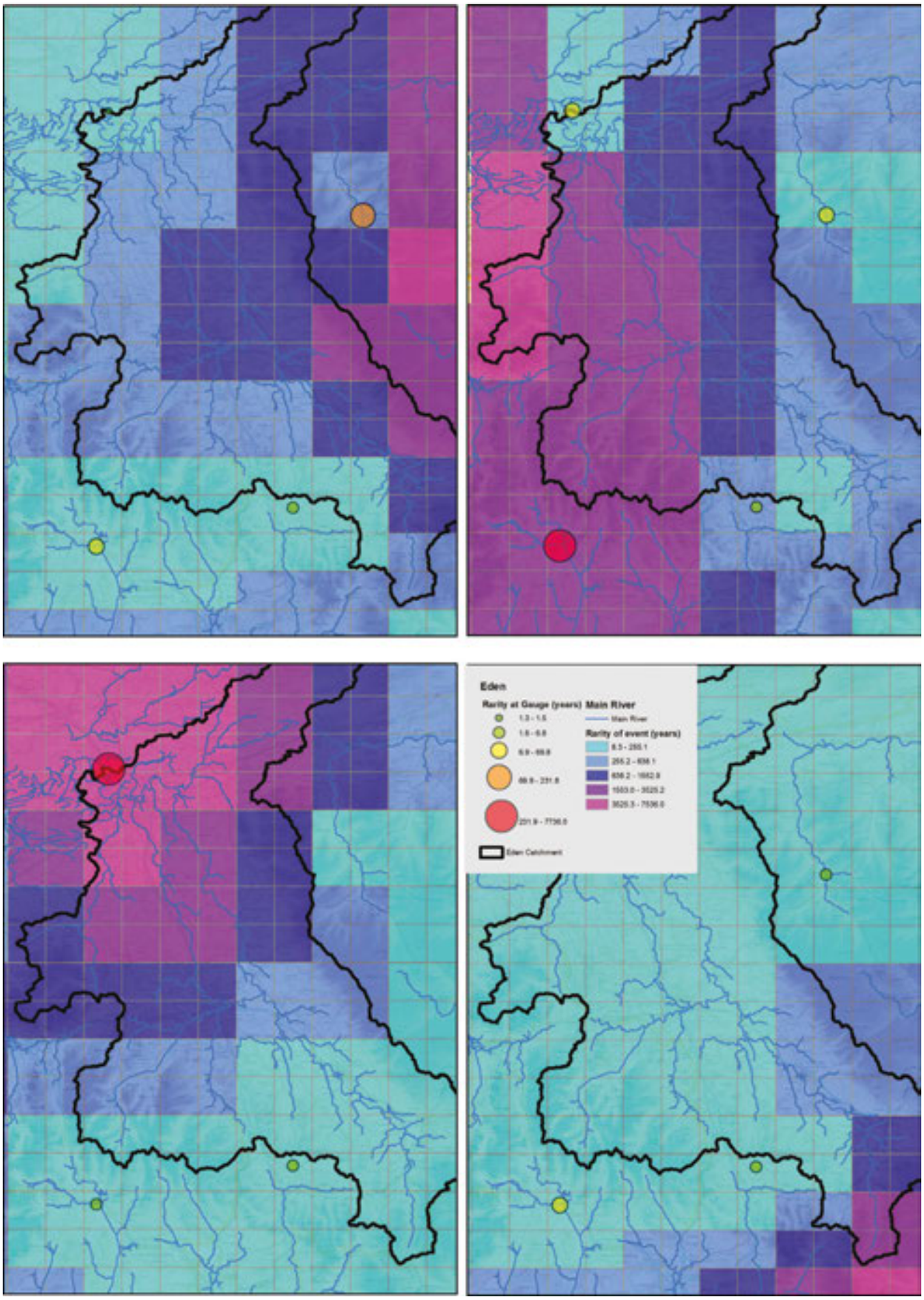


Figure 16. Spatial rainfall fields for plausible events.

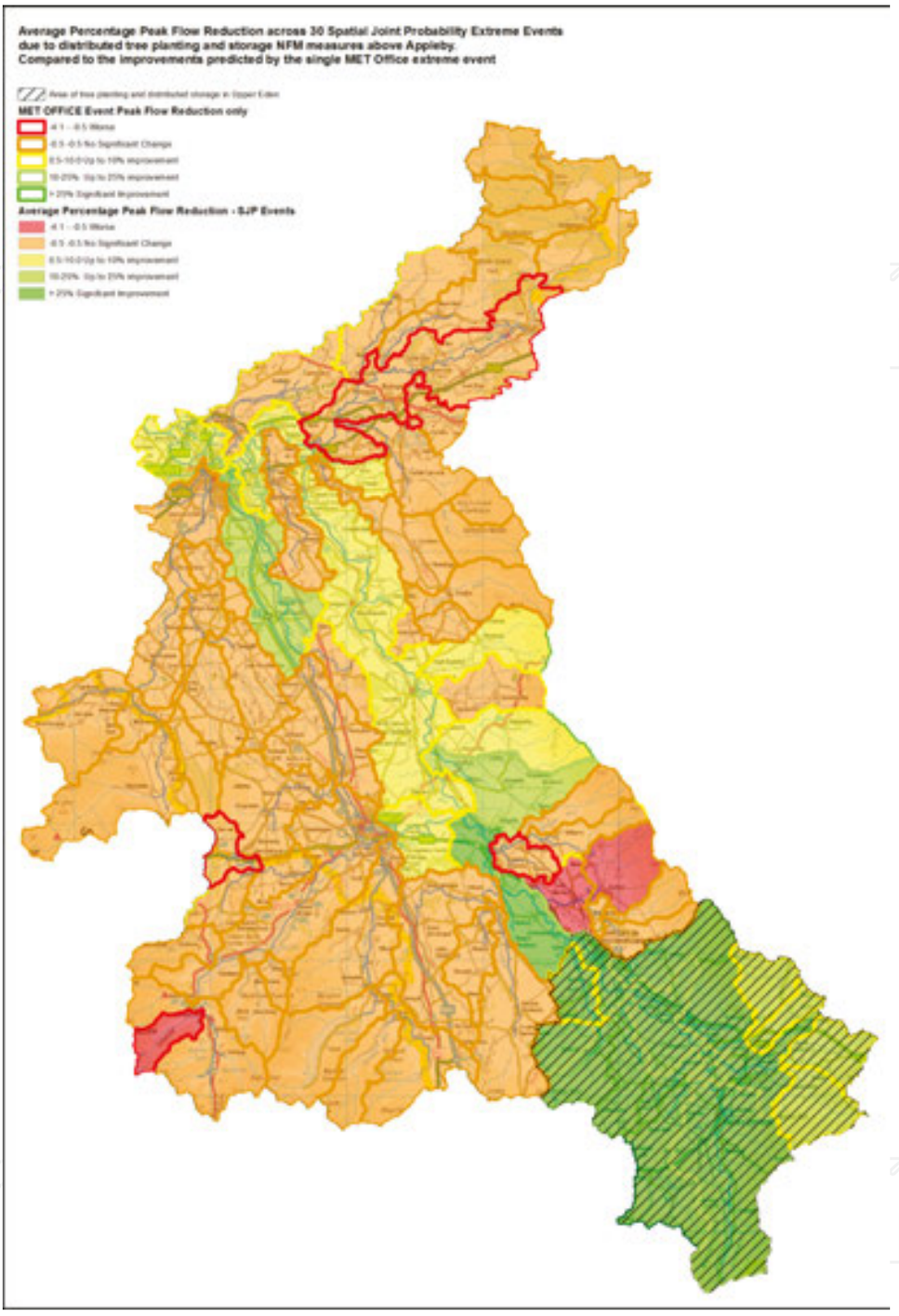


Figure 17. Average behaviour across 30 events with and without NFM.

7.1. Testing resilience

These types of analyses provide us with more confidence in the predicted response of the upper Kent to large-scale interventions of tree-planting and RAFs, yet we have not fully tested the long-term robustness nor the resilience in the face of different weather extremes. It would, in fact, be useful to test for a number of performance issues in order to gain greater confidence in the approach. These issues include:

- Synchronisation.
- Effect of sequences of events on antecedent conditions.
- Backwater effects.
- Sedimentation.
- Culvert or bridge blockage due to increased debris from tree-planting.

These can be examined and tested through modelling of extreme events with different spatial rainfall fields (especially for larger catchments) as performed for the Defra competition [6], for the Eden as shown in **Figure 16**.

Here the average beneficial effect of NFM across 30 extremes, but plausible, rainfall events was generated (**Figure 17**) in order to test for robustness in using such distributed events in the larger Eden catchment in Cumbria.

Ideally, the additional modes of failure of NFM should also be tested for through probabilistic modelling, as currently undertaken for established FRM in the UK. A systems-based approach could be applied [79] as discussed in relation to wider processes from synchronisation of flood peaks, backwater effects, sedimentation effects whereby RAFs fill in through time, and blockage of downstream features such as culverts near urban areas due to an increase in woody material in the longer term, although it is also important to re-think the implications of performance failure for very distributed small-scale measures, compared to established flood risk management approaches [80].

8. Conclusions

We have demonstrated a generic flood risk management framework that caters for the distinct differences between NFM and established approaches such as engineered downstream flood defences. NFM measures are characteristically small-scale and may need to be widely distributed to be effective at larger scales, and can influence a range of catchment processes. This combination means that modelling their effectiveness will be inherently uncertain, but we have demonstrated a framework that is tolerant of this uncertainty and the fuzziness in the evidence for how model 'effective' parameters can be plausibly changed to reflect their effect.

The tiered approach involves strategic modelling, mapping of opportunities and benefits, consultation and then prioritisation of areas for more detailed modelling and eventual implementation. The engagement phase is essential and ideally should be more of a continuous process through time with details of the model landscapes (topography, distributed roughness, storage, tree-cover, land-use), being revisited regularly. This is not new, but this chapter has hopefully shown how it can be achieved practically in the reasonable timescale of just 6 months.

However, differences in the model predictions from the different modelling approaches require careful interpretation and are only part of the picture set in the context of uncertainties on long-term ownership, maintenance and liabilities for NFM measures. The strategic overland flow process modelling is bound to lead to some different catchment responses than

for a complete hydrological model, yet both shed light on different risk management issues. For example, the surface water modelling approach is useful for identifying key flow pathways and accumulations where partial blockage or storage can make a greater difference, but Dynamic TOPMODEL tells us more about the whole hydrograph and can integrate with more of the processes that tree planting is thought to influence. 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 at large catchment scales. The models help shed more light on the complexities of parameterising change in model parameters, particularly at large catchment scales and for a range of flood events.

The potential for large-scale NFM delivery to provide significant flood risk benefits, even in extreme events, is based on a translation of the limited available evidence on the impacts of NFM between the 'real world' and the 'modelled world', using an uncertainty framework. If we believe that the model is a reasonable physical simulator of the whole catchment, then the potential benefits of following the risk management framework demonstrated are to help express model outputs in a language which highlights uncertainties and makes them more central to decision-making.

The models have helped to quantify by how much working with natural processes can improve flood regulation, depending on a fuzzy evidence base. The associated benefits can then be appraised alongside others, including carbon storage or reductions in diffuse pollution, sediment transport and improved community resilience through working together. However, we must stress the need for more information on the way in which model parameters might change as a result of land management changes as the information currently available is limited, in particular in respect of the type of flood event conditions relevant to NFM.

Acknowledgements

With thanks to the Rivers Trust for their guidance and engagement, and all the attendees of the workshop held on the 7th Oct 2016, and to the Environment Agency for the large quantities of data supplied.

Author details

Barry Hankin[1]*, Peter Metcalfe[2], David Johnson[3], Nick A. Chappell[2], Trevor Page[2], Iain Craigen[1], Rob Lamb[4] and Keith Beven[2]

*Address all correspondence to: barry.hankin@jbaconsulting.com

1 JBA Consulting, Warrington, UK

2 Lancaster University, Lancaster, UK

3 The Rivers Trust, Malvern, UK

4 JBA Trust and Lancaster University, UK

References

[1] Pitt M. The Pitt Review, 2008. Learning lessons from the 2007 floods. June 2008. http://archive.cabinetoffice.gov.uk/pittreview/thepittreview/final_report.html

[2] JBA Trust. Working With natural Processes: A catalogue of nature-based flood risk management projects in the UK. 2016. http://naturalprocesses.jbahosting.com/

[3] Beven K. Environmental Modelling: An Uncertain Future? Routledge; London. 2009. ISBN10: 0-415-45759-9

[4] Lamb R, Crossley A, Waller S. A fast 2D floodplain inundation model. Proceedings of the Institution of Civil Engineers: Water Management. 2009;**162**: pp. 363-370

[5] Metcalfe P, Beven K, Hankin B, Lamb R. A modelling framework for evaluation of the hydrological impacts of nature-based approaches to flood risk management, with application to in-channel interventions across a 29 km^2 scale catchment in the United Kingdom. Hydrological Processes. 2017. https://doi.org/10.1002/hyp.11140

[6] Hankin B, Lamb R, Craigen I, Page T, Chappell N, Metcalfe P. Winning Flood Modelling Competition Entry [Internet]. 2017 [Updated: 19-01-2017]. Available from: https://consult.defra.gov.uk/water-and-flood-risk-management/flood-risk-management-modelling-competition/results/jba_defra_winning_entry_full_report.pdf [Accessed: 23 January 2017]

[7] Lamb R, Keef C, Tawn J, Laeger S, Meadowcroft I, Surendran S, Dunning P, Batstone C. A new method to assess the risk of local and widespread flooding on rivers and coasts. Journal of Flood Risk Management. 2010;**3**(4):323-336 (14 p). DOI: 10.1111/j.1753-318X.2010.01081.x

[8] Keef C, Tawn JA, Lamb R. Estimating the probability of widespread flood events. Environmetrics. 2013;**24**(1):13-21. DOI: 10.1002/env.2190

[9] Beven K, Freer J. A dynamic TOPMODEL. Hydrological Processes. 2001;**15**(10):1993-2011

[10] Metcalfe P, Beven K, Freer J. Dynamic TOPMODEL: A new implementation in R and its sensitivity to time and space steps. Environmental Modelling & Software. 2015;**72**:155-172

[11] Marsh TJ, Kirby C, Muchan K, Barker L, Henderson E, Hannaford J. The winter floods of 2015/2016 in the UK—A review. Wallingford, UK: Centre for Ecology & Hydrology; 2016

[12] Flooding after Storm Desmond. PERC UK 2015. http://www.jbatrust.org/wp-content/uploads/2016/08/flooding-after-storm-desmond-PUBLISHED-24-August-2016.pdf

[13] Medeiros SC, Hagen SC, Weishampel JF, Comparison of floodplain surface roughness parameters derived from land cover data and field measurements. Journal of Hydrology. 2012;**452-453**:139-149

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

[15] Holden J, Kirkby MJ, Lane SN, Milledge DG, Brookes CJ, Holden V, McDonald AT. Overland flow velocity and roughness properties in peatlands. Water Resources Research. 2008;**44**. DOI: 10.1029/2007wr006052

[16] Holden J, Burt TP, Evans MG, Horton M. Impact of land drainage on peatland hydrology. Journal of Environmental Quality. 2006;**35**:1764-1778

[17] Chappell NA, Tych W, Chotai A, Bidin K, Sinun, W, Thang HC. BARUMODEL: Combined Data Based Mechanistic models of runoff response in a managed rainforest catchment. Forest Ecology and Management. 2006;**224**:58-80

[18] Wheater H, Reynolds B, McIntyre N, Marshall M, JacksonB, Frogbrook Z, Chell J. Impacts of upland land management on flood risk: Multi-scale modelling methodology and results from the Pontbren Experiment. 2008. (http://nora.nerc.ac.uk/5890/1/ur16_impacts_upland_land_management_wp2_2_v1_0.pdf)

[19] Deasy C, Quinton JN, Silgram M, Stoate C, Jackson R, Stevens CJ, Bailey AP. Mitigation Options for Phosphorus and Sediment (MOPS): Reducing pollution in runoff from arable fields. The Environmentalist. 2010;**108**:12-17

[20] Nicholson AR. Quantifying and simulating the impact of flood mitigation features in as small rural catchment [PhD thesis]. UK: Newcastle University; 2013

[21] Nicholson AR, Wilkinson ME, O'Donnell GM, Quinn PF. Runoff attenuation features: a sustainable flood mitigation strategy in the Belford catchment, UK. 2012;**44**(4):463-469

[22] Vincke C, Granier A, Breda N, Devillez F. Evapotranspiration of a declining *Quercus robur* (L.) stand from 1999 to 2001. II. Daily actual evapotranspiration and soil water reserve. Annals of Forest Science. 2005;**62**:615-623

[23] Rychnovská M. Transpiration in wet meadows and some other types of grassland. Folia Geobotanica & Phytotaxonomica. 1976;**11**:427-432

[24] Black TA, Kelliher FM. Process controlling understory evapotranspiration. Philosophical transactions of the Royal Society of London. Series B. 1989;**324**:207-231

[25] Roberts JM, Rosier PTW. Comparative estimates of transpiration of ash and beech forests at a chalk site in southern Britain. Journal of Hydrology. 1994;**162**:229-245

[26] Verón SR, Paruelo JM, Oesterheld M. Grazing-induced losses of biodiversity affect the transpiration of an arid ecosystem. Oecologia. 2011;**165**:501-510

[27] Reynolds ERC, Henderson CS. Rainfall Interception by beech, larch and Norway Spruce. Forestry. 1967;**40**:165-184

[28] Kirby C, Newson M, Gilman K. Plynlimon research: The first two decades. IH Report No.109. Wallingford: Institute of Hydrology; 1991 188p

[29] Thurow TL, Blackburn WH, Taylor CA. Rainfall interception losses by midgrass, shortgrass, and live oak mottes. Journal of Range Management. 1987;**40**:455-460

[30] Herbst M, Rosier PTW, McNeil DD, Harding RJ, Gowing DJ. Seasonal variability of interception evaporation from the canopy of a mixed deciduous forest. Agricultural and Forest Meteorology. 2008;**148**:1655-1667

[31] Brown AE, Zhang L, McMahon TA, Western AW, Vertessy RA. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. Journal of Hydrology. 2005;**310**:28-61

[32] Chappell NA, Tych W, Chotai A, Bidin K, Sinun W, Thang HC. 2006. BARUMODEL: Combined Data Based Mechanistic models of runoff response in a managed rainforest catchment. Forest Ecology and Management. 2006;**224**:58-80

[33] Chappell NA, Jones TD, Tych W, Krishnaswamy J. Role of rainstorm intensity underestimated by data-derived flood models: emerging global evidence from subsurface dominated watersheds. Environmental Modelling and Software. Volume 88, February 2017, Pages 1-9

[34] Finch JW. Modelling the soil moisture deficits developed under grass and deciduous woodland: The implications for water resources. Journal of the Chartered Institution of Water and Environmental Management 2000;**14**:371-376

[35] Calder IR, Harding RJ, Rosier PTW. An objective assessment of soil-moisture deficit models. Journal of Hydrology. 1983;**60**(1-4):329-355

[36] Horton RE. The role of infiltration in the hydrologic cycle. Transactions, American Geophysical Union. 1933;**14**:446-460

[37] Dunne T, Black RD. Partial area contributions to storm runoff in a small New England watershed. Water Resources Research. 1970;**6**:1296-1311

[38] Cook HL. The infiltration approach to the calculation of surface runoff. Transactions, American Geophysical Union. 1946;**27**:726-743

[39] FAO-UNESCO. Soil map of the world. Revised legend. Soils Bulletin. 1990;**66** FAO, Rome

[40] Jarvis RA, Bendelow VC, Bradley RI, Carroll DM, Furness RR, Kilgour INL, King SJ. Soils and their use in Northern England. Soil Survey of England and Wales Bulletin No **10**. Harpenden; 1984

[41] Chappell NA, Ternan JL. Flow-path dimensionality and hydrological modelling. Hydrological Processes. 1992;**6**:327-345

[42] Chappell NA, Ternan JL. Ring permeametry: Design, operation and error analysis. Earth Surface Processes and Landforms. 1997;**22**:1197-1205

[43] Chappell NA, Lancaster JW. Comparison of methodological uncertainty within permeability measurements. Hydrological Processes. 2007;**21**:2504-2514

[44] Soil Survey of England and Wales. Soils of England and Wales, Sheet **1**: Northern England; 1983

[45] Boorman DB, Hollis JM, Lilly A. Hydrology of Soil Types: A hydrologically-based classification of the soils of the United Kingdom. IH Report No. 126. Wallingford: Institute of Hydrology; 1995

[46] Nisbet T, Silgram M, Shah N, Morrow K, Broadmeadow S. Woodland for water: Woodland measures for meeting WFD objectives. Forest Research Monograph, 4, Forest Research, Surrey; 2011. 156 pp

[47] Chandler KR, Chappell NA. Influence of individual oak (*Quercus robur*) trees on saturated hydraulic conductivity. Forest Ecology and Management. 2008;**256**:1222-1229

[48] Archer NAL, Bonell M, Coles N, MacDonald AM, Stevenson R, Hallett P. The relationship of forest and improved grassland to soil water storage and its implication on Natural Flood Management in the Scottish Borders. In: BHS 11th National Symposium, Hydrology for a Changing World; 9-11 July 2012; Dundee, Scotland. 2012. DOI: 10.7558/bhs.2012.ns04

[49] Archer NAL, Bonell M, Coles N, MacDonald AM, Auton CA, Stevenson R. Soil characteristics and land cover relationships on soil hydraulic conductivity at a hillslope scale: a view towards local flood management. Journal of Hydrology. 2013;**497**:208-222

[50] Chappell NA, McKenna P, Bidin K, Douglas I, Walsh RPD. Parsimonious modelling of water and suspended-sediment flux from nested-catchments affected by selective tropical forestry. Philosophical Transactions of the Royal Society of London. B. 1999;**354**:1831-1846

[51] McDonnell JJ, Beven KJ. Debates—The future of hydrological sciences: A (common) path forward? A call to action aimed at understanding velocities, celerities, and residence time distributions of the headwater hydrograph. Water Resources Research. 2014;**50**(6): 5351-5359. DOI: 10.1002/2013WR015141

[52] Ockenden MC, Chappell NA. Identification of the dominant runoff pathways from the data-based mechanistic modelling of nested catchments in temperate UK. Journal of Hydrology. 2011;**402**:71-79

[53] Jones TD, Chappell NA, Tych W. First dynamic model of dissolved organic carbon derived directly from high frequency observations through contiguous storms. Environmental Science and Technology. 2014;**48**:13289-13297

[54] Lane SN, Odoni N, Landstrom C, Whatmore SJ, Ward N, Bradley S, Doing flood risk science differently: An experiment in radical scientific method. Transactions of the Institute of British Geographers. 2011;**NS 36**:15-36

[55] Wilkinson ME, Quinn PF, Welton P, Runoff management during the September 2008 floods in the Belford catchment, Northumberland. Journal of Flood Risk Management. 2010;**3**(4):285-295

[56] Quinn P, O'Donnell G, Nicholson A, Wilkinson M, Owen G, Jonczyk J, Barber N, Hardwick M, Davies G. Potential use of Runoff Attenuation Features in small rural catchments for flood mitigation. England: Newcastle University, Environment Agency, Royal Haskoning DHV; 2013

[57] Odoni NA, Lane SN. Assessment of the impact of upstream land management measures on flood flows in Pickering using OVERFLOW. Contract report to Forest Research for the Slowing the Flow at Pickering Project. Durham: Durham University; 2010

[58] Moors for the Future Partnership. Peak District Moorland Gully Blocking in Deep Peat. Moors for the Future Research Note No 2; 2005

[59] Thomas H, Nisbet TR. An assessment of the impact of floodplain woodland on flood flows. Water and Environment Journal. June 2007; **21**(2): 114-126

[60] Nisbet TR, Thomas H. Restoring floodplain woodland for flood alleviation. Final report for the Department of environment, food and rural affairs (Defra), Project SLD2316. Defra, London; 2008

[61] Broadmeadow S, Thomas H, Nisbet T. Opportunity mapping for woodland creation to reduce diffuse pollution and flood risk for England and Wales. Forest Research. 2014

[62] Packman JC, Quinn PF, Hollis J, O'Connell PE. Review of impacts of rural land use and management on flood generation short-term improvement to the FEH rainfall-runoff model: Technical background. R&D Project Record FD2114/PR3; 2004

[63] Palmer RC, Smith RP. Soil structural degradation in SW England and its impact on surface-water runoff generation. Soil Use and Management. 2013;**29**(4)567-575 DOI: 10.1111/sum.12068

[64] Hunter et al. Benchmarking 2d hydraulic models for urban flooding. Proceedings of the Institute of Civil Engineers, Water Management. 2008;**161**(1): 13-30 (WM1)

[65] Hankin B, Waller S, Astle G, Kellagher R. Mapping space for water: Screening for urban flash flooding. Journal of Flood Risk Management. 2008;**1**(1):13-22

[66] Kjeldsen TR, Stewart EJ, Packman JC, Folwell S, Bayliss AC. Revitalisation of the FSR/FEH Rainfall-Runoff Method. Defra R&D Technical Report FD1913/TR; 2005

[67] Environment Agency. What is the updated Flood Map for Surface Water? 2013. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/297432/LIT_8988_0bf634.pdf

[68] Penning-Rowsell E, Priest S, Parker D, Morris Tunstall S, Viavattene C, Chatterton J, Owen D. Handbook for Economic Appraisal (Multi-Coloured-Handbook). Flood and Coastal Erosion Risk Management. 2013

[69] Beven K. TOPMODEL: A critique. Hydrological Processes. 1997;**11**(9):1069-1085

[70] Beven KJ. Rainfall Runoff Modelling—The Primer. John Wiley & Sons; Chichester. 2003. ISBN 0-470-86671-3

[71] Davies J, Beven K, Rodhe A, Nyberg L, Bishop K. Integrated modeling of flow and residence times at the catchment scale with multiple interacting pathways. Water Resources Research. 2013;**49**(8):4738-4750

[72] Metcalfe P, Beven K, Freer J. Dynatopmodel: Implementation of the Dynamic TOPMODEL Hydrological Model. R package version 1.1. 2016. https://CRAN.R-project.org/package=dynatopmodel

[73] Buytaert W, Beven K. Regionalization as a learning process. Water Resources Research. 2009;**45** ISSN: 0043-1397. doi:10.1029/2008WR007359.

[74] Calder IR, Reid I, Nisbet TR, Green JC. Impact of lowland forests in England on water resources: Application of the Hydrological Land Use Change (HYLUC) model. Water Resources Research. 2003;**39**:1319

[75] Beven KJ. A manifesto for the equifinality thesis. Journal of Hydrology. 2006;**320**(1-2):18-36

[76] Beven K, Binley A. The future of distributed models: model calibration and uncertainty prediction. Hydrological Processes. 1992;**6**(3):279-298

[77] Beven K, Binley A. GLUE: 20 years on. Hydrological Processes. 2014;**28**(24):5897-5918

[78] Blazkova S, Beven KJ. A limits of acceptability approach to model evaluation and uncertainty estimation in flood frequency estimation by continuous simulation: Skalka catchment, Czech Republic. Water Resources Research. 2009;**45**;W00B16

[79] Hall JW, Dawson RJ, Sayers P, Rosu C, Chatterton J, Deakin R. A methodology for national-scale flood risk assessment. Proceedings of the Institution of Civil Engineers—Water & Maritime Engineering. 2003;**156**(3): 235-247

[80] Hankin B, Burgess-Gamble L, Bentley S, Rose S. How to model and map catchment processes when flood risk management planning. Science Report SC120015/R1. Bristol: Environment Agency; 2016. Available at https://www.gov.uk/government/publications/how-to-model-and-map-catchment-processes-when-flood-risk-management.pdf

[81] Carroll, Z.L., Bird, S.B., Emmett, B.A., Reynolds, B., Sinclair, F.L. Can tree shelterbelts on agricultural land reduce flood risk? September 2004; **20**(3): 357-359

[82] Herbst, M., Roberts, J.M., Rosier, P.T.W and Gowing, D.J. 2006. Measuring and modelling the rainfall interception loss by hedgerows in southern England. Agric. For. Meteorol. 141: 244-256.

[83] Noirfalise, A. 1959. Sur l'interception de la pluie par le couvert dans quelques forêts belges. Bulletin de la Soc. Roy. Forest de Belgique 10: 433-9.

[84] Leyton, L., Reynolds, E.R.C. and Thompson, F.B. 1967). Rainfall interception in forest and moorland: In: Forest Hydrology, eds . Sopper, W.E. and Lull, H.W., Pergamon, New York, 163-178.

[85] Aussenac, G. 1968. Interception des préc ipitation par le couvert forestier. Annales des Sciences Forestieres 25: 135-156.

[86] White, E.J. and Carlisle, A. 1967. The interception of rainfall by mixed deciduous woodland. Quarterly Journal of Forestry 62: 310-20.

[87] Thompson, F.B. 1972. Rainfall intercept ion by oak coppice (Quercus robur L .). In: Research Papers in Forest Meteorology. Ed . J .A . Taylor, Aberystwyth. 59-74.

[88] Dolman, A.J. 1987. Summer and winter rainfall interception in an oak forest: Predictions with an analytical and a numerical simulation model. Journal of Hydrology 90: 1-9.

[89] Schnock, G. 1969. Le bilan de l'eau dans l'écosystème forêt. Application à une chênaie mélangée de haute Belgique. In: Productivity of forest ecosystems. Ed. P. Duvigneaiid. Proceedings of the Brussels syinposium organised by Unesco und the International Biological Programme, 27-31 October 1969. 41-47.

[90] Staelens, J., De Schrijver, A., Verheyen, K. and Verhoest, N.E.C. 2008. Rainfall partitioning into throughfall, stemflow, and interception within a single beech (Fagus sylvatica L.) canopy: influence of foliation, rain event characteristics, and meteorology. Hydrol. Process. 22: 33-45.

[91] Carlisle, A., Brown, A.H.F. and White, E.J. 1965. The interception of precipitation by oak (Quercus petraea) on a high rainfall site. Quarterly Journal of Forestry 592: 140-143.

[92] Gerrits, M. 2010. The role of interception in the hydrological cycle PhD thesis, Technische Universiteit Delft.

[93] Mawdsley, T., Chappell, N.A. and Swallow, E. 2016. Report on the saturated hydraulic conductivity dataset, Tebay Common, Cumbria. Lancaster University.

[94] Marshall, M.R., Francis, O.J., Frogbrook, Z.L., Jackson, B.M., Mcintyre, N., Medeiros, S., Hagen, S. and Weishampel, J. 2012. Comparison of floodplain surface roughness parameters derived from land cover data and field measurements. J Hydrol 452-453: 139-149.

IntechOpen

IntechOpen

IntechOpen