Dadson, S., Hall, J. W., Murgatroyd, A., Acreman, M., Bates, P., Beven, K., ... Wilby, R. (2017). A restatement of the natural science evidence concerning catchment-based "natural" flood management in the United Kingdom. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences.

Peer reviewed version

A restatement of the natural science evidence concerning catchment-based "natural" flood management in the United Kingdom

Simon J. Dadson[1], Jim W. Hall[1], Anna Murgatroyd[1], Mike Acreman[2], Paul Bates[3], Keith Beven[4], Louise Heathwaite[4], Joseph Holden[5], Ian Holman[6], Stuart N. Lane[7], Enda O'Connell[8], Edmund Penning-Rowsell[1], Nick Reynard[2], David Sear[9], Colin Thorne[10], and Rob Wilby[11]

[1] School of Geography and the Environment, University of Oxford, South Parks Road, Oxford OX1 3QY, UK.

[2] Centre for Ecology & Hydrology, Crowmarsh Gifford, Wallingford, OX10 8BB, UK.

[3] School of Geographical Sciences, University of Bristol, Bristol, BS8 1SS, UK.

[4] Lancaster Environment Centre, Lancaster University, Lancaster, LA1 4YQ, UK.

[5] School of Geography, University of Leeds, Leeds, LS2 9JT, UK.

[6] Cranfield Water Science Institute, Cranfield University, Cranfield, MK43 0AL, UK.

[7] Faculté des géosciences et de l'environnement, Université de Lausanne, Lausanne, CH-1015, Switzerland.

[8] School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne, UK.

[9] Geography and Environment, University of Southampton, Southampton, UK.

[10] School of Geography, University of Nottingham, Nottingham, NG7 2RD, UK.

[11] Department of Geography, Loughborough University, Leicestershire, UK.

ABSTRACT

Flooding is a very costly natural hazard in Great Britain and is expected to increase further under future climate change scenarios. Flood defences are commonly deployed to protect communities and property from flooding, but in recent years flood management policy has looked towards solutions that seek to mitigate flood risk at flood-prone sites through targeted interventions throughout the catchment, sometimes using techniques which involve working with natural processes. This paper describes a project to provide a succinct summary of the natural science evidence base concerning the effectiveness of catchment-based “natural” flood management in the United Kingdom. The evidence summary is designed to be read by an informed but not technically-specialist audience. Each evidence statement is placed into one of four categories describing the nature of the underlying information. The evidence summary forms the appendix to this paper and an annotated bibliography is provided in the electronic supplementary material.

1. Introduction

Flooding is amongst the most damaging natural hazards globally, with inundation leading to disastrous consequences including the loss of lives and destruction of property. Flooding may be fluvial, pluvial, coastal, or groundwater related, or caused by a combination of these processes. Here we focus on fluvial (river) floods, which occur when the amount of water in a river exceeds the channel’s capacity. They are caused primarily by the downstream flow of runoff generated by heavy rainfall on wet ground.

Flooding is a natural process, but floodplains are also ideal for agriculture and urban development close to water resources and navigation. Consequently, development in floodplains has increased the exposure of people, property and infrastructure to floods. In many cases it is not practical, cost effective, or politically feasible to relocate communities, property, and economic activities away from areas prone to flooding, so measures are put in place to manage flood risk by reducing the probability of inundation and/or the negative consequences when a flood does occur.

In this restatement, we concentrate on the scientific evidence concerning the effectiveness of human interventions in river catchments that are intended to reduce fluvial flood hazard[1]. This hazard is typically associated with high river flows. The hazard is characterized by the depth of water at locations where it may cause harm, and also by the velocity of that water, the rate of rise of water levels, duration of inundation, and water quality. Interventions in river channels and floodplains that have been widely used to manage flood risk include the building of flood detention reservoirs and flood defences, channel straightening, and dredging.

Recent years have seen increasing interest in management interventions that seek to modify upland land use and land management, river channels, floodplains, and large upland reservoirs (where present), in order to reduce the frequency and severity of flooding, which we refer to here as “Catchment-Based Flood Management” (CBFM). One subset of CBFM is “Natural Flood Management” (NFM), which seeks to restore or enhance catchment processes that have been affected by human intervention. These activities aim to reduce flood hazard, while also sustaining or enhancing other potentially significant co-benefits including enhanced ecosystem services (aquatic, riparian, and terrestrial) such as: greater biodiversity, improved soil and water quality, carbon sequestration, reduced soil erosion, greater agricultural productivity, and improved public health and well-being.

While it is recognized that implementation of CBFM or NFM can produce multiple co-benefits, it is not easy to establish the precise nature and extent of those benefits. Often a complex set of trade-offs exists between costs and benefits that accrue to different stakeholder groups within and outside the catchment. Also, while the benefits are well understood in principle, uncertainty around the quantitative predictions of the potential for CBFM/NFM interventions to reduce local and downstream flood hazards remains high, especially in large catchments and for major floods. Differences between river catchments make it difficult to transfer empirical evidence from one location to another. The relative importance of the multiple factors that influence flooding varies spatially and with time, which means that even if an intervention may be beneficial locally, a positive impact on flooding downstream cannot be guaranteed for all possible events in all locations.

---

[1] It is conventional to distinguish between the three components that constitute flood risk to people and economies: *hazard* is the phenomenon with potential to cause harm (i.e., unusually high water levels); *exposure* describes the people or assets in harm’s way; and *vulnerability* is the susceptibility of people and property to loss when exposed to a hazard.

The aim of this restatement is to review the scientific evidence for the impacts of CBFM and NFM strategies on downstream flood hazard in the UK. Here we focus on the natural science evidence base; the social sciences and economics also provide important evidence for policy making but this is not considered here. The objective is to review processes that impact flood frequency[2] and hazard, principally with respect to flood volumes and flood levels but also velocity, duration and water depth. These include modifications to land cover and land management to retain water on and under the land before it flows into rivers, and modifications to and protection of channels and rivers to slow the flow of water and reduce water levels in floodplains downstream where there is a flood hazard (see Table 1).

---

[2] Flood frequency is a measure of likelihood, which in this restatement we measure using Annual Exceedence Probability (AEP). The AEP is the chance of a flood of this magnitude or greater occurring in any particular year

Table 1 Catchment-based measures that could contribute to flood management (after Beedell et al., 2011)

FRM Theme	Specific Measure	Examples
Retaining water in the landscape: water retention through management of infiltration and overland flow	Land-use changes	Arable to grassland conversion, forestry and woodland planting, restrictions on hillslope cropping (e.g., silage maize); moorland and peatland restoration
	Arable land-use practices	Spring cropping vs. winter cropping; cover crops; extensification; set aside
	Livestock land practices	Lower stocking rates, restriction of the grazing season
	Tillage practices	Conservation tillage, contour/cross slope ploughing
	Field drainage (to increase storage)	Deep cultivations and drainage to reduce impermeability
	Buffer strips and buffer zones	Contour grass strips, hedges, shelter belts, bunds, riparian buffer strips, controls on bank erosion
	Machinery management	Low ground pressures, avoiding wet conditions
	Urban land use	Increased permeable areas and surface storage
Retaining water in the landscape: managing connectivity and conveyance	Management of hillslope connectivity	Blockage of farm ditches and moorland grips
	Buffer strips and buffering zones to reduce connectivity	Contour grass strips, hedges, shelter belts, bunds, field margins, riparian buffer strips
	Channel maintenance	Modifications to maintenance of farm ditches
	Drainage and pumping operations	Modifications to drainage and pumping regimes
	Field and farm structures	Modifications to gates, yards, tracks and culverts
	On-farm retention	Retention ponds and ditches
	River restoration	Restoration of river profile and cross sections; channel realignment and changes to planform pattern
	Upland water retention	Farm ponds, ditches, wetlands
Making space for water: floodplain conveyance and storage	Water storage areas	On- or off-line storage, washlands, polders, impoundment reservoirs
	Wetlands	Wetland creation, engineered storage scrapes, controlled water levels
	River restoration / retraining	River re-profiling, channel works, riparian works
	River and water course management	Vegetation clearance, channel maintenance and riparian works
	Floodplain restoration	Setback of embankments, reconnecting rivers and floodplains

2. Materials and methods

The restatement is intended to provide a succinct summary of the natural science evidence relevant to policy-making in the UK as of June 2016. The restatement offers a consensus judgement on the strength of the different evidence components using the abbreviated codes established in previous Oxford Martin School restatements:

[D_{ata}] a strong evidence base involving experimental studies or field data collection, with appropriate detailed statistical or other quantitative analysis;

[E_{xp_op}] a consensus of expert opinion extrapolating results from relevant studies and well-established principles;

[S_{upp_ev}] some supporting evidence but further work would improve the evidence base substantially; and

[P_{rojns}] projections made using well-established models that are based on the available physical principles and/or robust empirical evidence gathered in a wide range of settings.

The categories employed are based on those used in previous restatements (Godfray et al., 2013, Godfray et al., 2014), which were themselves developed from the medical and climate change literature. The statements are qualitative in nature and are not intended to form a ranking. We note that, in many cases, evidence is context- or scale-specific. Moreover, interventions that may be effective in one location and at one scale may have a different effect in another setting. Where further gradation is necessary to reflect the quality of evidence, this is done in the accompanying text.

We note in particular the wide range of models used in hydrological science. Some models are based on well-established physical principles such as conservation of mass, energy, and momentum, which are fundamental properties of physical systems but which nonetheless require generalisations about parameter values or model equations in order to be applied. Other models represent generalizations from necessarily limited sets of observations whose conclusions cannot be expected to hold in settings different from those in which they were generated.

3. Results

The summary of the natural science evidence base relevant to catchment-based “natural” flood management in the United Kingdom is given in the appendix, with an annotated bibliography provided as the electronic supplementary material.

4. Discussion

In this restatement we have drawn attention to some important evidence gaps. We highlight several immediate priorities:

1. National monitoring networks provide essential data for estimating flood risk and determining the efficacy of interventions. Maintenance and enhancement of monitoring systems should pay particular attention to the accurate measurement of high water levels and out-of-bank flows. Significant uncertainty about the impacts of different types of intervention both when used individually and in combination arises in part because there has not been sufficient research to establish causal links between CBFM and NFM actions and downstream effects. Long-term monitoring is necessary because major floods are rare events; it is also necessary that prospective studies establish good experimental controls and collect accurate baseline data.
2. Recent model studies have begun to reproduce field measurements from relatively small monitored catchments. These models could now be used to simulate the impact of changes in land use and management practices in larger catchments. Model studies of large recently-flooded catchments (e.g., Yorkshire Ouse, Eden, Parrett, Thames) could help to establish the scale and spatial location of different types of catchment-based intervention that might be required to have a noticeable effect on flooding. It is important to investigate whether the models' findings can be extrapolated to regions larger than those for which they have been evaluated, given the constraints posed by their formulation and uncertainties in validation data, and to understand whether the benefits of CBFM/NFM measures are more, less, or equally predictable than the benefits of hard engineered assets.
3. The Environment Agency's Catchment Flood Management Plans (CFMPs) assess flood risks across a catchment and can include maintaining or restoring natural processes among the measures that might be taken in the course of flood risk management. Moreover, a large number of catchment-based schemes are currently under way, promoted by Rivers Trusts, Wildlife Trusts and flooded community groups, for example. Many of these local initiatives are neither being planned nor evaluated at larger spatial scales. The lack of monitored baselines and experimental controls creates a risk that the wider and scale-dependent impacts cannot be properly investigated or used to inform decision-making. Research and data available within the water management industry (e.g., Water Companies, Internal Drainage Boards, land and estate management organizations) would add to the evidence base if it were disseminated more widely.

4. The performance, longevity and operation and maintenance of CBFM/NFM should be systematically compared with traditional engineering solutions. The risks and uncertainties and benefits associated with each approach need to be more fully understood and communicated. The interactions between fluvial floods and other flood types (e.g., pluvial, coastal and groundwater) also warrant further systematic study. The potential for CBFM/NFM interventions in groundwater-dominated and heavily-engineered and drained river systems needs further research. The extent to which these interventions add resilience to the impacts of climate change is also worthy of further investigation.
5. A practitioner toolkit would help to share practical experience (whilst noting context-specific issues), paying attention to appropriate design criteria. A practitioner toolkit might comprise a set of documents outlining best practices and the situations in which their effectiveness has been demonstrated, drawing on well-studied examples. This could be accompanied by a protocol for coordinated, high quality, monitoring of the catchment, river corridor and hydro-meteorological conditions, drawing on modern sensor, communications, and information technologies.
6. There would be benefits from improved communication and collaboration between groups undertaking research in river catchments (e.g., water quality, sediment transport, river restoration, biodiversity, agriculture, forestry), which are all relevant to flood risk management. On the basis of current evidence, the cost-effectiveness of NFM at medium-large scales is likely to rely on understanding interactions between flows, debris, and sediment management taking into account the range of ecosystem service benefits that accompany NFM.

5. Acknowledgements

The project was funded by the Oxford Martin School (part of the University of Oxford), and though many groups were consulted, the project was conducted completely independently of any stakeholder. We thank Charles Godfray, Angela McLean, John Beddington, and Andrea Stephens. Thanks are also due to Ailsa Allen who drafted the figures. We are very grateful for insightful comment, criticism, and help from the following: Jonathan Baker, David Balmforth, John Boardman, Ella Adlen, Lydia Burgess-Gamble, Deanna Donovan, Heather Forbes, Fiona Harrison, Alan Jenkins, Daniel Johns, Rob Lamb, Catharina Landstrom, Paul Murby, Tom Nisbet, David Pirie, Mike Potter, Matthew Quinn, Martin Rogers, Paul Samuels, Paul Sayers, Innes Thompson, Howard Wheater, Doug Wilson and Simon Wightman. While these inputs have strongly influenced the final document, not all suggested changes have been included and the authors alone are responsible for the evidence summary. We thank two anonymous reviewers for their comments, which have substantially improved the article.

Appendix A. A restatement of the natural science evidence concerning catchment-based "natural" flood management in the United Kingdom.

(a) Introduction and aims

(1) [*Background*]

Flooding causes hundreds of millions of pounds of damage in the UK and climate change is projected to increase the frequency and intensity of heavy rainfall in the future. Flooding may be fluvial, pluvial[3], coastal, or groundwater related, or a combination of these. Here we focus on fluvial floods, which are primarily caused by the downstream flow of runoff generated by heavy rainfall on wet ground. Most investment to reduce flood risk goes into engineered systems like flood defences and channel modification. "Catchment-Based Flood Management" (CBFM) consists of interventions of any kind that seek to modify land use, land management, upstream river channels and floodplains, in order to reduce the frequency and severity of flooding. CBFM aims to alter flood risk by making changes within the wider catchment rather than managing flood hazard locally at the point where flooding occurs. One subset of CBFM is "Natural Flood Management" (NFM[4]) which seeks to restore catchment and river processes that have been adversely affected by human intervention. CBFM and NFM may help reduce the frequency and severity of flooding as well as delivering other environmental, social and economic benefits. However, because CBFM and NFM interventions often occur alongside other factors that influence flooding, including spatial and temporal variability in rainfall and runoff, assessing the effectiveness of these interventions is challenging.

(2) [*Principles*]

The magnitude of fluvial flooding depends upon: (i) the rate of runoff from hillslopes into river channels, (ii) the rate of propagation of the runoff downstream in river channels and (iii) how runoff contributions from multiple hillslopes and sub-catchments combine via the channel network to generate the downstream flood hydrograph. In small catchments[5], the peak of the flood hydrograph is dominated by runoff from hillslopes in response to storm

---

[3] Pluvial flooding is caused by excess surface water during locally-intense rainfall.

[4] The terms Working with Natural Processes (WwNP), Nature Based Solutions (NBS), and Building with Nature (BwN) are often used synonymously with NFM.

[5] We assess interventions at the plot scale (~ 100 m^2), hillslope scale (~ 0.1 km^2), small catchment scale (< 20 km^2), medium catchment scale (20–100 km^2) or large catchment scale (> 100 km^2).

rainfall. In larger catchments, the river channel network determines which areas of the catchment contribute to the peak of the flood hydrograph to cause flooding [D_{ata}]. The impact of NFM/CBFM measures on flooding therefore depends on their location within the catchment, the size of the catchment and the connectivity of the channel network [P_{rojns}]. Simple extrapolation of small-scale changes to larger catchment areas is therefore not possible, and the effects of NFM/CBFM must be assessed within the context of the whole catchment [E_{xp_op}]. Relatively few studies adopt such a catchment-scale framework; some of those that do are summarized in Section (20) [E_{xp_op}].

(3) [*Evidence*]

Many individual studies have investigated the direct effect on runoff and river flow of variations in natural land cover, human-modified land use, and specific details of land and river channel management practices. Several integrated studies have investigated the potential effect of CBFM and NFM on flooding. Together, these strands of research have generated a large amount of important, policy-relevant information. However, because each flood is a consequence of a unique combination of conditions, evidence needs to be interpreted with care. Here, we summarize the evidence base relevant to policy-making in the areas of CBFM and NFM, in the United Kingdom, as of June 2016. We look principally at evidence from the United Kingdom, but make reference to studies undertaken overseas where appropriate. We focus mainly on peer-reviewed academic studies, although we have indicated the existence of practitioner-led evidence databases and catalogues where relevant.

(4) [*Aim*]

We provide a consensus judgement on the nature of the different evidence components using the abbreviated codes, which are based on those used in previous Oxford Martin School Restatements:

[D_{ata}] a strong evidence base involving experimental studies or field data collection, with appropriate detailed statistical or other quantitative analysis;

[E_{xp_op}] a consensus of expert opinion extrapolating results from relevant studies and well-established principles;

[S_{upp_ev}] some supporting evidence but further work would improve the evidence base substantially; and

[P$_{\text{rojns}}$] projections made using well-established models that are based on the available physical principles and/or robust empirical evidence gathered in a wide range of settings.

(b) Meteorological drivers of flooding

(5) [*Meteorological data and trends*]

The UK benefits from a meteorological observation network that is dense by global standards. Annual precipitation totals vary considerably from year to year, but there has been no detectable long-term change in spatially-averaged annual precipitation totals since the 18th Century [D$_{\text{ata}}$]. Over this time period the UK has, however, experienced a statistically-significant increase in winter precipitation, and a reduction in summer precipitation (see Figure 1a) [D$_{\text{ata}}$]. Winter precipitation in uplands has increased more than in lowlands [D$_{\text{ata}}$].

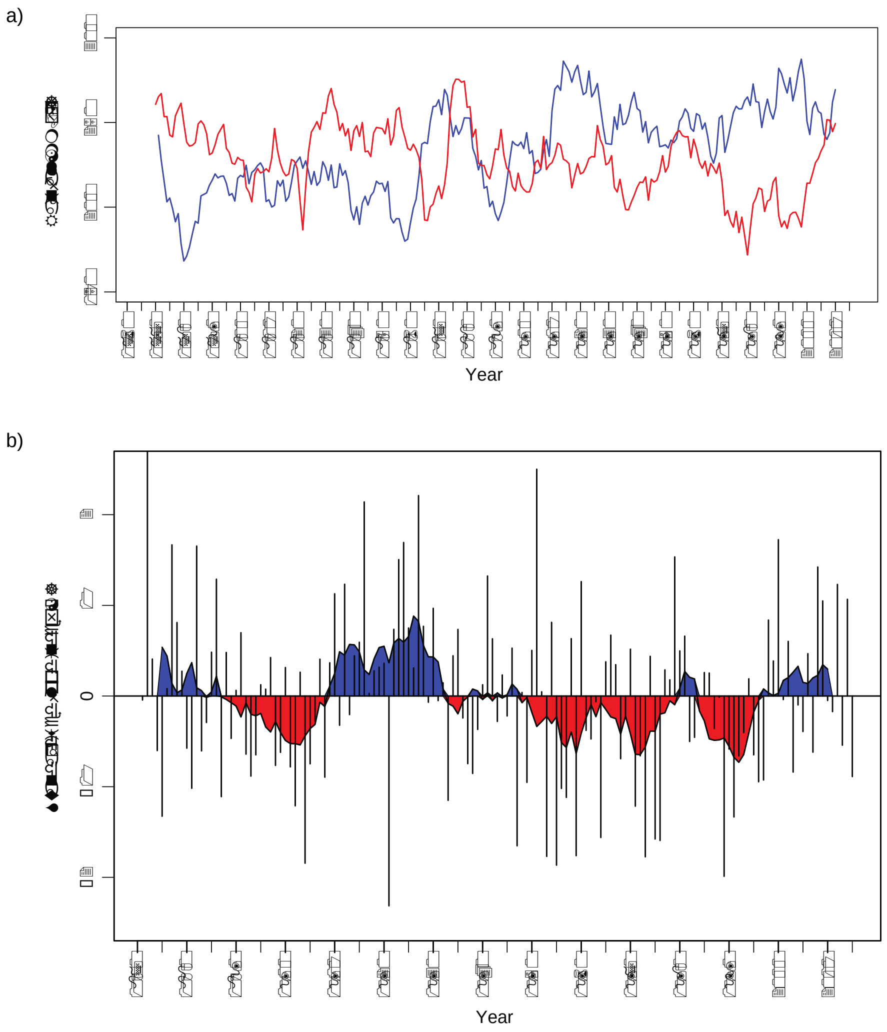

Figure 1 Climate variability and flooding. (a) England and Wales precipitation seasonality (1776-2015); the blue line shows winter (DJF) precipitation; the red line

indicates summer (JJA) precipitation. Data: Alexander and Jones (2001); http://www.metoffice.gov.uk/hadobs/hadukp/. (B) Annual mean flood index (1871-2015). The blue and red shading shows flood-rich and flood-poor periods respectively Data: Wilby and Quinn (2013); https://crudata.uea.ac.uk/cru/data/lwt/.

(6) [*River flow variability and trends*]

Extensive catchment and river channel modifications including impoundments, diversions, and water withdrawals have modified river flow, making climate-driven trends, if present, difficult to detect. The challenge is exacerbated by changes in measurement techniques and instrument locations. ‘Benchmark’ river basins that have not experienced widespread channel modification, abstraction or urbanization during the period of record show a pattern of increased winter extremes between the 1960s and the early-2000s in the north and west of the UK, but this trend is not present in their south-eastern counterparts [D$_{ata}$].

(7) [*Flood magnitude and frequency*]

Increases in flood frequency do not always imply increases in flood magnitude [D$_{ata}$]. The longest UK river flow datasets show that flood magnitudes observed since 1960 are not unusual compared with earlier observations. The Thames, which has the longest gauged record in the UK, shows no significant long-term trend in flood magnitude since 1883 [D$_{ata}$]. Similar results hold for the Wye and Scottish Dee, back to the 1930s [D$_{ata}$].

(8) [*Flood rich and flood poor periods*]

Climate variability results in clusters of flood-rich (e.g., 1908–1934, and 1998–present) and flood-poor periods (e.g., 1950–1980; see Figure 1b) [D$_{ata}$]. Flood-rich episodes are associated with westerly airflows and cyclonic conditions across the UK [D$_{ata}$]. The flood-rich period starting in the late-1990s has been attributed to warmer conditions in the North Atlantic Ocean [S$_{upp\_ev}$]. Sedimentary deposits laid down after torrential flood flows in small catchments provide evidence for a similarly flood-rich period between 1840 and 1890; in the 17th–19th centuries floods were both more frequent and more severe than those experienced since 1998 [D$_{ata}$].

(9) [*Climate change projections*]

Projections from the latest global and regional climate models do not suggest a systematic change in annual rainfall totals in the UK between now and 2080 (80% of the simulations show between a 16% reduction and a 14% increase) [P$_{rojns}$]. The models suggest some change in the spatial distribution of rainfall, with a projected increase in winter rainfall on the west coast of between +9% and +70%, and reduction in summer precipitation in southern England of -65% to -6% by 2080 [P$_{rojns}$]. Higher rainfall maxima are expected, and storms are expected to occur more often, especially in the summer [P$_{rojns}$]. Winter upland rainfall totals may also increase [P$_{rojns}$]. Under warmer conditions, winter precipitation is more likely to be in the form of rain rather than snow [P$_{rojns}$].

(c) The effects of land cover and land management on flooding

(10) [*Historical changes in land cover*]

Land cover has changed radically in the UK due to human influence, with forest covering much of the UK in prehistoric times and declining to a minimum of 6% in 1930 and then increasing to 12% currently (2007 figures) [D$_{ata}$]. There have been major changes to agricultural practices, upland management, and to the extent and type of urbanization [D$_{ata}$].

(11) [*The influence of land cover on flooding*]

At small spatial scales (< 20 km^2) the effect of land cover and land management on flood flows is evident in some studies, but not for the most extreme floods [S$_{upp\_ev}$]. Measured data for land use impacts in larger catchments (> 100 km^2) are lacking [S$_{upp\_ev}$]. The Flood Studies Report and Flood Estimation Handbook concluded (from studies of 553 and 943 catchments respectively) that urban extent was the only land cover factor that was significantly related to the magnitude of the mean annual flood in UK rivers [D$_{ata}$]. Numerical modelling suggests that the effect of land cover changes on river flows in the Thames catchment is small compared with natural climatic variability [P$_{rojns}$].

(12) [*Effects of forest cover*]

The impacts of upland conifer forestry on water availability and runoff have been the subject of several experimental studies in the UK. One of the longest-running investigations was based in two UK experimental catchments at Plynlimon (10.6 km^2 and 8.7 km^2) in mid-Wales where:

(a) Mature forest produced higher evaporative losses than grassland under equivalent conditions, owing to the greater amount of water intercepted within the tree canopy [D$_{ata}$].

(b) For smaller storms (less than 20% of the mean annual flood), flow peaks per unit area were smaller in the forested catchment than under grassland although it is noted that these storms do not usually pose a significant flood hazard [D$_{ata}$].

(c) By contrast, during high flood flows no significant difference was found between flood peaks (per unit area) in the two Plynlimon catchments [D$_{\text{ata}}$].

Limited suppression of flood peaks in the forested catchment was attributed to the relatively small amount of canopy storage and generally drier soils beneath forest stands compared with grassland [E$_{\text{xp\_op}}$]. Under sustained winter rainfall, soil saturation will occur and little mitigation of high flood flows would be expected [E$_{\text{xp\_op}}$].

(13) [*Timber planting and harvesting; forestry operations*]

Planting forests and harvesting timber can have long-lasting effects on runoff, stream flow and flood risk due to soil compaction by machinery, construction and use of forest roads, artificial drainage, and by increasing soil loss. The magnitude of these effects depends critically on management practices [D$_{\text{ata}}$].

(a) Evidence from Europe and North America shows timber harvesting can exacerbate peak flows and lead to flooding [D$_{\text{ata}}$]. UK studies (e.g., Plynlimon) show augmented low flows but not increased peak flows [D$_{\text{ata}}$]; the difference with international studies is attributed to good forestry practice [E$_{\text{xp\_op}}$].

(b) In two small highland catchments in Scotland, approximately 30 km northeast of Stirling at Balquhidder (6.85 and 7.70 km^2), clear-felling of 50% of the catchment is estimated (with the aid of a model) to have led to a small increase in total flow of approximately 3%. The calculated difference is likely to be within the range of model calibration uncertainty [P$_{\text{rojns}}$].

(c) Establishment of conifer plantations in the 1.5 km^2 Coalburn catchment in the Kielder Forest (NW England) on previously rough grazing land increased the rate of runoff after storms for 20 years [D$_{\text{ata}}$], likely due to improvements to drainage prior to planting [E$_{\text{xp\_op}}$]. Once the plantation forest in this location reached maturity, a 200–300 mm decrease in annual runoff was observed, compared with that prior to afforestation [D$_{\text{ata}}$].

(d) Simulated peak flows are higher at Coalburn when small trees are present compared with taller trees, but the bigger the flood the smaller is the difference [P$_{\text{rojns}}$].

(14) [*Impact of agricultural practices*]

Changing agricultural practices over the last century have led to: (i) removal of hedgerows to create larger fields; (ii) soil compaction; (iii) land drains; (iv) increased flow through cracks and sub-surface drains (macropore flow); (v) concentrated overland flow in ditches, tracks, and wheel tracks; (vi) narrowing or removal of non-agricultural riparian corridors and buffer strips; and (vii) changes in crop type and switches from spring-sown to autumn-sown arable crops. Grassland management practices, including intensive grazing, have led to soil structural degradation in local cases and these changes have been shown to increase runoff production [$\mathrm{D_{ata}}$]. Localised increases in flooding at the plot and hillslope scale have been attributed to changes in land cover, crop type (including the expansion of crops such as maize) and intensification of farming [$\mathrm{D_{ata}}$].

(15) [*Impact of land drainage*]

Drainage to control water levels has complex effects on runoff, which depend on the type of drainage used.

(a) At the plot scale, drainage reduces peak flows from impermeable (e.g., clay) soils, but increases those from more permeable soils [$\mathrm{D_{ata}}$].
(b) By drying soils, drainage increases their capacity to store water after a rainfall event, but when the soils become saturated drainage increases flows [$\mathrm{D_{ata}}$].
(c) At the plot scale, higher flow peaks result from open ditches compared with subsurface drains. Higher peaks arise from the use of a ‘mole plough’ to create sub-surface channels in impermeable soils (‘mole’ drainage) in combination with other forms of subsurface drainage [$\mathrm{D_{ata}}$].
(d) Extension of drainage networks up hillsides increases the speed with which runoff is transported to rivers [$\mathrm{D_{ata}}$].

(16) [*Soil compaction*]

Both arable and livestock agriculture practices can cause surface and sub-surface soil compaction, and at local scales this has been demonstrated to increase surface runoff [$\mathrm{D_{ata}}$]. Effects at catchment scale have not been identified, though there have been few relevant studies [$\mathrm{E_{xp\_op}}$].

(a) Soil compaction due to higher livestock density increased the flood peak after a storm in NW England by 7%, according to a model simulation in the 36 km^2 Scandal Beck tributary of the River Eden in north-west England [$\mathrm{P_{rojns}}$].
(b) A recent survey in south-west England has shown that 75% of survey plots that had been planted with late-harvested crops (e.g., maize or potatoes) suffered severe degradation of soil structure due to soil compaction, generating additional surface runoff and surface water pollution, and reducing aquifer recharge [$\mathrm{D_{ata}}$].

(c) In a plot-scale experiment at Pontbren in mid-Wales, tree-planted plots produced between 48% and 78% less runoff than the grazed control plots, although there was a high degree of variability between sites [$\mathrm{D_{ata}}$]. Five years on, soil infiltration rates were 67 times higher in tree-planted plots compared with grazed pasture, and the effect of tree planting was separate from the effect of excluding sheep [$\mathrm{D_{ata}}$].

(17) [*Upland and peatland impacts*]

Upland areas often receive heavy rainfall. Management practices affect peak water flows downstream [$\mathrm{D_{ata}}$]. Most evidence demonstrating flood response to upland interventions is at the small catchment scale (< 20 km^2) rather than at the large catchment scale (> 100 km^2).

(a) Higher flood peaks and shorter times to reach peak flow are associated with peatland degradation and removal of vegetation cover [$\mathrm{D_{ata}}$].

(b) Locating dense ground cover such as *Sphagnum* moss along more gentle gradient slopes and near watercourses has the greatest impact on flood peak reduction (or the converse for bare ground) when compared to having the same proportion of dense surface cover elsewhere in the catchment [$\mathrm{P_{rojns}}$].

(c) A study of the effects of heather burning to encourage grouse found mixed effects: slower runoff after moderate rainfall (owing to deeper water tables) but faster runoff for the highest 20% of events (owing to faster flow over sparsely-vegetated, saturated ground) [$\mathrm{S_{upp\_ev}}$].

(18) [*Upland ditch blocking*]

Upland ditches may increase or decrease flood peaks at the local scale depending on the layout of the drains, topography and flood peak synchronization in the main channel [$\mathrm{P_{rojns}}$]. Upland ditch blocking (i.e., using sequences of dams along each ditch) has been common over the last 15 years in the UK, mainly to benefit biodiversity or water quality or both.

(a) Ditch blocking in upland peat is effective in reducing flow peaks only in the steepest, smoothest drains; surface roughness of the surrounding vegetated peat may be more important than the presence or absence of ditches [$\mathrm{P_{rojns}}$].

(b) A five-year monitoring study in the Peak District showed that the effects of drains depended on their configuration, and on the velocity differential between overland flow and flow in the drains themselves [$\mathrm{D_{ata}}$]. Modelling studies have suggested that ditch blocking can sometimes reduce peak flows, though to a degree dependent on the details of topography and how ditches are blocked [$\mathrm{P_{rojns}}$].

(19) [*Impacts of urbanization and Sustainable Drainage Systems (SuDS)*]

Urbanization tends to increase peak flood flows because of reduced infiltration under paved areas and rapid flow over the surface, along channelized streams, and through culverts and pipes [Data]. Urban flooding is generally greatest from intense convective storms in summer [Data].

(a) Engineering interventions, including permeable paving, stormwater retention and storage basins and Sustainable Drainage Systems (SuDS), can avoid, mitigate or even reverse the adverse effects of urbanization on surface runoff [Data];

(b) Restoration of urban watercourses and their vegetated riparian corridors, plus reconnection of their floodplains can be used to convey or store urban runoff while encouraging infiltration and improving water quality [Data].

(20) [*Catchment-scale effects of land management practices*]

Understanding how local changes in land cover and land management affect water flows and flood risk downstream in large catchments is a major research challenge, which has been addressed by several large projects including the Catchment Hydrology and Sustainable Management Programme (CHASM), Flood Risk Management Research Consortium (FRMRC), and Flood Risk from Extreme Events (FREE) research programmes. Nonetheless, the hydrological responses to land-use change tend to be context-specific and translating results between one context and another is difficult.

(a) Under the United Utilities' Sustainable Catchment Management Plan (SCaMP) project, changes to upland land-use management have been carried out in the 260 km^2 Hodder catchment (a tributary of the River Ribble, north-west England) primarily to reduce suspended sediment and colouration in water used for public supply. The changes, which covered 25 km^2 within a 58 km^2 sub-catchment, included moorland ditch blocking in areas of blanket peat, tree planting, and reduction in livestock stocking density. The possible consequences of these changes for downstream flooding were evaluated at multiple scales, to test whether small-scale impacts propagate through the river network. SCaMP changes had minimal short-term effects on the pattern of flood flows [Data]. No effects were found at the larger scale of the entire Hodder catchment (260 km^2) during the period of study [Data]. This finding was corroborated by a modelling study that showed that the median reduction in the flood peak associated with an extreme rainfall event produced by a realistic suite of land-use management changes was only 2%, assuming that channel conveyance did not change, but with an uncertainty range of a 1% increase to a 6% decrease [P$_{\text{rojns}}$].

(b) Results from the Pontbren multi-scale experiment illustrate the potential use of tree shelterbelts to reduce plot-scale runoff [E$_{\text{xp\_op}}$]. Plot-scale monitoring took place on 12×12 m plots at four sites in a 12 km^2 catchment in the headwaters of the Upper Severn in mid-Wales (see Section (16)). Field-scale monitoring and modelling included looking at the impacts of tree shelterbelts. Small catchment-scale monitoring looked at how land-use impacts flows and sediments (see Section (22)).

   i. A field-scale modelling study suggested that planting tree shelterbelts near the bottom of all improved grassland fields in a 6 km^2 sub-catchment might reduce peak flows by 13–48% for the largest storm seen in the study period (peak rainfall intensity 54 mm hr^{-1}), with a 15 minute reduction in time-to-peak [P$_{\text{rojns}}$].

   ii. For a hypothetical extreme storm with rainfall of 140 mm over two days (estimated 0.6% Annual Exceedance Probability; AEP[6]) the simulated reduction in peak flows was 2–11% and there was no reduction in time-to-peak [P$_{\text{rojns}}$].

   iii. The authors note the high levels of uncertainty associated with their model predictions and leave open the question of whether reductions in flood peaks would be possible at spatial scales larger than 6 km^2 [E$_{\text{xp\_op}}$].

(c) In the River Axe catchment (288.5 km^2) in south-west England, an assessment of the observable historical effects of land-use change on basin-scale runoff showed they are limited to high flows that arise from moderate rainfalls (10–30 mm day^{-1}) after a period of dry weather [D$_{\text{ata}}$]. For flows of this magnitude (which usually remain within the river's channel) the results suggest that farming practices that minimize soil degradation and compaction may produce a reduction in river flows in this catchment [S$_{\text{upp\_ev}}$]. The authors note, however, that in nine other catchments no significant changes could be identified, owing to natural variability and data limitations [D$_{\text{ata}}$].

---

[6] AEP, Annual Exceedence Probability, the chance of a flood of this magnitude or greater occurring in any particular year.

(21) [*Summary*]

Summary There is clear evidence that appropriately chosen land-use and land-cover interventions can reduce local peak water flows after moderate rainfall events [$\mathrm{D}_{\mathrm{ata}}$]. The evidence does not suggest these interventions will have a major effect on nearby downstream flood risk for the most extreme events [$\mathrm{S}_{\mathrm{upp\_ev}}$]. The evidence available for the downstream effects of upstream land-use changes at large catchment scales is more limited, but at present it does not suggest that realistic land-use changes will make a major difference to downstream flood risk [$\mathrm{E}_{\mathrm{xp\_op}}$]. Moreover, it should be recognised that, although the UK landscape has undergone extensive change due to the multiplicity of intensive farming interventions over many decades, the effects of these interventions on flooding have been difficult to detect. [$\mathrm{E}_{\mathrm{xp\_op}}$]. Long-term monitoring is needed to separate the effects of land management from those of climatic variability; without this it is unwise to extrapolate the findings from individual studies to larger scales, or to settings with different soil and vegetation types [$\mathrm{E}_{\mathrm{xp\_op}}$].

(d) Channel flow

(22) [*Geomorphic processes and river channel form*]

Erosion, transport, and deposition of sediment can, over time, result in major changes in channel morphology (cross-section and profile) and even channel pattern in some cases [$\mathrm{D}_{\mathrm{ata}}$]. If the amount of sediment flow from a catchment increases, some of it will tend to accumulate downstream in places where the pattern of water flow is insufficient to keep material in suspension. Sedimentation reduces the channel’s capacity to convey flow, resulting in higher water levels for a given discharge, and increasing the frequency of flooding [$\mathrm{D}_{\mathrm{ata}}$]. These processes are commonly overlooked in flood risk mapping exercises, but are likely to be important in any river system which receives high rates of sediment delivery and which in the past would have deposited much of its sediment on the floodplain [$\mathrm{E}_{\mathrm{xp\_op}}$].

(a) A simulation study of a river in Yorkshire showed that over a 16-month period changes in channel configuration due to coarse sediment deposition led to a substantial increase in the area that flooded for the highest flows that were recorded during the study period [$\mathrm{P}_{\mathrm{rojns}}$].

(b) In a simulation study of 41 rivers across England and Wales it has been calculated that, on average, a 10% reduction in channel capacity would increase flooding by 1.5

days per year and that, conversely, a 10% increase in channel capacity would decrease flooding by 1.5 days per year [P$_{\text{rojns}}$].

(c) Some agricultural land practices are known to cause sediments to accumulate in drainage channels and rivers [E$_{\text{xp\_op}}$]. Annual surveys of sediment accumulation in ten small wetlands built on four farms in Cumbria and Leicestershire have shown that on-farm interventions can trap significant quantities of sediment (in this case 0.04–0.8 t ha^{-1} yr^{-1}), particularly during intense rainfall at times when crop cover is poor [D$_{\text{ata}}$].

(d) In Pontbren in mid-Wales (see Section (20)), sediment loads were 5–12 times higher in a stream draining improved grassland than in one draining traditionally-managed moorland, with implications for sediment delivery downstream [D$_{\text{ata}}$].

(23) [*Hydraulic effects of channel modification*]

Traditional flood-control channel designs have included enlarging the natural channel cross section and straightening meanders to increase the hydraulic gradient and therefore conveyance of water. While increasing the channel cross-section will reduce local water levels, the resulting higher flows can increase the flood hazard downstream [E$_{\text{xp\_op}}$]. In a large flood, when much of the water flow is outside the river, the effect of channel modification is relatively small [E$_{\text{xp\_op}}$].

(24) [*Sedimentary effects of channel modification*]

Excessive widening or deepening of natural watercourses can initiate channel instabilities resulting in erosion and sedimentation, requiring maintenance work to preserve the design capacity of the scheme [E$_{\text{xp\_op}}$]. Dredging to re-grade the channel slope in order to increase flood conveyance is particularly susceptible to such problems [E$_{\text{xp\_op}}$]. Greater flow velocities can result in more sediment from upstream riverbeds being transported and deposited in lower reaches, requiring further dredging at these sites to maintain the artificial channel form [E$_{\text{xp\_op}}$]. Removing sediment from the channel can have significant negative effects on aquatic biodiversity [D$_{\text{ata}}$].

(25) [*Bank stabilization*]

River management that prevents flooding and the consequent deposit of sediment on the flood plain often results in the build up of sediment and a reduction in the capacity of the river to move water downstream [E$_{\text{xp\_op}}$]. Conversely, where past management has destabilized banks leading to erosion and unnatural widening, bank stabilization can reduce further erosion and consequent sediment deposition and so reduce flood risk. In these cases stabilizing banks by re-vegetation can be particular effective [E$_{\text{xp\_op}}$]. Riverbank stabilization performed to prevent *natural* bank erosion is likely to exacerbate flood risk in aggrading river reaches because, without lateral shifting, channel conveyance capacity cannot be maintained [E$_{\text{xp\_op}}$].

(26) [*River restoration*]

River restoration seeks to recreate natural channel properties in rivers that have been modified - often "channelized" - in the past. Where it increases the ability of the river to flow onto its floodplain, or creates storage in areas that were once part of the river's floodplain, river restoration can reduce flood risk downstream [E$_{\text{xp\_op}}$]. In many cases the motive for river restoration is conservation of biodiversity, with the aim that there should be no negative flood impact.

(a) In the New Forest, river restoration has been used to reconnect channelized rivers to their floodplains. For small and medium-sized drainage basins (< 100 km^2) there is evidence that restoration of river channel morphology and floodplain woodland with associated large wood logjams may reduce flood risk, although only for high flows with Annual Exceedance Probability (see paragraph 20) greater than 50% [D$_{\text{ata}}$].

(b) Floodplain forest restoration can reduce peak discharge at the catchment outlet by a combination of the processes described in (27)–(29). For an event with Annual Exceedance Probability of 3%, peak discharge was reduced by up to 19% under mature forest. In areas where only 20–35% of the overall catchment area was restored to forest, peak discharge was reduced by 6% [D$_{\text{ata}}$].

(27) [*Channel and bank vegetation*]

Vegetation growing on banks and in the river itself can increase "channel roughness" which slows water flows and increase sediment deposition. Reduced vegetation in winter reduces roughness and accounts for higher seasonal flows (by up to 50% in a study of the River Stour in Dorset) [D$_{\text{ata}}$]. The cultivation and maintenance of bankside and river channel vegetation (often of value for biodiversity) can induce a small decrease in water flow (and hence reduce downstream flood risk) in their immediate vicinity in narrow rivers (where the width is less than 16 times the depth) [D$_{\text{ata}}$].

(28) [*Riparian buffer strips*]

Non-agricultural riparian buffer strips of 10–30 m around channels limit catchment sediment inputs to river channels, which is important in maintaining channel conveyance [D$_{\text{ata}}$]. Buffer strips also provide co-benefits in the form of reducing movements of agricultural pollutants into watercourses, and shading of river channels from excess heat which benefits aquatic biodiversity [D_{ata}]. Wider buffer strips maintain habitat diversity and ecological functioning better than narrow ones [E_{xp_op}].

(29) [*Large Wood*]

At local scales (~1 km river reaches), large items of wood caught in the channel can significantly increase the amount of water that flows over the bank, the quantity depending on the size of the items and how they are trapped (often by bridges and other manmade structures) [D_{ata}]. This causes local flooding but the water stored decreases flood risk downstream [D_{ata}]. During floods, wood can be mobilized and deposited at natural or artificial entrapment points in the channel. Blockage of bridges, trash racks and culverts with large wood can cause flooding upstream of the blockage [D_{ata}]. Log-jams can be installed to store flood water; their effectiveness depends on log size and the density of wood entrapment sites [D_{ata}].

(30) [*Beavers*]

In general, beaver dams reduce the mean velocity and discharge downstream of dams. Beaver ponds also trap sediment, the depth and volume of which substantially increases with dam age and frequency [D_{ata}]. No evidence is available on their effects on extreme flows. Dam failures can cause minor flood waves [E_{xp_op}].

(a) The effects of beaver reintroductions on flood hydrology in the UK remain to be established. The introduction of beavers in Knapdale, Argyll, Scotland in 2009 resulted in slight changes in the configuration of woody debris in streams, although the animals in the study constructed only 0.3 dams km^{-1} (cf. 0.14–19 dams km^{-1} observed in other countries) [D_{ata}], because the catchment concerned already contained well-vegetated standing water [E_{xp_op}].

(31) [*Summary*]

Summary The effect of modifications to river channels depends on channel cross-section, roughness, and slope [D_{ata}] and on where they are situated within river networks. Inappropriately located interventions may even worsen flooding due to synchronization of flood peaks. Interventions intended to reduce flooding are also likely to have effects on sedimentary, geomorphological and ecological processes in the river, as well as direct hydrological effects [E_{xp_op}]. The role of sediment transport in affecting flood hazard is less well understood than that of hydraulics, but it is known that accelerated sedimentation in rivers can significantly increase downstream flood hazards, and that CBFM and NFM have the potential to reduce catchment sediment yields elevated by intensive farming [E$_{xp\_op}$].

(e) Flood storage and floodplain conveyance

(32) [*Storage*]

Water is stored naturally in catchments in forest canopies, wetlands, soils, aquifer rocks, river channels and floodplains. Management actions to increase storage may range from widespread small-scale impoundments (such as blocked ditches and micro-ponds) to large-scale flood detention reservoirs, which are major engineering works. All of these schemes store water upstream and then release it slowly over varying lengths of time depending on capacity and flood conditions. Their effectiveness at reducing flood hazard downstream depends on whether the stored water would have contributed to the flood peak. Small stores may fill up early and have no further effect in a large flood, while controllable larger storage (i.e., with gates or sluices) can be synchronized to maximize the effect on the peak of the forecast flood wave.

(a) In the 5.7 km^2 Belford Burn catchment in North Northumberland, a pond adjacent to the river with 800–1,000 m^3 storage capacity was installed in a 0.5 km^2 sub-catchment. During a storm in September 2008, which delivered 96 mm rainfall in 36 hours (estimated to be a rainfall event with Annual Exceedance Probability of 2%), the pond increased the average time-to-peak by 15 minutes [D$_{ata}$]. Several such features would thus be necessary in order to achieve a major reduction in flood hazard (and once full cannot help if a further event occurs before they have drained) [E$_{xp\_op}$].

(b) The ‘Slowing the Flow at Pickering’ scheme, within the 69 km^2 Pickering Beck catchment, is designed to protect the North Yorkshire town through: (i) measures in the upland landscape (tree planting, large woody debris dams, timber-built bunds, heather bale dams within moorland drains and gullies, farm woodland, riparian woodland and buffer strips), and (ii) a clay bund and engineered offline storage (designed to protect against a flood with 4% Annual Exceedance Probability). Initial analysis of the scheme during a period of heavy rainfall in December 2015 showed a complex relationship between rainfall and river flow, and the need for more data to assess the performance of the measures, especially against the most extreme rainfall events [E$_{xp\_op}$].

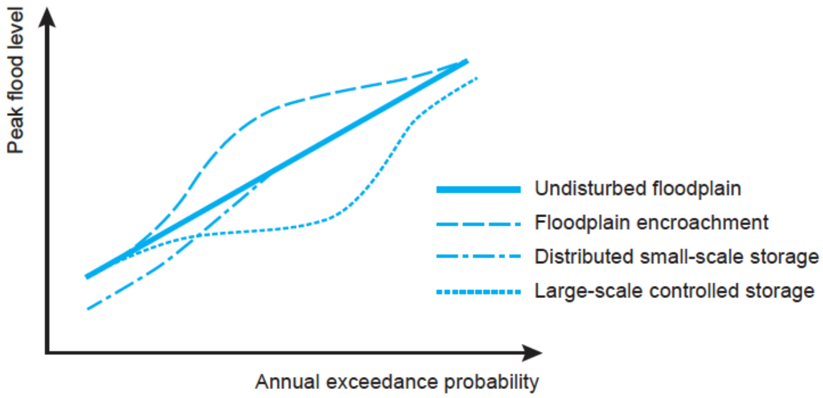

Figure 2 Hypothesized impact of three types of engineering activities on the flood frequency curve. After Hall et al. (2014).

(33) [*Floodplain cross-section*]

River flows that just exceed the bank-full level are stored in the floodplain, whilst the channel remains the main mechanism for conveying water downstream. For higher flood flows, velocities on the floodplain approach that in the channel and the floodplain has an active role in conveyance. Modifications to the floodplain cross-section, typically by encroachment of built-up development protected with flood defences, will modify these floodplain functions – by reducing the natural floodplain storage and reducing the floodplain conveyance during extreme floods. Reducing the floodplain cross-section in this way will increase the water depth in the flood plain for a given flow. On the other hand, removing these obstructions increases the floodplain cross-section and reduced water depths [D$_{\text{ata}}$]. When flood defences are overtopped or breaches occur, their effect on water levels diminishes, although they may provide additional floodplain roughness and resistance to flow [E$_{\text{xp\_op}}$]. These modifications will not only influence local water levels but will also have downstream impacts, which can be verified with a well-calibrated hydrodynamic model. In a model study of a 5 km reach of the River Cherwell, central England, construction of embankments separating the river from its floodplain (thus reducing the floodplain cross-section) increased peak flood flows downstream by 50 to 150% and raised water levels by up to 0.5 m [P$_{\text{rojns}}$].

(34) [*Floodplain roughness*]

Riparian and floodplain forests provide “floodplain roughness” which dissipates flood energy and provides resistance at times of high flow [E$_{\text{xp\_op}}$]. Removing floodplain roughness will increase flow velocities and reduce water levels locally, although this may exacerbate flooding downstream [E$_{\text{xp\_op}}$]. However the effects of changes in floodplain roughness tend to be very small, as floodplain flow velocities tend to be low in all but the largest of floods.

(35) [*Summary*]

Summary Increasing the cross-sectional area of the floodplain (by retreating flood defences or removing other obstructions from the floodplain) provides additional storage and conveyance capacity. The relative importance of storage versus conveyance depends on the flow, with the conveyance effect dominating as floodplain flows increase. The effect of storage on flooding downstream depends on whether the stored water would have contributed to the flood peak [E_{xp_op}]. Increasing the floodplain cross-section will reduce flood water levels locally [E_{xp_op}]. Increasing floodplain roughness (for example by afforestation or other obstructive vegetation) has a very small effect on flood levels, unless flow velocities on the floodplain are of the same order as the river channel, in which case increasing roughness will slow the flow [E_{xp_op}]. The downstream effects of modifications to channel conveyance can be verified with hydrodynamic models [E_{xp_op}].

(f) Co-benefits

(36) [*Co-benefits*]

CBFM and NFM can yield multiple co-benefits, including mitigation of diffuse pollution from agricultural land, reduced water discolouration from peatland-fed watercourses, and mitigation of soil erosion impacts on in-stream and lake ecology. The creation and restoration of terrestrial (riparian, moorland, forest) and aquatic (river, wetland) habitats and associated carbon storage may also be significant. Additional co-benefits may include aquifer recharge and retention of water upstream that can supplement water resources at times of low flow, and protection from the adverse ecological impacts of high water temperatures. These benefits can help to reduce downstream water treatment costs, sustain the productivity of agricultural soils, preserve and enhance ecosystems and biodiversity, enhance recreational value and help build the resilience of ecosystems to other stressors, including climate change. Whilst there are many co-benefits that might arise from CBFM/NFM, to date there have few studies that have systematically quantified these co-benefits [E_{xp_op}].

(g) Conclusions

(37) [*Conclusions I*]

The hazard associated with small floods in small catchments may be significantly reduced by CBFM and NFM although the evidence does not suggest these interventions will have a major effect on the most extreme events. Large fluvial floods are caused primarily by heavy rainfall on wet, frozen or impermeable ground. It is possible that a flood will occur that is so extreme that it will overwhelm any risk management measures or flood defences, natural or otherwise. Land use and channel form influence the severity of these floods in a fairly subtle way [E_{xp_op}]. The effectiveness of NFM and CBFM varies with the severity of the event – for example, tree shelterbelts or drain blocking may offer mitigation against small floods, but are likely to be less effective during extremely intense or prolonged high rainfall [E_{xp_op}]. Actions that provide small-scale local benefits have not been shown to provide significant benefits at the spatial scale of a larger catchment [S_{upp_ev}]. Although a simple extrapolation would imply that many small interventions (each creating local benefits) should combine to create large benefits at large scale, this is not always the case because: (i) local benefits are attenuated downstream by the channel network, and (ii) interactions amongst local events mean that slowing water flow in one catchment can make a flood worse further downstream when waters from several catchments meet [E_{xp_op}]. Where multiple interventions have taken place it can be difficult to disentangle the effects of an individual intervention, the effect of which depends upon catchment properties (in particular size, shape, topography, geology, soils, and both hydrological and sediment connectivity) and the extent and location of the intervention within the catchment [E_{xp_op}]. With the current state of scientific knowledge, it is not possible to state unequivocally whether the lack of demonstrable effect at large scale is because noticeable flood mitigation could not be achieved in a large catchment, or because a sufficiently large-scale set of interventions have not yet been implemented [E_{xp_op}].

(38) [*Conclusions II*]

The larger the catchment and the larger the flood, the smaller is the scope for slowing the flood or storing the floodwater to reduce the flood hazard. We highlight the following main conclusions, which are summarized graphically in Figure 3a,b: (i) Interventions that increase the ability of soils to absorb and retain water (through changes to land cover and land management) are at their most effective in smaller floods and at smaller scales. Once soils become saturated the effect is no longer noticeable; (ii) Storage (from distributed micro-ponds, through natural floodplains, to large detention basins) can be effective in reducing flood risk, depending on how much storage is provided, where it is located, and how and when it is used; and (iii) Increasing the cross-sectional area of floodplains by setting back flood defences that have disconnected areas of the floodplain from the river can reduce peak river flows and flood water levels.

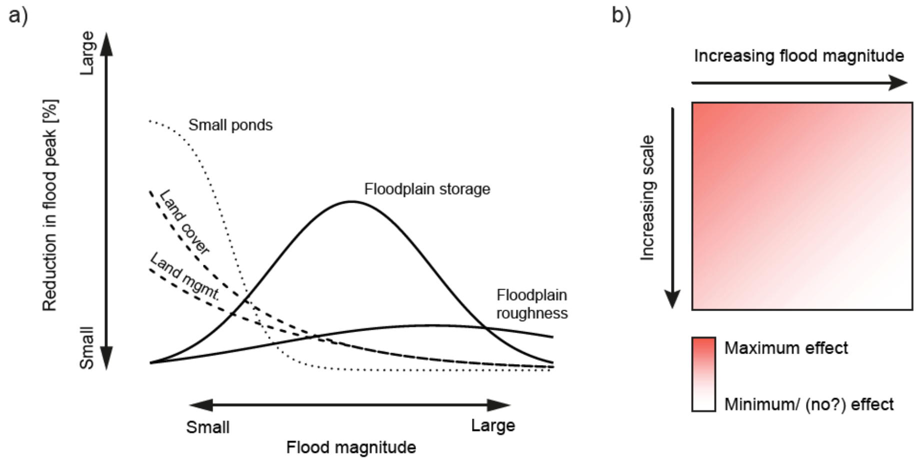

Figure 3 Schematic diagram showing relative effects of catchment-scale interventions on flood peaks. (a) Effect of different types of intervention on flood peak reduction [E_{xp_op}]; (b) combined effect of CBFM interventions with flood magnitude and catchment scale [E_{xp_op}]. We note that the effects achievable in practice will depend on the details of the particular intervention and the context in which it is deployed.

Annotated Bibliography

Paragraph numbers correspond to those in the main document: full references are given at the end.

(1) [*Background*] The complexity of flooding and flood risk management in a UK context is discussed by Sayers et al. (2002), Pattison and Lane (2012) and Thorne (2014) and, in a broader European context, by Hall et al. (2014). The process of Integrated Flood Management is introduced by WMO (2009), and a recent review of strategic flood management is given by Sayers et al. (2015a). The SEPA Natural Flood Management Handbook gives a recent, comprehensive introduction to the principles and application of NFM (SEPA, 2016). Examples of studies that have sought to draw together evidence from multiple investigations include the Foresight Project on Flood and Coastal Defence, described in Evans et al. (2004), Thorne et al. (2007), and Evans et al. (2008). The Flood Risk Management Consortium FRMRC (2004-2011) conducted research on multiple aspects of flooding, including field and model studies of land use and sediment impacts. FRMRC Fact Sheets, academic papers and technical reports may be downloaded from the FRMRC legacy website: https://web.sbe.hw.ac.uk/frmrc/. The role of extreme events in shaping policy on flood management is scrutinized by Lane et al. (2013) and the use of risk-based decision-making to prioritize investments in reducing exposure to flooding is discussed in detail by Hall et al. (2005a) and Hall (2010). For some UK examples of groundwater flooding (in an urban context), see MacDonald et al. (2012). The effect of urbanization on flood risk in urban areas is covered by Miller et al. (2014) in a UK context. Coastal flooding and the effects of sea level changes are analysed by Dawson et al. (2005), Dawson et al. (2009), Dawson et al. (2011), and Hall et al. (2005b).

(2) [*Principles*] Relevant hydrological principles are covered in introductory texts (Ward and Robinson, 1999, Shaw et al., 2011, Beven, 2012). The importance of scale in hydrology is articulated well by Dooge (1986), Blöschl and Sivapalan (1995) and, in relation to the effects of land cover on flooding, Blöschl et al. (2007). The relative importance of hillslope and channel network routing in hydrograph formation has been studied extensively as a function of catchment scale (e.g., Kirkby, 1976, Beven and Wood, 1993, Robinson et al., 1995, Botter and Rinaldo, 2003, D'Odorico and Rigon, 2003). Theoretical consideration of how hydrodynamic and geomorphic dispersion affect flood wave propagation can be found in Saco

and Kumar (2002), Viglione et al. (2010), and Zoccatelli et al. (2015). An example of how this translates into flood hazard is provided for the UK by Pattison et al. (2014).

(3) [*Evidence*] Multi-scale analyses of the effectiveness of interventions from plot to catchment scale are given by O'Connell et al. (2007) and McIntyre et al. (2013). Theoretical work on the decomposition of risk into its components: hazard, exposure and vulnerability is summarized by Rougier et al. (2013), and discussed in detail in relation to flooding by Beven and Hall (2014).

(4) [*Aim*] Further examples of studies in other fields in which the strength of scientific evidence is judged in order to inform policy are given by Godfray et al. (2013), Godfray et al. (2014).

(5) [*Meteorological data and trends*] The basic principles of hydrology and hydrometry are covered in a range of introductory textbooks (Ward and Robinson, 1999, Shaw et al., 2011, Beven, 2012). The UK hydrometric network is described in Dixon et al. (2013). Historical trends in rainfall since 1961 are described by Jones and Conway (1997) and Osborn et al. (2000). Analysis of upland and lowland precipitation is based on Burt and Holden (2010).

(6) [*River flow variability and trends*] Several writers have sought to identify trends in river flow data (Mudelsee et al., 2003, Kundzewicz et al., 2005, Svensson et al., 2006). In the UK, there are several recent accounts of historical changes in runoff and river flows (Wilby et al., 2008, Hannaford and Marsh, 2008, Hannaford, 2015, Watts et al., 2015). Trends in daily maxima and 30-day maxima between 1960 and the early 2000s have been identified in some parts of the UK, notably the north and west (Hannaford and Marsh, 2008), who also comment on the continuity of these trends in earlier periods.

(7) [*Flood frequency*] The review by Hannaford (2015) is particularly comprehensive. The long-term study for the Thames is by Marsh and Harvey (2012).

(8) [*Flood rich and flood poor periods*] Flood-rich and flood-poor periods during the twentieth century are identified by Wilby and Quinn (2013), Burt et al. (2015), and Foulds and Macklin (2015), in the context of prevailing weather types. The North Atlantic Oscillation (NAO) influences the pattern of wet winters and dry summers experienced in parts

of the British Isles. The NAO is controlled partly by sea surface temperatures in the Atlantic Ocean, via the Atlantic Multi-decadal Oscillation (AMO). There is much recent work on the link between NAO and hydro-climatic regime in the UK (Hannaford and Marsh, 2008, Burt and Howden, 2013, Burt et al., 2015). The role of the North Atlantic Ocean in driving the pattern of anomalously wet summers in northern Europe since the 1990s is explained by Sutton and Dong (2012). Emerging evidence suggests that the North Atlantic may be affected by climate variability in the tropical Pacific (e.g., El Niño; Hoerling et al., 2001) and the stratosphere (explained by Scaife et al., 2005).

The role of atmospheric rivers in bringing anomalously wet winters is introduced by Lavers et al. (2011) who subsequently rule out any effect on summer precipitation (Champion et al., 2015). The effect of arctic sea ice on Northern Hemisphere circulation is documented by Cohen et al. (2014). The frequency of cyclonic conditions is analysed by Matthews et al. (2015). Slingo and Palmer (2011) summarize the state of the art with respect to seasonal predictability in a UK context. Evidence from the sedimentary record – in the form of boulder berm and debris flow deposits dated by using lichenometry – is catalogued by Macklin and Rumsby (2007) and interpreted in the context of recent UK flooding by Foulds and Macklin (2015).

(9) [*Climate change projections*] Several recent reviews of the hydrological impacts of climate change are global in scope (Bates et al., 2008, Trenberth, 2011). The theoretical link between warming and precipitation is discussed by Allen and Ingram (2002). The most accessible review of current state of the art is given by Watts et al. (2015), from which estimates of future precipitation changes quoted in this paragraph are taken. Several model-based results showing the projected effects of climate change on river flows are available (Prudhomme et al., 2012, Christierson et al., 2012, Kay et al., 2014, Kundzewicz et al., 2014) along with projections of future impacts on flood risk (Sayers et al., 2015b).

(10) [*Historical changes in land cover*] The history of British forest is covered by Hoskins (1955), Rackham (1976), and the palaeo-ecological basis for reconstructing land cover during pre-historic times is summarized by Roberts (1998). Modern data on land cover in Great Britain are from Fuller et al. (1994) and Morton et al. (2011). Land management practices are widely known to affect magnitude and timing of runoff generation in the local vicinity (Ferrier and Jenkins, 2009).

(11) [*The influence of land cover on flooding*] International studies indicate an important link between land cover and hydrological response (De Roo et al., 2003, Oudin et al., 2008). Nonetheless, in large UK catchments the influence of land-cover on flood peaks is hard to discern (e.g., in the Thames, Crooks and Davies, 2001). Extensive analysis of the impact of catchment properties on flooding is contained within the Flood Studies Report and the Flood Estimation Handbook (Natural Environment Research Council, 1975, Institute of Hydrology, 1999). More recent studies include the EPSRC-funded FRMRC projects and NERC-funded Flooding from Intense Rainfall projects, which are summarized in (1).

(12) [*Effects of forest cover*] Houghton-Carr (2013a) and Houghton-Carr (2013b) provide a rapid evidence assessment for the effects of forest cover on water balance. See Marc and Robinson (2007) for a comprehensive review of the Plynlimon catchment experiments. Further information is also given in Hudson and Crane (1997) and Howe et al. (1967).

(13) [*Timber harvesting; forestry operations*] Findings relating to timber harvesting and its effects on flood peaks are documented by Robinson and Dupeyrat (2005). Time-dependent effects of plantation forestry have been noted in many settings (e.g., Hudson and Crane, 1997, Scott and Prinsloo, 2008). Robinson et al. (2003) review the effects of forestry in several European settings. Effects of timber harvesting on stream flows through soil compaction, construction and use of forest roads, and changes in vegetation are documented by Jones and Grant (1996), while scale dependence is shown by Dung et al. (2012). Results from the Balquhidder and Coalburn experiments are described by Johnson (1995) and Robinson (1998), respectively. The effects of mature forest and simulations of peak flows at Coalburn are reported in Birkinshaw et al. (2014).

(14) [*Impact of agricultural practices*] For comprehensive reviews of the impacts of land management on flood generation see O'Connell et al. (2004), Beven et al. (2006), O'Connell et al. (2007) and Lane et al. (2007a). The total number of sheep and lambs in England peaked in 1990 at 20.8 million and has since declined by approximately 27%; over the same period the number of cattle and calves has declined by approximately 20% to 5.4 million (DEFRA, 2016). The effects of pasture and arable management practices on soil structural degradation in local cases are documented by Holman et al. (2003). Several studies have examined the impacts of agriculture on local-scale runoff production (Heathwaite et al., 1989, Heathwaite et

al., 1990, O’Connell et al., 2004) and specifically in flood generation (Boardman et al., 1994, Boardman et al., 2003).

(15) [*Impact of land drainage*] Comprehensive data on the effects of land drainage on river flows are compiled by Robinson (1990) and reviewed by Robinson and Rycroft (1999). A summary of the state-of-the-art and a list of studies into the effects of drainage is given by (CREW, 2012). The impact of agricultural drainage on historical channel network extent is documented by Ovenden and Gregory (1980). The key practitioner reference work is Buisson et al. (2008).

(16) [*Soil compaction*] The survey of soil compaction in arable and grassland plots in south-west England by Palmer and Smith (2013) shows that the effects of intensive farming depend on soil type, crop type. O'Donnell (2007) used modelling to explore the possible effect of soil compaction in the Scandal Beck sub-catchment of the River Eden on downstream flood flows. The studies on soil compaction at Pontbren are by Marshall et al. (2009) and Marshall et al. (2014).

(17) [*Upland and peatland impacts*] The complexities of managing peat in uplands are reviewed by Holden et al. (2004). Specific details of runoff production mechanisms in upland areas are outlined in Evans et al. (1999), Holden and Burt (2003), and Holden (2008). The study on overland flow velocities across peat surfaces was conducted by Holden et al. (2008) and the 11.4 km^2 catchment study at Trout Beck in the North Pennines was by Grayson et al. (2010). The burning study by Holden et al. (2015) compared five catchments with and five without patch burning, examining differences in peat properties, water tables and streamflow response to rainfall. Modelling studies highlighting the importance of surface roughness in upland peatlands include Ballard et al. (2011), Lane and Milledge (2013b), and Gao et al. (2015) while experiments on spatial sensitivity to surface roughness within headwater catchments were conducted by Gao et al. (in press) The complexities of flow responses to upland peat drainage are discussed by Holden et al. (2004), Holden (2005), Acreman and Holden (2013), and O’Connell et al. (2007). The Exmoor Mires Project has demonstrated the benefits for ecosystem services (e.g., water and carbon storage and improvements to water quality) that can arise from the restoration of peatlands (Grand-Clement et al., 2013).

(18) [*Upland ditch blocking*] Ramchunder et al. (2009) investigate the effectiveness of drain blocking. Lane and Milledge (2013b) quantify the effects of upland drains on downstream flood risk. The simulation study by Ballard et al. (2012) looked in detail at when drain blocking can be effective in upland peat catchments while the other modelling studies indicated the importance of surrounding peat surface roughness (Ballard et al., 2011, Lane and Milledge, 2013a). The Peak District peatland revegetation and gully blocking study was documented in detail by Pilkington et al. (2015).

(19) [*Impacts of urbanization and Sustainable Drainage Systems (SuDS)*] Urban surfaces are often assumed to be highly impervious thus converting large proportions of rainfall into surface runoff. However, empirical studies have demonstrated that the hydrological properties of urban surfaces depend on the type of surfacing and its condition with potentially complex, seasonally variable hydrological behaviour shown for some surfaces. The hydrological properties of different urban surfaces are covered by Mansell and Rollet (2006). Kjeldsen (2009) gives some examples of current approaches to flood frequency estimation in urban areas. Urban flooding during extreme summer convective storms was typified by the Summer 2007 floods in England and Wales (Marsh and Hannaford, 2007). Several studies have evaluated the role and effectiveness of Sustainable Drainage Systems (Smith et al., 2002, Nelson et al., 2006). The definitive technical work is The SuDS Manual (Woods Ballard et al., 2015) published by the Construction Industry Research and Information Association (CIRIA; ciria.org). The multiple-benefits of restoring natural functions in urban drainage systems and watercourses as part of ‘Blue-Green’ approaches to urban flood risk and water management have received attention in research (http://www.bluegreencities.ac.uk/) and practice-led (http://bgd.org.uk/) consortia.

(20) [*Catchment-scale effects of land management practices*] McIntyre and Thorne (2013) give a comprehensive review of the effects of land management on flooding. The conceptual difficulties associated with the extrapolation of results from one site and scale to another are discussed by several scholars (Blöschl et al., 2007, Viglione et al., 2010, Pattison and Lane, 2012), and results from numerical simulations reinforce this apparent complexity (Dunn and Mackay, 1995, Ewen et al., 2013). O’Connell et al. (2007) reviews how local-scale changes propagate downstream, both individually and collectively, and several catchment-scale demonstrations have been documented in the literature (Marshall et al., 2009, McIntyre and Ballard, 2012, McIntyre et al., 2013). O'Donnell (2007) has developed a modelling method

for tracking impacts through the river channel network while O'Donnell et al. (2011) have used modelling to provide catchment sensitivity maps for the impacts of land management changes. There have been several recent advances in modelling methods to investigate land management impacts on flood flows at larger scales (Bulygina et al., 2011, Bulygina et al., 2012, McIntyre et al., 2013, Bulygina et al., 2013, Ewen et al., 2013)

The Hodder study is described in O'Donnell et al. (2011) and Ewen et al. (2015). Source area risk attribution is pioneered by Ewen et al. (2013). The SCaMP programme is described by McGrath and Smith (2006) and the results concerning the impacts of changes on the flood hydrograph are given by Ewen et al. (2015).

The Pontbren study is documented in Wheater et al. (2008), Marshall et al. (2009), and Marshall et al. (2014). Modelled impacts on flood peaks at the 6 km^2 catchment scale are reported by Wheater et al. (2008), Jackson et al. (2008), and McIntyre and Marshall (2010). Results from the River Axe are reported by Climent-Soler et al. (2009) and Archer et al. (2010).

Parrott et al. (2009) discuss the way in which the effectiveness of NFM diminishes with catchment size. The role of tributary timing on flood risk is explored in a modelling study by Pattison et al. (2014). Runoff and sediment transfer are scale-dependent processes, and hence cannot be transferred directly between scales (Deasy et al., 2011, Deasy et al., 2014).

(21) [*Summary*] Peer-reviewed evaluations of the effectiveness of NFM and CBFM interventions are listed in Table 2. Further practitioner-led implementations of NFM and CBFM can be found in databases compiled by the Environment Agency (Barlow et al., 2014), James Hutton Institute, and the JBA Trust. (https://www.gov.uk/government/publications/working-with-natural-processes-to-reduce-flood-risk-a-research-and-development-framework; http://www.crew.ac.uk/content/natural-flood-management-database; http://naturalprocesses.jbahosting.com/). An evidence directory compiled by the Environment Agency (SC15005 – Working with Natural Processes – evidence base & catchment/coastal laboratories), gives a synthesis of best practice drawn from twenty projects that have implemented CBFM/NFM measures in England and Wales (http://evidence.environment-agency.gov.uk/FCERM/en/Default/FCRM/Project.aspx?ProjectID=d17370c6-135f-4ceb-8ed7-23867eaa2efd&PageID=4c167c62-3bba-475d-8965-

d6528b5d5f61). Details of the Environment Agency's Catchment Flood Management Plans can be found here: https://www.gov.uk/government/collections/catchment-flood-management-plans

[TABLE 2]

(22) [*Geomorphic processes and river channel form*] Channel morphology and stability reflect the net sediment budget, which in turn reflects: (i) the net erosion and deposition observed; and (ii) the supply and connectivity of sediment from the hillslopes and upstream reaches. Effects on floodplain and channel morphology are widely discussed in the geomorphological literature (e.g., Hey, 1979, Kleinhans et al., 2013). For sediment budgets see Hooke (2003). The simulation by Lane et al. (2007b) shows the effects of flood related sedimentation on river channel form. Slater et al. (2015), Slater (2016) detect the effects of channel capacity changes by quantifying the non-stationarity in stage-discharge records. The role of fine sediments in nutrient transport is summarized by Owens and Walling (2002). The implications of UK farming intensification for sediment-related flood risks in upland and lowland basins are investigated in doctoral theses by Henshaw (2009) and Dangerfield (2013), respectively. Results of field experiments with on-farm wetlands in Cumbria and Leicestershire are reported by Ockenden et al. (2014). The comparison of sediment yields in basins dominated by improved grassland with those from traditionally-managed[8] moorland at Pontbren is by Henshaw (2009) and Thorne et al. (2011b).

(23) [*Hydraulic effects of channel modification*] The hydraulic effects of modifications to the geometry of channels are governed by known physical laws of steady and unsteady flow (Jain, 2001). Hall et al. (2014) review these principles in the context of changes to the flood regime in Europe.

(24) [*Sedimentary effects of channel modification*] Tracking and predicting river channel adjustment and the complex interrelationships between flood conveyance, sediment transport, channel morphology and adjustment to natural and artificial disturbance is a mainstay of fluvial geomorphology (Gilbert, 1880, Mackin, 1948, Hack, 1957, Schumm, 1979). Work on the effects of channel modification on channel stability is summarized by Darby and Thorne

---

[8] Moorland managed through lower stocking densities of local breeds of sheep (Welsh Mountain instead of Merino), conservation of native vegetation and no underdrainage.

(1996). The effect of bed lowering on bank stability is considered in detail in several studies (Schumm, 1979, Thorne and Osman, 1988, Sear et al., 1995, Harvey, 2001, Hooke, 2003). A modern set of tools provided to assess the problem of dealing with sediment in flood risk management is given by Thorne et al. (2011a).

(25) [*Bank stabilization*] Advances in understanding river bank erosion, its natural controls and its management are covered by Lawler et al. (1997) and Midgley et al. (2012). The impacts of artificially restricting lateral channel movement on sedimentation and in-channel conveyance are explained by Raven et al. (2010). A good practice guide to using bank stabilization as part of sustainable river and flood risk management is provided by the Scottish Environmental Protection Agency (SEPA, 2008, SEPA, 2012). The importance of vegetation in controlling bank erosion is reviewed by Solari et al. (2016).

(26) [*River restoration*] The type and scale of river restoration in the UK is summarized by Sear et al. (2000) and Newson et al. (2002), with updates available via the River Restoration Centre website (http://www.therrc.co.uk). Examples of the hydrological effects of river restoration are given in modelling studies (Acreman et al., 2003) and field and modelling data (Dixon et al., 2016). Local hydraulic impacts of restoration can be found in Sear et al. (2004) with reviews in Brookes and Shields (1996). The role of large wood in headwater streams in the New Forest is investigated by Dixon and Sear (2014) and the reduction in flood risk that might be achieved with floodplain forest restoration is quantified by Dixon et al. (2016).

(27) [*Channel and bank vegetation*] In-channel vegetation can reduce water velocity and elevate water levels significantly thus enhancing the flood hazard at that site and upstream. Early flow-resistance guides such as those of Chow (1959) and Barnes (1967) assist with the estimation of channel roughness parameters but do not properly account for composite roughness nor the time-varying roughness of vegetation subject to different depths and flow velocities (Masterman and Thorne, 1992). HR Wallingford’s more advanced Conveyance Estimation System, which partitions hydrodynamic roughness between its various components, is described in McGahey et al. (2006) and reviewed comprehensively by (Knight et al., 2010). Alternatives for representing vegetation effects on roughness are reviewed by Marjoribanks et al. (2014). The study in the River Stour is documented by Bates et al. (1998); the effect of vegetation on conveyance in summer floods is widely noted (Marsh and Hannaford, 2007).

(28) [*Riparian buffer strips*] The effects of interventions in riparian vegetation on flood conveyance are covered by Downs and Thorne (2000). The broader range of benefits conferred by riparian buffer strips is the subject of many papers in the hydrological and freshwater biological literatures, which are reviewed by Broadmeadow and Nisbet (2004). The co-benefits for sediment management are illustrated by Owens et al. (2007) and the co-benefits for biodiversity are articulated by Correll (2005).

(29) [*Large Wood*] The general effects of wood in rivers are documented by Abbe and Montgomery (1996) and more recently by USBR (2016). As the size of debris approaches the order of the channel width, their role alters from simply providing additional resistance to fluid flow in the channel, to a role in which the debris can exert a strong structural control on channel morphology and stability. In a UK context, the reach-scale hydraulic effects are considered by Jeffries et al. (2003) and Sear et al. (2010).

(30) [*Beavers*] The role of beavers is reviewed by Gurnell (1998). International evidence concerning the effectiveness of beaver dams at trapping sediment is presented by Meentemeyer and Butler (1999) and Butler and Malanson (2005). Pollock et al. (2015) give practical information on the role of beavers in river restoration. Scottish Natural Heritage has published results from the Scottish Beaver Trial in a series of reports, including Perfect et al. (2015). Several additional studies of the reintroduction of beaver are underway (e.g., the Mid-Devon Beaver Trial and the River Otter Beaver Trial) but results were not available at the time of writing

(31) [*Summary*] No referencess

(32) [*Storage*] A series of European studies consider the issues associated with managing offline storage (Hooijer et al., 2004, Bronstert et al., 2007, Salazar et al., 2012). Work at Belford is described by Wilkinson et al. (2010). Similar storage features are in use at other locations, e.g., Lustrum Beck, Stockton-on-Tees, although full evaluations of their performance have not been published at the time of writing. The Pickering scheme is documented by Lane et al. (2011) and Nisbet et al. (2015). A briefing note on post-event analysis following heavy rain in December 2015 is available here: Slowing the Flow Partnership Briefing: Boxing Day 2015 Flood Event

http://www.forestry.gov.uk/pdf/160329_PBeck_Boxing_Day_2015_Final.pdf/$FILE/160329_PBeck_Boxing_Day_2015_Final.pdf

(33) [*Floodplain cross-section*] International studies have examined floodplain modification on the Mekong (Hoa et al., 2008), Po (Di Baldassarre et al., 2009), Rhine (Vorogushyn and Merz, 2013), and Danube (Blöschl et al., 2013). Work on flood risk in the Cherwell associated with disconnection from the flood plain and the potential effects of floodplain and channel restoration is presented by Acreman et al. (2003). The effect of wetlands on flood risk is discussed by Bullock and Acreman (2003).

(34) [*Floodplain roughness*] The effects of riparian forest on resistance to flow are documented widely in the international literature (Everitt, 1968, Swanson and Sparks, 1990, Hupp and Osterkamp, 1996, Stromberg et al., 1993). Controls on flood peak attenuation are investigated by Valentová et al. (2010) and sensitivity to floodplain roughness is presented by Hall et al. (2005b). A study that documents a case where floodplain friction has only a limited impact on flooding is reported by Aronica et al. (2002).

(35) No references cited

(36) The need for further quantitative evaluation of the co-benefits associated with nature-based solutions like CBFM/NFM is articulated by Jones et al. (2012).

(37)–(38) No references cited.

References

ABBE, T. B. & MONTGOMERY, D. R. 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. *Regulated Rivers Research Management,* 12**,** 201-221.

ACREMAN, M. & HOLDEN, J. 2013. How wetlands affect floods. *Wetlands,* 33**,** 773-786.

ACREMAN, M. C., RIDDINGTON, R. & BOOKER, D. J. 2003. Hydrological impacts of floodplain restoration: a case study of the River Cherwell, UK. *Hydrology and Earth System Sciences,* 7**,** 75-85.

ALEXANDER, L. V. & JONES, P. D. 2001. Updated precipitation series for the U.K. and discussion of recent extremes. *Atmospheric Science Letters,* doi:10.1006/asle.2001.0025.

ALLEN, M. R. & INGRAM, W. J. 2002. Constraints on future changes in climate and the hydrological cycle. *Nature,* 419**,** 224-232.

ARCHER, D. R., CLIMENT-SOLER, D. & HOLMAN, I. P. 2010. Changes in discharge rise and fall rates applied to impact assessment of catchment land use. *Hydrology Research,* 41**,** 13-26.

ARONICA, G., BATES, P. D. & HORRITT, M. S. 2002. Assessing the uncertainty in distributed model predictions using observed binary pattern information within GLUE. *Hydrological Processes,* 16**,** 2001-2016.

BALLARD, C. E., MCINTYRE, N. & WHEATER, H. S. 2012. Effects of peatland drainage management on peak flows. *Hydrology and Earth System Sciences,* 16**,** 2299-2310.

BALLARD, C. E., MCINTYRE, N., WHEATER, H. S., HOLDEN, J. & WALLAGE, Z. E. 2011. Hydrological modelling of drained blanket peat. *Journal of Hydrology,* 407**,** 81-93.

BARLOW, B., MOORE, F. & BURGESS-GAMBLE, L. 2014. *Working with natural processes to reduce flood risk,* Bristol, Environment Agency R&D framework: science report SC130004/R2.

BARNES, H. H. 1967. Roughness characteristics of natural channels. Washington, D.C. : U.S. Government Printing Office.

BATES, B. C., KUNDZEWICZ, Z. W., WU, S. & PALUTIKOF, J. P. 2008. Climate Change and Water. Geneva: IPCC Secretariat.

BATES, P. D., STEWART, M. D., SIGGERS, G. B., SMITH, C. N., HERVOUET, J.-M. & SELLIN, R. H. J. 1998. Internal and external validation of a two dimensional finite element model for river flood simulation. . *Proceedings of the Institution of Civil Engineers, Water Maritime and Energy,* 130**,** 127-141.

BEEDELL, J., MORRIS, J. & HESS, T. M. 2011. Mobilising the Contribution of Rural Land Management to Flood Risk Management in Scotland. *Report to Scottish Government,* CR/2010/14.

BEVEN, K. 2012. *Rainfall-Runoff Modelling: the Primer,* Chichester, Wiley.

BEVEN, K. & WOOD, E. F. 1993. Flow routing and the hydrological response of channel networks. *In:* BEVEN, K. & KIRKBY, M. (eds.) *Channel Network Hydrology.* Chichester: Wiley.

BEVEN, K., YOUNG, P., ROMANOWICZ, R., O'CONNELL, E., EWEN, J., O'DONNELL, G., HOLLIS, J., MORRIS, J., HOLMAN, I., LAMB, R., ROSE, S. & ARCHER, D. 2006. Project FD2120: Analysis of Historical Data Sets to look for Impacts of Land Use and Management Change on Flood Generation. Final Science Report to the Environment Agency.

BEVEN, K. J. & HALL, J. W. 2014. *Applied Uncertainty Analysis in Flood Risk Management,* London, Imperial College Press.

BIRKINSHAW, S. J., BATHURST, J. C. & ROBINSON, M. 2014. 45 years of non-stationary hydrology over a forest plantation growth cycle, Coalburn catchment, Northern England. *Journal of Hydrology,* 519, Part A**,** 559-573.

BLÖSCHL, G., ARDOIN-BARDIN, S., BONELL, M., DORNINGER, M., GOODRICH, D., GUTKNECHT, D., MATAMOROS, D., MERZ, B., SHAND, P. & SZOLGAY, J. 2007. At what scales do climate variability and land cover change impact on flooding and low flows? *Hydrological Processes,* 21**,** 1241-1247.

BLÖSCHL, G., NESTER, T., KOMMA, J., PARAJKA, J. & PERDIGÃO, R. A. P. 2013. The June 2013 flood in the Upper Danube Basin, and comparisons with the 2002, 1954 and 1899 floods. *Hydrol. Earth Syst. Sci.,* 17**,** 5197-5212.

BLÖSCHL, G. & SIVAPALAN, M. 1995. Scale issues in hydrological modelling: A review. *Hydrological Processes,* 9**,** 251-290.

BOARDMAN, J., EVANS, R. & FORD, J. 2003. Muddy floods on the South Downs, southern England: Problem and responses. *Environmental Science and Policy,* 6**,** 69-83.

BOARDMAN, J., LIGNEAU, L., DE ROO, A. & VANDAELE, K. 1994. Flooding of property by runoff from agricultural land in northwestern Europe. *Geomorphology,* 10**,** 183-196.

BOTTER, G. & RINALDO, A. 2003. Scale effect on geomorphologic and kinematic dispersion. *Water Resources Research,* 39**,** 1286.

BROADMEADOW, S. & NISBET, T. R. 2004. The effects of riparian forest management on the freshwater environment: a literature review of best management practice. *Hydrology and Earth System Sciences,* 8**,** 286-305.

BRONSTERT, A., BÁRDOSSY, A., BISMUTH, C., BUITEVELD, H., DISSE, M., ENGEL, H., FRITSCH, U., HUNDECHA, Y., LAMMERSEN, R., NIEHOFF, D. & RITTER, N. 2007. Multi-scale modelling of land-use change and river training effects on floods in the Rhine basin. *River Research and Applications,* 23**,** 1102-1125.

BROOKES, A. & SHIELDS, D. 1996. *River Re-naturalisation,* Chichester, Wiley.

BUISSON, R. S. K., WADE, P. M., CATHCART, R. L., HEMMINGS, S. M., MANNING, C. J. & MAYER, L. 2008. *The Drainage Channel Biodiversity Manual: Integrating Wildlife and Flood Risk Management,* Peterborough, Association of Drainage Authorities and Natural England.

BULLOCK, A. & ACREMAN, M. 2003. The role of wetlands in the hydrological cycle. *Hydrology and Earth System Sciences,* 7**,** 358-389.

BULYGINA, N., BALLARD, C., MCINTYRE, N., O'DONNELL, G. & WHEATER, H. S. 2012. Integrating different types of information into the hydrological model parameter estimation: Application to ungauged catchments and land use scenario analysis. *Water Resources Research,* 48**,** W06519.

BULYGINA, N., MCINTYRE, N. & WHEATER, H. S. 2011. Bayesian conditioning of a rainfall-runoff model for predicting flows in ungauged catchments and under land use changes. *Water Resources Research,* 47**,** W02503.

BULYGINA, N., MCINTYRE, N. & WHEATER, H. S. 2013. A comparison of rainfall-runoff modelling approaches for estimating impacts of rural land management on flood flows. *Hydrology Research,* 44**,** 467-483.

BURT, T. P. & HOLDEN, J. 2010. Changing temperature and rainfall gradients in the British Uplands. *Climate Research,* 45**,** 57-70.

BURT, T. P. & HOWDEN, N. J. K. 2013. North Atlantic Oscillation amplifies orographic precipitation and river flow in upland Britain. *Water Resour. Res.,* 49.

BURT, T. P., JONES, P. D. & HOWDEN, N. J. K. 2015. An analysis of rainfall across the British Isles in the 1870s. *International Journal of Climatology,* 35**,** 2934-2947.

BUTLER, D. R. & MALANSON, G. P. 2005. The geomorphic influence of beaver dams and failures of beaver dams. *Geomorphology,* 71, 48-60.

CHAMPION, A. J., ALLAN, R. P. & LAVERS, D. A. 2015. Atmospheric rivers do not explain UK summer extreme rainfall. *Journal of Geophysical Research-Atmospheres,* 120, 6731-6741.

CHOW, V. T. 1959. *Open channel hydraulics,* Tokyo, Japan, McGraw ‑ Hill.

CHRISTIERSON, B. V., VIDAL, J.-P. & WADE, S. D. 2012. Using UKCP09 probabilistic climate information for UK water resource planning. *Journal of Hydrology,* 424-425, 48-67.

CLIMENT-SOLER, D., HOLMAN, I. P. & ARCHER, D. R. 2009. Application of flow variability analysis to identify impacts of agricultural land-use change on the River Axe, southwest England. *Hydrology Research,* 40, 380-393.

COHEN, J., SCREEN, J. A., FURTADO, J. C., BARLOW, M., WHITTLESTON, D., COUMOU, D., FRANCIS, J., DETHLOFF, K., ENTEKHABI, D., OVERLAND, J. & JONES, J. 2014. Recent Arctic amplification and extreme mid-latitude weather. *Nature Geosci,* 7, 627-637.

CORRELL, D. L. 2005. Principles of planning and establishment of buffer zones. *Ecological Engineering,* 24, 433-439.

CREW 2012. ￼*Natural flood management (NFM) knowledge system: Part 3 - The effect of land drainage on flood risk and farming practice,* Aberdeen, Centre of Expertise for Waters, James Hutton Institute.

CROOKS, S. & DAVIES, H. 2001. Assessment of land use change in the Thames catchment and its effect on the flood regime of the river. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere,* 26, 583-591.

D'ODORICO, P. & RIGON, R. 2003. Hillslope and channel contributions to the hydrologic response. *Water Resources Research,* 39, 1113.

DANGERFIELD, S. F. 2013. *The effects of sediment loading on morphology and flood risk in a lowland river system.* University of Nottingham.

DARBY, S. E. & THORNE, C. R. 1996. Predicting Stage-Discharge Curves in Channels with Bank Vegetation. *Journal of Hydraulic Engineering,* 122, 583-586.

DAWSON, R. J., BALL, T., WERRITTY, J., WERRITTY, A., HALL, J. W. & ROCHE, N. 2011. Assessing the effectiveness of non-structural flood management measures in the Thames Estuary under conditions of socio-economic and environmental change. *Global Environmental Change,* 21, 628-646.

DAWSON, R. J., DICKSON, M. E., NICHOLLS, R. J., HALL, J. W., WALKDEN, M. J. A., STANSBY, P. K., MOKRECH, M., RICHARDS, J., ZHOU, J., MILLIGAN, J., JORDAN, A., PEARSON, S., REES, J., BATES, P. D., KOUKOULAS, S. & WATKINSON, A. R. 2009. Integrated analysis of risks of coastal flooding and cliff erosion under scenarios of long term change. *Climatic Change,* 95, 249-288.

DAWSON, R. J., HALL, J. W., BATES, P. D. & NICHOLLS, R. J. 2005. Quantified analysis of the probability of flooding in the Thames Estuary under imaginable worst case sea-level rise scenarios. *International journal of Water Resources Development,* 21, 577-591.

DE ROO, A., SCHMUCK, G., PERDIGAO, V. & THIELEN, J. 2003. The influence of historic land use changes and future planned land use scenarios on floods in the Oder catchment. *Physics and Chemistry of the Earth,* 28, 1291-1300.

DEASY, C., BAXENDALE, S. A., HEATHWAITE, A. L., RIDALL, G., HODGKINSON, R. & BRAZIER, R. E. 2011. Advancing understanding of runoff and sediment transfers in agricultural catchments through simultaneous observations across scales. *Earth Surface Processes and Landforms,* 36, 1749-1760.

DEASY, C., TITMAN, A. & QUINTON, J. N. 2014. Measurement of flood peak effects as a result of soil and land management, with focus on experimental issues and scale. *Journal of Environmental Management,* 132**,** 304-312.

DEFRA 2016. *Structure of the Agricultural Industry: Annual statistics on the number of livestock in England and the UK in June and December*, London, DEFRA (https://www.gov.uk/government/statistical-data-sets/structure-of-the-livestock-industry-in-england-at-december).

DI BALDASSARRE, G., CASTELLARIN, A. & BRATH, A. 2009. Analysis of the effects of levee heightening on flood propagation: example of the River Po, Italy. *Hydrological Sciences Journal,* 54**,** 1007-1017.

DIXON, H., HANNAFORD, J. & FRY, M. 2013. The effective management of national hydrometric data – experiences from the United Kingdom. *Hydrological Sciences Journal,* 58**,** 1383-1389.

DIXON, S. J. & SEAR, D. A. 2014. The influence of geomorphology on large wood dynamics in a low gradient headwater stream. *Water Resources Research,* 50**,** 9194-9210.

DIXON, S. J., SEAR, D. A., ODONI, N. A., SYKES, T. & LANE, S. N. 2016. The effects of river restoration on catchment scale flood risk and flood hydrology. *Earth Surface Processes and Landforms*.

DOOGE, J. C. I. 1986. Looking for hydrologic laws. *Water Resour. Res.*, 22(9S)**,** 46S–58S.

DOWNS, P. W. & THORNE, C. R. 2000. Rehabilitation of a lowland river: Reconciling flood defence with habitat diversity and geomorphological sustainability. *Journal of Environmental Management,* 58**,** 249-268.

DUNG, B. X., GOMI, T., MIYATA, S., SIDLE, R. C., KOSUGI, K. & ONDA, Y. 2012. Runoff responses to forest thinning at plot and catchment scales in a headwater catchment draining Japanese cypress forest. *Journal of Hydrology,* 444-445**,** 51-62.

DUNN, S. M. & MACKAY, R. 1995. Spatial variation in evapotranspiration and the influence of land use on catchment hydrology. *Journal of Hydrology,* 171**,** 49-73.

EVANS, E., ASHLEY, R., HALL, J., PENNING-ROWSELL, E., SAUL, A., SAYERS, P., THORNE, C. & WATKINSON, A. 2004. *Foresight: Future Flooding. Scientific Summary: Volume 1—Future Risks and Their Drivers*, London, Office of Science and Technology.

EVANS, E. P., SIMM, J. D., THORNE, C. R., ARNELL, N. W., ASHLEY, R. M., HESS, T. M., LANE, S. N., MORRIS, J., NICHOLLS, R. J., PENNING-ROWSELL, E. C., REYNARD, N. S., SAUL, A. J., TAPSELL, S. M., WATKINSON, A. R. & WHEATER, H. S. 2008. *An update of the Foresight Future Flooding 2004 qualitative risk analysis*, London (http://webarchive.nationalarchives.gov.uk/20100807034701/http:/archive.cabinetoffice.gov.uk/pittreview/_/media/assets/www.cabinetoffice.gov.uk/flooding_review/evidence/foresight_report pdf.pdf), Cabinet Office.

EVANS, M. G., BURT, T. P., HOLDEN, J. & ADAMSON, J. K. 1999. Runoff generation and water table fluctuations in blanket peat: Evidence from UK data spanning the dry summer of 1995. *Journal of Hydrology,* 221**,** 141-160.

EVERITT, B. L. 1968. Use of the cottonwood in an investigation of the recent history of a flood plain. *American Journal of Science,* 266**,** 417-439.

EWEN, J., GERIS, J., O'CONNELL, E., O'DONNELL, G. & MAYES, W. 2015. Multiscale experimentation, monitoring and analysis of long-term land use changes and flood risk. *Project Report SC060092/R1*. Bristol: Environment Agency.

EWEN, J., O'DONNELL, G., BULYGINA, N., BALLARD, C. & O'CONNELL, E. 2013. Towards understanding links between rural land management and the catchment flood hydrograph. *Quarterly Journal of the Royal Meteorological Society,* 139**,** 350-357.

FERRIER, R. C. & JENKINS, A. 2009. Handbook of Catchment Management. *Handbook of Catchment Management***,** 1-540.

FOULDS, S. A. & MACKLIN, M. G. 2015. A hydrogeomorphic assessment of twenty-first century floods in the UK. *Earth Surf. Process. Landforms*.

FULLER, R. M., SHEAIL, J. & BARR, C. J. 1994. The Land of Britain, 1930-1990: A Comparative Study of Field Mapping and Remote Sensing Techniques. *The Geographical Journal,* 160**,** 173-184.

GAO, J., HOLDEN, J. & KIRKBY, M. J. 2015. A distributed TOPMODEL for modelling impacts of land-cover change on river flow in upland peatland catchments. *Hydrological Processes,* 29**,** 2867-2879.

GAO, J., HOLDEN, J. & KIRKBY, M. J. in press. The impact of land-cover change on flood peaks in peatland basins. Water Resources Research.

GILBERT, G. K. 1880. *Report on the Geology of the Henry Mountains,* Washington DC, US Government Printing Office.

GODFRAY, C., BLACQUIERE, T., FIELD, L. M., HAILS, R. S., PETROKOFSKY, G., POTTS, S. G., RAINE, N. E., VANBERGEN, A. J. & MCLEAN, A. R. 2014. A restatement of the natural science evidence base concerning neonicotinoid insecticides and insect pollinators. *Proceedings of the Royal Society B: Biological Sciences,* 281**,** 20140558.

GODFRAY, H. C. J., DONNELLY, C. A., KAO, R. R., MACDONALD, D. W., MCDONALD, R. A., PETROVSKY, G., WOOD, J. L. N., WOODROFFE, R., YOUNG, D. B. & MCLEAN, A. R. 2013. A restatement of the natural science evidence base relevant to the control of bovine tuberculosis in Great Britain. *Proceedings of the Royal Society B: Biological Sciences,* 280**,** 20131634.

GRAND-CLEMENT, E., ANDERSON, K., SMITH, D., LUSCOMBE, D., GATIS, N., ROSS, M. & BRAZIER, R. E. 2013. Evaluating ecosystem goods and services after restoration of marginal upland peatlands in South-West England. *J Appl Ecol,* 50**,** 324-334.

GRAYSON, R., HOLDEN, J. & ROSE, R. 2010. Long-term change in storm hydrographs in response to peatland vegetation change. *Journal of Hydrology,* 389**,** 336-343.

GURNELL, A. M. 1998. The hydrogeomorphological effects of beaver dam-building activity. *Progress in Physical Geography,* 22**,** 167-189.

HACK, J. T. 1957. Studies of longitudinal stream profiles in Virginia and Maryland. *US Geological Survey Professional Paper,* 294-B.

HALL, J., ARHEIMER, B., BORGA, M., BRÁZDIL, R., CLAPS, P., KISS, A., KJELDSEN, T. R., KRIAUČIŪNIENĖ, J., KUNDZEWICZ, Z. W., LANG, M., LLASAT, M. C., MACDONALD, N., MCINTYRE, N., MEDIERO, L., MERZ, B., MERZ, R., MOLNAR, P., MONTANARI, A., NEUHOLD, C., PARAJKA, J., PERDIGÃO, R. A. P., PLAVCOVÁ, L., ROGGER, M., SALINAS, J. L., SAUQUET, E., SCHÄR, C., SZOLGAY, J., VIGLIONE, A. & BLÖSCHL, G. 2014. Understanding flood regime changes in Europe: a state-of-the-art assessment. *Hydrology and Earth System Sciences,* 18**,** 2735-2772.

HALL, J. W. 2010. Editorial. *Journal of Flood Risk Management,* 3**,** 1-2.

HALL, J. W., SAYERS, P. B. & DAWSON, R. J. 2005a. National-scale assessment of current and future flood risk in England and Wales. *Natural Hazards,* 36**,** 147-164.

HALL, J. W., TARANTOLA, S., BATES, P. D. & HORRITT, M. S. 2005b. Distributed Sensitivity Analysis of Flood Inundation Model Calibration. *Journal of Hydraulic Engineering,* 131**,** 117-126.

HANNAFORD, J. 2015. Climate-driven changes in UK river flows: A review of the evidence. *Progress in Physical Geography,* 39**,** 29-48.

HANNAFORD, J. & MARSH, T. 2008. High flow and flood trends in a network of undisturbed catchments in the UK. *International Journal of Climatology,* 28**,** 1325-1338.

HARVEY, A. M. 2001. Coupling between hillslopes and channels in upland fluvial systems: implications for landscape sensitivity, illustrated from the Howgill Fells, northwest England. *Catena,* 42**,** 225-250.

HEATHWAITE, A. L., BURT, T. P. & TRUDGILL, S. T. 1989. Runoff, sediment, and solute delivery in agricultural drainage basins:a scale-dependent approach. *IAHS Publication,* 182**,** 175-190.

HEATHWAITE, A. L., BURT, T. P. & TRUDGILL, S. T. 1990. Land-use controls on sediment production in a lowland catchment, south- west England. *In:* BOARDMAN, J., FOSTER, I. D. L. & DEARING, J. A. (eds.) *Soil Erosion on Agricultural Land.* Chichester: Wiley.

HENSHAW, A. J. 2009. *Impacts of land use changes and land management practices on upland catchment sediment dynamics: Pontbren, mid-Wales.* Ph.D., University of Nottingham.

HEY, R. D. 1979. FLOW RESISTANCE IN GRAVEL-BED RIVERS. *Journal of the Hydraulics Division-Asce,* 105**,** 365-379.

HOA, L. T. V., SHIGEKO, H., NHAN, N. H. & CONG, T. T. 2008. Infrastructure effects on floods in the Mekong River Delta in Vietnam. *Hydrological Processes,* 22**,** 1359-1372.

HOERLING, M. P., HURRELL, J. W. & XU, T. 2001. Tropical origins for recent North Atlantic climate change. *Science,* 292**,** 90-92.

HOLDEN, J. 2005. Peatland hydrology and carbon cycling: why small-scale process matters. *Philosophical Transactions of the Royal Society A,* 363**,** 2891-2913.

HOLDEN, J. 2008. Upland hydrology. *In:* BONN, A., HUBACEK, K., STEWART, A. & ALLOTT, T. (eds.) *Drivers of change in upland environments.* London: Routledge.

HOLDEN, J. & BURT, T. P. 2003. Runoff production in blanket peat covered catchments. *Water Resources Research,* 39**,** 1191.

HOLDEN, J., CHAPMAN, P. J. & LABADZ, J. C. 2004. Artificial drainage of peatlands: hydrological and hydrochemical process and wetland restoration. *Progress in Physical Geography,* 28**,** 95-123.

HOLDEN, J., KIRKBY, M. J., LANE, S. N., MILLEDGE, D. J., BROOKES, C. J., HOLDEN, V. & MCDONALD, A. T. 2008. Overland flow velocity and roughness properties in peatlands. *Water Resources Research,* 44**,** W06415.

HOLDEN, J., PALMER, S. M., JOHNSTON, K., WEARING, C., IRVINE, B., L., P. & BROWN, L. E. 2015. Impact of prescribed burning on blanket peat hydrology. *Water Resources Research,* 51**,** 6472-6484.

HOLMAN, I. P., HOLLIS, J. M., BRAMLEY, M. E. & THOMPSON, T. R. E. 2003. The contribution of soil structural degradation to catchment flooding: a preliminary investigation of the 2000 floods in England and Wales. *Hydrology and Earth System Sciences,* 7**,** 754-765.

HOOIJER, A., KLIJN, F., PEDROLI, G. B. M. & VAN OS, A. G. 2004. Towards sustainable flood risk management in the Rhine and Meuse river basins: synopsis of the findings of IRMA-SPONGE. *River Research and Applications,* 20**,** 343-357.

HOOKE, J. 2003. Coarse sediment connectivity in river channel systems: a conceptual framework and methodology. *Geomorphology,* 56**,** 79-94.

HOSKINS, W. G. 1955. *The Making of the English Landscape,* London, Hodder and Stoughton.

HOUGHTON-CARR, H. A., BOORMAN, D.B AND HEUSER, K. Land use , climate change and water availability : Phase 2a Development of the Rapid Evidence Assessment protocol. 2013a.

HOUGHTON-CARR, H. A., BOORMAN, D.B AND HEUSER, K. Land use, climate change and water availability: Phase 2a. Rapid Evidence Assessment: Results and synthesis. 2013b.

HOWE, G. M., SLAYMAKER, H. O. & HARDING, D. M. 1967. Some Aspects of the Flood Hydrology of the Upper Catchments of the Severn and Wye. *Transactions of the Institute of British Geographers,* 41**,** 33-58.

HUDSON, J. A. & CRANE, S. B. 1997. The impact of the growth of new plantation forestry on evaporation and streamflow in the Llanbrynmair catchments. *Hydrology and Earth System Sciences,* 1**,** 463-475.

HUPP, C. R. & OSTERKAMP, W. R. 1996. Riparian vegetation and fluvial geomorphic processes. *Geomorphology,* 14**,** 277-295.

INSTITUTE OF HYDROLOGY 1999. *Flood Estimation Handbook,* Crowmarsh Gifford, Institute of Hydrology.

JACKSON, B. M., WHEATER, H. S., MCINTYRE, N. R., CHELL, J., FRANCIS, O. J., FROGBROOK, Z., MARSHALL, M., REYNOLDS, B. & SOLLOWAY, I. 2008. The impact of upland land management on flooding: insights from a multiscale experimental and modelling programme. *Journal of Flood Risk Management,* 1**,** 71-80.

JAIN, S. C. 2001. *Open-Channel Flow,* New York, Wiley.

JEFFRIES, R., DARBY, S. E. & SEAR, D. A. 2003. The influence of vegetation and organic debris on flood-plain sediment dynamics: Case study of a low-order stream in the New Forest, England. *Geomorphology,* 51**,** 61-80.

JOHNSON, R. C. 1995. Effects of Upland Afforestation on Water Resources: The Balquhidder Experiment 1981-1991. *Institute of Hydrology Report 116 (2nd Edition).*

JONES, H. P., HOLE, D. G. & ZAVALETA, E. S. 2012. Harnessing nature to help people adapt to climate change. *Nature Climate Change,* 2**,** 504-509.

JONES, J. A. & GRANT, G. E. 1996. Peak flow responses to clear cutting and roads in small and large basins, western Cascades, Oregon. *Water Resources Research,* 32**,** 959-974.

JONES, P. D. & CONWAY, D. 1997. Precipitation in the British Isles: An analysis of area-average data updated to 1995. *International Journal of Climatology,* 17**,** 427-438.

KAY, A. L., CROOKS, S. M., DAVIES, H. N., PRUDHOMME, C. & REYNARD, N. S. 2014. Probabilistic impacts of climate change on flood frequency using response surfaces I: England and Wales. *Regional Environmental Change,* 14**,** 1215-1227.

KIRKBY, M. 1976. Tests of the random network model, and its application to basin hydrology. *Earth Surf. Processes,* 1**,** 197-212.

KJELDSEN, T. R. 2009. Modelling the impact of urbanisation on flood runoff volume. *Water Management,* 162**,** 329-336.

KLEINHANS, M. G., FERGUSON, R. I., LANE, S. N. & HARDY, R. J. 2013. Splitting rivers at their seams: bifurcations and avulsion. *Earth Surface Processes and Landforms,* 38**,** 47-61.

KNIGHT, D. W., MCGAHEY, C., LAMB, R. & SAMUELS, P. 2010. *Practical Channel Hydraulics: Roughness, Conveyance and Afflux,* CRC Press.

KUNDZEWICZ, Z. W., GRACZYK, D., MAURER, T., PINSKWAR, I., RADZIEJEWSKI, M., SVENSSON, C. & SZWED, M. 2005. Trend detection in river flow series: 1. Annual maximum flow. *Hydrological Sciences Journal,* 50**,** 797-810.

KUNDZEWICZ, Z. W., KANAE, S., SENEVIRATNE, S. I., HANDMER, J., NICHOLLS, N., PEDUZZI, P., MECHLER, R., BOUWER, L. M., ARNELL, N., MACH, K., MUIR-WOOD, R., BRAKENRIDGE, G. R., KRON, W., BENITO, G., HONDA, Y., TAKAHASHI, K. & SHERSTYUKOV, B. 2014. Flood risk and climate change: global and regional perspectives. *Hydrological Sciences Journal,* 59**,** 1-28.

LANE, S. N. & MILLEDGE, D. G. 2013a. Impacts of upland open drains upon runoff generation: A numerical assessment of catchment-scale impacts. *Hydrological Processes,* 27**,** 1701-1726.

LANE, S. N. & MILLEDGE, D. G. 2013b. Impacts of upland open drains upon runoff generation: a numerical assessment of catchment-scale impacts. *Hydrological Processes,* 27**,** 1701-1726.

LANE, S. N., MORRIS, J., O'CONNELL, P. E. & QUINN, P. F. 2007a. Rural land management response measures. *In:* THORNE, C. R. (ed.) *Future Flooding.* London: Thomas Telford.

LANE, S. N., NOVEMBER, V., LANDSTRÖM, C. & WHATMORE, S. 2013. Explaining Rapid Transitions in the Practice of Flood Risk Management. *Annals of the Association of American Geographers,* 103**,** 330-342.

LANE, S. N., ODONI, N., LANDSTRÖM, C., WHATMORE, S. J., WARD, N. & BRADLEY, S. 2011. Doing flood risk science differently: An experiment in radical scientific method. *Transactions of the Institute of British Geographers,* 36**,** 15-36.

LANE, S. N., TAYEFI, V., REID, S. C., YU, D. & HARDY, R. J. 2007b. Interactions between sediment delivery, channel change, climate change and flood risk in a temperate upland environment. *Earth Surface Processes and Landforms,* 32**,** 429-446.

LAVERS, D. A., ALLAN, R. P., WOOD, E. F., VILLARINI, G., BRAYSHAW, D. J. & WADE, A. J. 2011. Winter floods in Britain are connected to atmospheric rivers. *Geophysical Research Letters,* 38.

LAWLER, D. M., COUPERTHWAITE, J., BULL, L. J. & HARRIS, N. M. 1997. Bank erosion events and processes in the Upper Severn basin. *Hydrol. Earth Syst. Sci.,* 1**,** 523-534.

MACDONALD, D., DIXON, A., NEWELL, A. & HALLAWAYS, A. 2012. Groundwater flooding within an urbanised flood plain. *Journal of Flood Risk Management,* 5**,** 68-80.

MACKIN, J. H. 1948. Concept of the Graded River. *Geological Society of America Bulletin,* 59**,** 463-512.

MACKLIN, M. & RUMSBY, B. 2007. Changing climate and extreme floods in the British uplands. *Transactions of the Institute of British Geographers,* 32**,** 168-186.

MANSELL, M. & ROLLET, F. 2006. Water balance and the behaviour of different paving surfaces. *Water and Environment Journal,* 20**,** 7-10.

MARC, V. & ROBINSON, M. 2007. The long-term water balance (1972–2004) of upland forestry and grassland at Plynlimon, mid-Wales. *Hydrological Sciences Journal,* 11**,** 44-60.

MARJORIBANKS, T. I., HARDY, R. J., LANE, S. N. & PARSONS, D. R. 2014. High-resolution numerical modelling of flow—vegetation interactions. *Journal of Hydraulic Research,* 52**,** 775-793.

MARSH, T. & HARVEY, C. L. 2012. The Thames flood series: a lack of trend in flood magnitude and a decline in maximum levels. *Hydrology Research,* 43**,** 203-214.

MARSH, T. J. & HANNAFORD, J. 2007. *The Summer 2007 Floods in England and Wales – A Hydrological Appraisal,* Wallingford, Centre for Ecology & Hydrology.

MARSHALL, M. R., BALLARD, C. E., FROGBROOK, Z. L., SOLLOWAY, I., MCINTYRE, N., REYNOLDS, B. & WHEATER, H. S. 2014. The impact of rural land management changes on soil hydraulic properties and runoff processes: results from experimental plots in upland UK. *Hydrological Processes,* 28**,** 2617-2629.

MARSHALL, M. R., FRANCIS, O. J., FROGBROOK, Z. L., JACKSON, B. M., MCINTYRE, N., REYNOLDS, B., SOLLOWAY, I., WHEATER, H. S. & CHELL, J. 2009. The impact of upland land management on flooding: results from an improved pasture hillslope. *Hydrological Processes,* 23**,** 464-475.

MASTERMAN, R. & THORNE, C. R. 1992. Predicting Influence of Bank Vegetation on Channel Capacity. *Journal of Hydraulic Engineering,* 118**,** 1052-1058.

MATTHEWS, T., MURPHY, C., WILBY, R. L. & HARRIGAN, S. 2015. A cyclone climatology of the British Isles 1871-2012. *International Journal of Climatology*.

MCGAHEY, C., SAMUELS, P. G. & KNIGHT, D. W. A practical approach to estimating the flow capacity of rivers – application and analysis. *In:* ALVES, E., CARDOSO, A., LEAL, J. & FERREIRA, R., eds. International Conference on Fluvial Hydraulics, 2006 Lisbon, Portugal, 6-8 September 2006.

MCGRATH, M. & SMITH, M. Sustainable Catchment Management Programme (SCaMP): From hilltop to tap. *In:* DURHAM, U., ed. BHS 9th National Hydrology Symposium, 2006. British Hydrological Society.

MCINTYRE, N. & BALLARD, C. The potential for reducing flood risk through changes to rural land management: outcomes from the Flood Risk Management Research Consortium. 2012. 8.

MCINTYRE, N., BALLARD, C., BRUEN, M., BULYGINA, N., BUYTAERT, W., CLUCKIE, I., DUNN, S., EHRET, U., EWEN, J., GELFAN, A., HESS, T., HUGHES, D., JACKSON, B., KJELDSEN, T., MERZ, R., PARK, J.-S., CONNELL, E. O., DONNELL, G. O., OUDIN, L., TODINI, E., WAGENER, T. & WHEATER, H. 2013. Modelling the hydrological impacts of rural land use change: current state of the science and future challenges. *Hydrology Research,* In Press**,** 1-19.

MCINTYRE, N. & MARSHALL, M. 2010. Identification of rural land management signals in runoff response. *Hydrological Processes,* 24**,** 3521-3534.

MCINTYRE, N. & THORNE, C. (eds.) 2013. *Land use management effects on flood flows and sediments - guidance on prediction,* London: CIRIA.

MEENTEMEYER, R. K. & BUTLER, D. R. 1999. Hydrogeomorphic effects of beaver dams in Glacier National Park, Montana. *Physical Geography,* 20**,** 436-446.

MIDGLEY, T. L., FOX, G. A. & HEEREN, D. M. 2012. Evaluation of the bank stability and toe erosion model (BSTEM) for predicting lateral retreat on composite streambanks. *Geomorphology,* 145–146**,** 107-114.

MILLER, J. D., KIM, H., KJELDSEN, T. R., PACKMAN, J., GREBBY, S. & DEARDEN, R. 2014. Assessing the impact of urbanization on storm runoff in a peri-urban catchment using historical change in impervious cover. *Journal of Hydrology,* 515**,** 59-70.

MORTON, D., ROWLAND, C., WOOD, C., MEEK, L., MARSTON, C., SMITH, G., WADSWORTH, R. & SIMPSON, I. C. 2011. *Final Report for LCM2007 - the new UK land cover map,* Countryside Survey Technical Report No 11/07. (CEH Project Number: C03259). NERC/Centre for Ecology & Hydrology.

MUDELSEE, M., BÖRNGEN, M., TETZLAFF, G. & GRÜNEWALD, U. 2003. No upward trend in the occurrence of extreme floods in central Europe. *Nature,* 425**,** 166-169.

NATURAL ENVIRONMENT RESEARCH COUNCIL 1975. *Flood Studies Report,,* Swindon, NERC.

NELSON, P. A., SMITH, J. A. & MILLER, A. J. 2006. Evolution of channel morphology and hydrologic response in an urbanizing drainage basin. *Earth Surface Processes and Landforms,* 31**,** 1063-1079.

NEWSON, M. D., PITLICK, J. & SEAR, D. A. 2002. Running water: Fluvial geomorphology and river restoration. *In:* PERROW, M. R. & DAVY, A. J. (eds.) *Handbook of Ecological Restoration.* Cambridge: Cambridge University Press.

NISBET, T., ROE, P., MARRINGTON, S., THOMAS, H., BROADMEADOW, S. & VALATIN, G. 2015. Project RMP5455: Slowing the Flow at Pickering. Final Report to Forestry Commission *Final Report to Forestry Commission* London: DEFRA.

O'DONNELL, G., EWEN, J. & O'CONNELL, P. E. 2011. Sensitivity maps for impacts of land management on an extreme flood in the Hodder catchment, UK. *Physics and Chemistry of the Earth,* 36**,** 630-637.

O'DONNELL, G. M. 2007. *Information Tracking for Flood Impact of Land Use and Management Change.* PhD Thesis, Newcastle University.

O’CONNELL, P. E., EWEN, J., O’DONNELL, G. & QUINN, P. 2007. Is there a link between agricultural land-use management and flooding? *Hydrology and Earth System Sciences,* 11**,** 96-107.

O’CONNELL, P. E. O., BEVEN, K., CLEMENTS, R. O. & HARRIS, G. Review of Impacts of Rural Land Use and Management on Flood Generation. Impact Study Report. Appendix A: Review of UK data sources relating to the impacts of land use and management on flood generation. R&D Technical Report FD2114/TR. 2004.

OCKENDEN, M. C., DEASY, C., QUINTON, J. N., SURRIDGE, B. & STOATE, C. 2014. Keeping agricultural soil out of rivers: Evidence of sediment and nutrient accumulation within field wetlands in the UK. *Journal of Environmental Management,* 135**,** 54-62.

OSBORN, T. J., HULME, M., JONES, P. D. & BASNETT, T. A. 2000. Observed trends in the daily intensity of United Kingdom precipitation. *International Journal of Climatology,* 20**,** 347-364.

OUDIN, L., ANDRÉASSIAN, V., LERAT, J. & MICHEL, C. 2008. Has land cover a significant impact on mean annual streamflow? An international assessment using 1508 catchments. *Journal of Hydrology,* 357**,** 303-316.

OVENDEN, J. C. & GREGORY, K. J. 1980. The permanence of stream networks in Britain. *Earth Surface Processes,* 5**,** 47-60.

OWENS, P., DUZANT, J., DEEKS, L., WOOD, G., MORGAN, R. & COLLINS, A. 2007. Evaluation of contrasting buffer features within an agricultural landscape for reducing sediment and sediment-associated phosphorus delivery to surface waters. *Soil Use and Management,* 23**,** 165-175.

OWENS, P. & WALLING, D. E. 2002. The phosphorus content of fluvial sediment in rural and industrialized river basins. *Water Research,* 36**,** 685-701.

PALMER, R. C. & SMITH, R. P. 2013. Soil structural degradation in SW England and its impact on surface-water runoff generation. *Soil Use and Management,* 29**,** 567-575.

PARROTT, A., BROOKS, W., HARMAR, O. & PYGOTT, K. 2009. Role of rural land use management in flood and coastal risk management. *Journal of Flood Risk Management,* 2**,** 272-284.

PATTISON, I. & LANE, S. N. 2012. The link between land-use management and fluvial flood risk: A chaotic conception? *Progress in Physical Geography,* 36**,** 72-92.

PATTISON, I., LANE, S. N., HARDY, R. J. & REANEY, S. M. 2014. The role of tributary relative timing and sequencing in controlling large floods. *Water Resources Research,* 50**,** 5444–5458.

PERFECT, C., GILVEAR, D., LAW, A. & WILLBY, N. 2015. The Scottish Beaver Trial: Fluvial geomorphology and river habitat 2008-2013, final report. *Scottish Natural Heritage Commissioned Report No. 683.*

PILKINGTON, M., WALKER, J., MASKILL, R., ALLOTT, T. & EVANS, M. 2015. *Restoration of blanket bogs; flood risk reduction and other ecosystem benefits, Final report of the Making Space for Water project: Moors for the Future Partnership, Edale; summary and 8 detailed annexes available at:* http://www.moorsforthefuture.org.uk/making-space-water-2.

POLLOCK, M. M., LEWALLEN, G., WOODRUFF, K., JORDAN, C. E. & CASTRO, J. M. (eds.) 2015. *The Beaver Restoration Guidebook: Working with Beaver to Restore Streams, Wetlands, and Floodplains.*, Portland, Oregon. Online at: http://www.fws.gov/oregonfwo/ToolsForLandowners/RiverScience/Beaver.asp: United States Fish and Wildlife Service.

PRUDHOMME, C., DADSON, S., MORRIS, D., WILLIAMSON, J., GOODSELL, G., CROOKS, S., BOELEE, L., DAVIES, H., BUYS, G., LAFON, T. & WATTS, G. 2012. Future Flows Climate: an ensemble of 1-km climate change projections for hydrological application in Great Britain. *Earth Syst. Sci. Data,* 4**,** 143-148.

RACKHAM, O. 1976. *Trees and Woodlands in the British Landscape,* London, J. M. Dent.

RAMCHUNDER, S. J., BROWN, L. E. & HOLDEN, J. 2009. Environmental effects of drainage, drain-blocking and prescribed vegetation burning in UK upland peatlands. *Progress in Physical Geography,* 33**,** 49-79.

RAVEN, E. K., LANE, S. N. & BRACKEN, L. J. 2010. Understanding sediment transfer and morphological change for managing upland gravel-bed rivers. *Progress in Physical Geography,* 34**,** 23-45.

ROBERTS, N. 1998. *The Holocene: an Environmental History,* Oxford, Blackwell.

ROBINSON, J. S., SIVAPALAN, M. & SNELL, J. D. 1995. On the relative roles of hillslope processes, channel routing, and network geomorphology in the hydrologic response of natural catchments. *Water Resources Research,* 31**,** 3089-3101.

ROBINSON, M. 1990. *Impact of improved land drainage on river flows,* Report 113, Institute of Hydrology

ROBINSON, M. 1998. 30 years of forest hydrology changes at Coalburn: water balance and extreme flows. *Hydrology and Earth System Sciences,* 2**,** 233-238.

ROBINSON, M., COGNARD-PLANCQ, A. L., COSANDEY, C., DAVID, J., DURAND, P., FÜHRER, H. W., HALL, R., HENDRIQUES, M. O., MARC, V., MCCARTHY, R., MCDONNELL, M., MARTIN, C., NISBET, T., O'DEA, P., RODGERS, M. & ZOLLNER, A. 2003. Studies of the impact of forests on peak flows and baseflows: A European perspective. *Forest Ecology and Management,* 186**,** 85-97.

ROBINSON, M. & DUPEYRAT, A. 2005. Effects of commercial timber harvesting on streamflow regimes in the Plynlimon catchments, mid-Wales. *Hydrological Processes,* 19**,** 1213-1226.

ROBINSON, M. & RYCROFT, D. W. 1999. The impact of drainage on streamflow. *In:* SKAGGS, W. & VAN SCHILFGAARDE, J. (eds.) *Agricultural Drainage.* Madison, Wisconsin: American Society of Agronomy.

ROUGIER, J., SPARKS, S. & HILL, L. J. 2013. *Risk and Uncertainty Assessment for Natural Hazards,* Cambridge University Press.

SACO, P. M. & KUMAR, P. 2002. Kinematic dispersion in stream networks – 1. Couplinghydraulic and network geometry. *Water Resour. Res.,* 38**,** 1244.

SALAZAR, S., FRANCÉS, F., KOMMA, J., BLUME, T., FRANCKE, T., BRONSTERT, A. & BLÖSCHL, G. 2012. A comparative analysis of the effectiveness of flood management measures based on the concept of "retaining water in the landscape" in different European hydro-climatic regions. *Nat. Hazards Earth Syst. Sci.,* 12**,** 3287-3306.

SAYERS, P. B., GALLOWAY, G., PENNING-ROWSELL, E., SHEN, F., WEN, K., CHEN, Y. & LE QUESNE, T. 2015a. Strategic flood management: ten 'golden rules' to guide a sound approach. *International Journal of River Basin Management,* 13**,** 137-151.

SAYERS, P. B., HALL, J. W. & MEADOWCROFT, I. C. 2002. Towards risk-based flood hazard management in the UK. *Civil Engineering,* 150**,** 36-42.

SAYERS, P. B., HORRITT, M., PENNING-ROWSELL, E. & MCKENZIE, A. 2015b. *Climate Change Risk Assessment 2017: Projections of future flood risk in the UK,* London, Committee on Climate Change (Research undertaken by Sayers and Partners on behalf of the Committee on Climate Change).

SCAIFE, A. A., KNIGHT, J. R., VALLIS, G. & FOLLAND, C. K. 2005. A stratospheric influence on the winter NAO and north Atlantic surface climate. *Geophys. Res. Lett.,* 32**,** L187152.

SCHUMM, S. A. 1979. Geomorphic Thresholds: The Concept and Its Applications. *Transactions of the Institute of British Geographers,* 4**,** 485-515.

SCOTT, D. F. & PRINSLOO, F. W. 2008. Longer-term effects of pine and eucalypt plantations on streamflow. *Water Resources Research,* 44.

SEAR, D. A., MILLINGTON, C. E., KITTS, D. R. & JEFFRIES, R. 2010. Logjam controls on channel: floodplain interactions in wooded catchments and their role in the formation of multi-channel patterns. *Geomorphology,* 116**,** 305-319.

SEAR, D. A., NEWSON, M. D. & BROOKES, A. 1995. Sediment-related river maintenance: The role of fluvial geomorphology. *Earth Surf. Process. Landforms,* 20**,** 629-647.

SEAR, D. A., NEWSON, M. D. & THORNE, C. R. 2004. *Guidebook of Applied Fluvial Geomorphology,* Swindon, WRc.

SEAR, D. A., WILCOCK, D., ROBINSON, M. R. & FISHER, K. R. 2000. Channel modifications and impacts. *In:* ACREMAN, M. (ed.) *The Changing Hydrology of the UK.* London: Routledge.

SEPA 2008. *Engineering in the Water Environment. Good Practice Guide: Bank Protection Rivers and Lochs. Document reference: WAT-SG-23,* Stirling, SEPA.

SEPA 2012. *Bank Protection: Position Statement to support the implementation of the Water Environment (Controlled Activities) (Scotland) Regulations 2011. Document reference WAT-PS-07-02,* Stirling, SEPA.

SEPA 2016. *Natural Flood Management Handbook,* Stirling, SEPA.

SHAW, E., BEVEN, K., CHAPPELL, N. A. & LAMB, R. 2011. *Hydrology in Practice,* Abingdon, Spon Press.

SLATER, L. 2016. To what extent have changes in channel capacity contributed to flood hazard trends in England and Wales? *Earth Surface Processes and Landforms,* 41**,** 1115–1128.

SLATER, L. J., SINGER, M. B. & KIRCHNER, J. W. 2015. Hydrologic versus geomorphic drivers of trends in flood hazard. *Geophysical Research Letters,* 42**,** 370-376.

SLINGO, J. & PALMER, T. 2011. Uncertainty in weather and climate prediction. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* 369**,** 4751-4767.

SMITH, J. A., BAECK, M. L., MORRISON, J. E., STURDEVANT-REES, P., TURNER-GILLESPIE, D. F. & BATES, P. D. 2002. The Regional Hydrology of Extreme Floods in an Urbanizing Drainage Basin. *Journal of Hydrometeorology,* 3**,** 267-282.

SOLARI, L., VAN OORSCHOT, M., BELLETTI, B., HENDRIKS, D., RINALDI, M. & VARGAS-LUNA, A. 2016. Advances on Modelling Riparian Vegetation—Hydromorphology Interactions. *River Research and Applications,* 32**,** 164-178.

STROMBERG, J. C., RICHTER, B. D., PATTEN, D. T. & WOLDEN, L. G. 1993. Response Of A Sonoran Riparian Forest To A 10-Year Return Flood. *Great Basin Naturalist,* 53**,** 118-130.

SUTTON, R. T. & DONG, B. 2012. Atlantic Ocean influence on a shift in European climate in the 1990s. *Nature Geosci,* 5**,** 788-792.

SVENSSON, C., HANNAFORD, J., KUNDZEWICZ, Z. W. & MARSH, T. 2006. Trends in river floods: why is there no clear signal? *IAHS Publication,* 305.

SWANSON, F. J. & SPARKS, R. E. 1990. Long-Term Ecological Research and the Invisible Place. *BioScience,* 40.

THORNE, C. 2014. Geographies of UK flooding in 2013/4. *The Geographical Journal,* 180**,** 297-309.

THORNE, C., WALLERSTEIN, N., SOAR, P., BROOKES, A., WISHART, D., BIEDENHARN, D., GIBSON, S., LITTLE JR, C., MOONEY, D., WATSON, C. C., GREEN, T., COULTHARD, T. & VAN DE WIEL, M. 2011a. Accounting for sediment in flood risk management. *In:* PENDER, G. & FAULKNER, H. (eds.) *Flood Risk Science and Management.* Oxford: Blackwell.

THORNE, C. R., EVANS, E. P. & PENNING-ROWSELL, E. (eds.) 2007. *Future Flooding and Coastal Erosion Risks,* London: Thomas Telford.

THORNE, C. R., HENSHAW, A. J. & DANGERFIELD, S. 2011b. *Catchment sediment dynamics and flood risk: Impacts of upland agricultural land management on catchment sediment dynamics at Pontbren, mid-Wales.,* EPSRC Grant No. EP/FP202511/1, FRMRC Fact Sheet

THORNE, C. R. & OSMAN, A. M. 1988. Riverbank Stability Analysis: II Applications. *Journal of Hydraulic Engineering,* 114**,** 151-172.

TRENBERTH, K. E. 2011. Changes in precipitation with climate change. *Climate Research,* 47**,** 123-138.

USBR 2016. *National Large Wood Manual: Assessment, Planning, Design, and Maintenance of Large Wood in Fluvial Ecosystems: Restoring Process, Function, and Structure,* http://www.usbr.gov/pn/, Bureau of Reclamation and U.S. Army Engineer Research and Development Center (USBR and ERDC).

VALENTOVÁ, J., VALENTA, P. & WEYSKRABOVÁ, L. 2010. Assessing the retention capacity of a floodplain using a 2D numerical model. *Journal of Hydrology and Hydromechanics,* 58**,** 221-232.

VIGLIONE, A., CHIRICO, G. B., WOODS, R. & BLÖSCHL, G. 2010. Generalised synthesis of space–time variability in flood response: an analytical framework. *J. Hydrol.,* 394**,** 198–212.

VOROGUSHYN, S. & MERZ, B. 2013. Flood trends along the Rhine: the role of river training. *Hydrol. Earth Syst. Sci.,* 17**,** 3871-3884.

WARD, R. C. & ROBINSON, M. R. 1999. *Principles of Hydrology,* Maidenhead, McGraw-Hill.

WATTS, G., BATTARBEE, R., BLOOMFIELD, J. P., CROSSMAN, J., DURANCE, I., ELLIOT, J., GARNER, G., HANNAH, D. M., HESS, T., JACKSON, C. R., KAY, L., KERNAN, M., KNOX, J., MACKAY, J., DON, T., ORMEROD, S., RANCE, J., STUART, M. E., WADE, A. J., WADE, S. D., WEATHERHEAD, K., WHITEHEAD, P. G. & WILBY, R. L. 2015. Climate change and water in the UK – past changes and future prospects. *Progress in Physical Geography,* 39**,** 6 - 28.

WHEATER, H. S., REYNOLDS, B., MCINTYRE, N., M.R., M., JACKSON, B. M., FROGBROOK, Z. L., SOLLOWAY, I., FRANCIS, O. J. & CHELL, J. 2008. *Impacts of upland land management on flood risk: multi-scale modelling methodology and results from the Pontbren experiment,* Flood Risk Management Research Consortium, Manchester, FRMRC Research Report UR16.

WILBY, R. L., BEVEN, K. J. & REYNARD, N. S. 2008. Climate change and fluvial flood risk in the UK: more of the same? *Hydrological Processes,* 22**,** 2511 - 2523.

WILBY, R. L. & QUINN, N. W. 2013. Reconstructing multi-decadal variations in fluvial flood risk using atmospheric circulation patterns. *Journal of Hydrology,* 487**,** 109-121.

WILKINSON, M. E., QUINN, P. F. & WELTON, P. 2010. Runoff management during the September 2008 floods in the Belford catchment, Northumberland. *Journal of Flood Risk Management,* 3.

WILSON, L., WILSON, J., HOLDEN, J., JOHNSTONE, I., ARMSTRONG, A. & MORRIS, M. 2011. The impact of drain blocking on an upland blanket bog during storm and drought events, and the importance of sampling-scale. *Journal of Hydrology,* 404**,** 198-208.

WMO 2009. *Integrated Flood Management: Concept Paper,* Geneva, World Meteorological Organisation.

WOODS BALLARD, B., WILSON, S., UDALE-CLARKE, H., ILLMAN, S., SCOTT, T., ASHLEY, R. & KELLAGHER, R. 2015. *The SuDS Manual,* London, CIRIA.

ZOCCATELLI, D., BORGA, M., CHIRICO, G. B. & NIKOLOPOULOS, E. I. 2015. The relative role of hillslope and river network routing in the hydrologic response to spatially variable rainfall fields. *Journal of Hydrology,* 531, Part 2**,** 349-359.

Table 2 Studies evaluating the effectiveness of CBFM/NFM techniques (After: Environment Agency, JBA Consulting)

Name of Scheme	Type of intervention	Location	Study area	Summary of effect	Sponsor / Funder	Ref
Belford	Off-channel storage	Northumberland	5.7 km^2	Runoff attenuation by off-channel storage feature resulted in increased time-to-peak during a 2% AEP rainfall event for 0.5 km^2 sub-catchment.	Environment Agency	1
Pontbren	Tree planting; ditch blocking	Mid Wales	12.5 km^2	Infiltration rates up to 67 times higher in woodland compared with pasture; tree shelterbelts simulated to reduce peak flows by 2-11% for a 0.6% AEP rainfall event in a 6 km^2 sub-catchment.	Flood Risk Management Consortium (FRMRC), Coed Cymru, Coed Cadw Woodland Trust	2
Pickering	Off-channel storage, and upland land management measures	North Yorkshire	69 km^2	Off-channel storage, and other woodland, moorland and farmland interventions are estimated to provide protection against a 4% AEP flood. The Pickering project has two types of intervention: NFM in the upland landscape, and a clay bund and engineered offline storage. The latter is what gives the 4% AEP flood protection but at a cost of approximately £3m.	Ryedale District Council North Yorkshire County Council; Local Flood Levy; Defra, Forestry Commission	3
New Forest LIFE3 (Blackwater)	Runoff attenuation features	Hampshire	12 km^2	Attenuation of flood peak due to added roughness and storage	Forestry Commission, Environment Agency, Natural England	4
Berwyn Drain Blocking	Drain blocking	Mid Wales	100 km^2	Drain blocking led to raised water tables and diminished flood peaks	RSPB, EU-LIFE-Nature	6
SCaMP Hodder	Tree planting, ditch blocking	Lancashire	260 km^2	Modelling study showing that upland restoration over would lead to only 2% reduction in flood peak	Environment Agency, United Utilities	5

AEP, Annual Exceedance Probability, the chance of a flood of this magnitude or greater occurring in any particular year; 1. Wilkinson et al. (2010); 2. Jackson et al. (2008); 3. Nisbet et al. (2015); 4. http://www.newforestlife.org.uk/life3/; 5. Ewen et al. (2013); 6. Wilson et al. (2011).