

Peatland Catchments and Natural Flood Management

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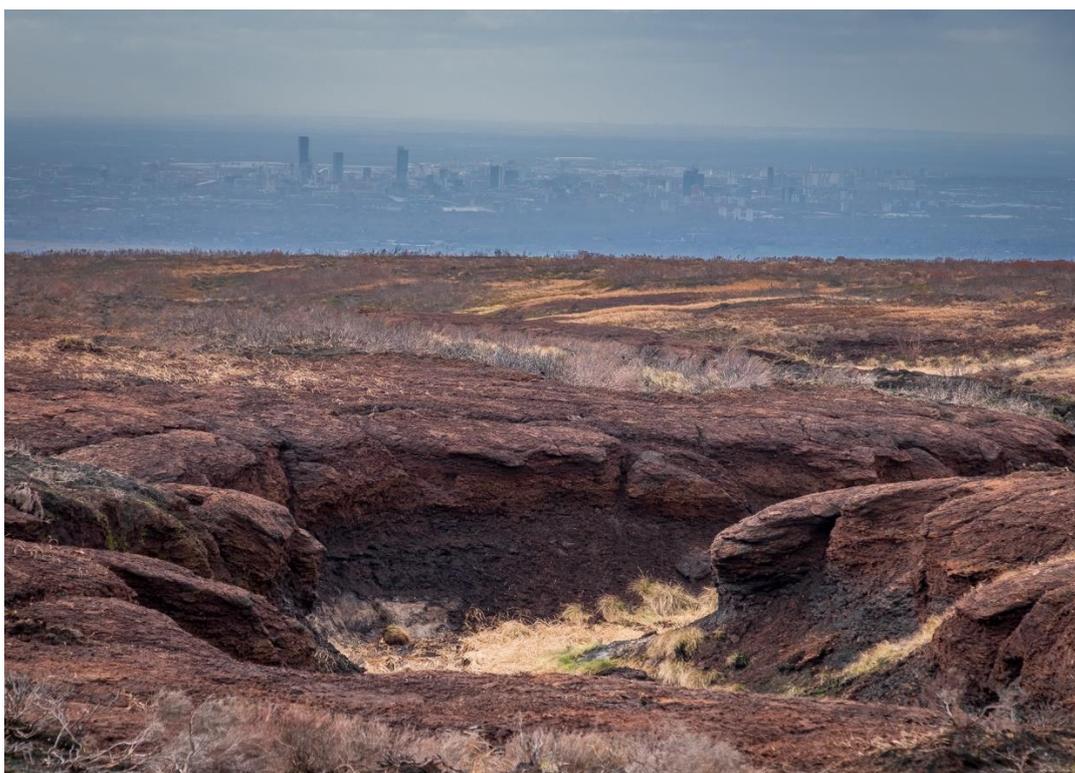
Peatland Catchments and Natural Flood Management

Report to the IUCN UK Peatland Programme's Commission of Inquiry on Peatlands Update

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Plain English Summary

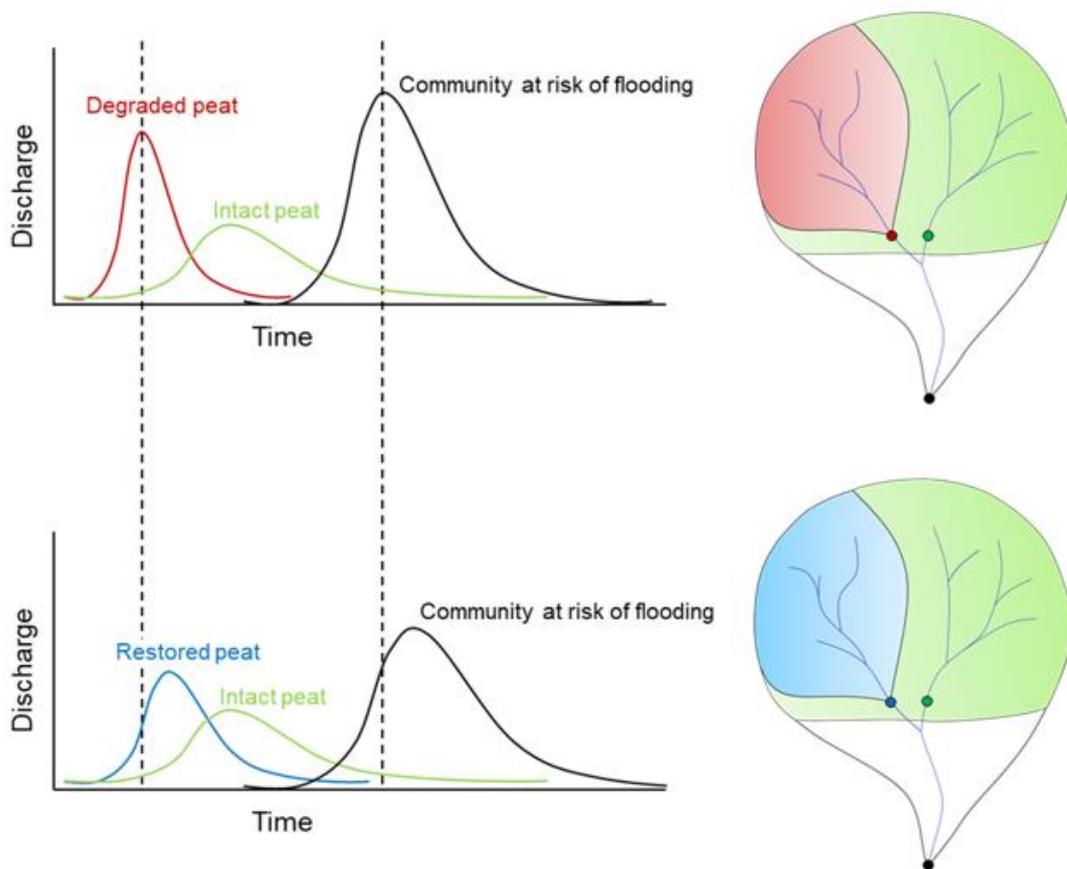
There is increasing interest in the use of Natural Flood Management (NFM) to reduce flood risk for vulnerable communities. NFM seeks to reduce flood risk by restoring or enhancing landscape processes and natural hydrological functions that have been damaged by human activities. Peatlands cover nearly 10% of the UK's land cover but few of our peatlands are in a near-natural state. Most have been damaged by drainage, air pollution, fire, erosion and other land-use pressures, and the last decade has seen a dramatic increase in the number of projects aiming to restore peatland landscapes. Many communities at risk of flooding have large areas of peatland in their upstream catchments, and it is increasingly common to see claims that peatland restoration can reduce flood risk. This report therefore reviews the evidence that restoration of peatlands can reduce the peak flows of rivers and so contribute meaningfully to NFM.

We have good understanding of how storm runoff is generated from peatlands and the changes associated with peat restoration that could contribute to NFM. Restoration may provide increased storage of flood waters in peatland. This is more likely to be associated with restoring surface storage in pools, hollows and depressions than (as is often assumed) through water storage in the peat itself. Any benefits of increased storage would be limited in large rainfall events. Restoration measures can also contribute to NFM by reducing how quickly stormwater moves into river channels ('slowing the flow'), so delaying and reducing flood peaks. The nature of the peat surface and the 'roughness' to stormflow presented by the peatland vegetation cover and vegetation type are key controls on this process.

Recent studies have measured or modelled the impacts of different types of peatland restoration on peak flows in rivers and streams. Some of these have used field monitoring to directly measure change in flood peaks after restoration, but such monitoring is only appropriate in small catchments due to the need to eliminate other (non-restoration) factors. Assessments at larger catchment scales therefore use computer models to upscale the data from field measurements. There is increasing evidence from these various studies that peat restoration alters catchment runoff and can reduce peak flows, and therefore contribute to NFM, in small (<20 km²) catchments. There is some evidence from modelling that the effects could extend into larger catchments. However, the evidence is not consistent across all types of restoration. We have high confidence that the re-vegetation of bare peat and the re-introduction of *Sphagnum* moss to degraded peatlands can reduce peak flows by slowing storm runoff on hillslopes. We also have field data showing that drain blocking can reduce peak flows through increased storage or by slowing flows, but modelling studies predict mixed results, including potential increases in flood peaks for particular orientations and characteristics of drainage. We currently have limited field data on the impacts on peak flows of gully blocking, peat restoration by forest removal, and severe wildfire plus subsequent recovery from fire, although our current understanding of the relevant hydrological processes predicts that gully blocking will reduce peak flows, while forest removal and severe fire will have the opposite effect, particularly immediately after disruption and if no efforts are made to restore deforested or burnt peatlands.

We therefore need more field studies of the impacts of several types of peatland restoration to improve our predictions of change in peak flow and to quantify potential NFM effects, particularly over timescales that are longer than five years. There is also a need for further refinement and testing of our models and the development of modelling capacity to provide more comprehensive, catchment specific assessment of the potential NFM benefits (or adverse effects where relevant) of peatland restoration interventions. These assessments need to be extended to catchments of different sizes and geographies, including more routinely for peatland catchments containing communities at risk of flooding and for rainfall/flood events of different sizes (return periods).

Graphical Abstract



Restoration Measure	Impact on Peak Flows
Re-vegetation of bare peat	↓
Re-introduction of Sphagnum	↓
Gully blocking	↓
Restoration after severe fire	↓
Ditch blocking	Variable
Commercial forest removal	↑

Conceptual and evidence-base for peatland restoration and Natural Flood Management (NFM)

Key Findings

1. There is increasing evidence from both field and modelling studies that peatland restoration measures can alter catchment runoff regimes, reduce peak flows and contribute to Natural Flood Management (NFM) at the small (<20 km²) catchment scale, with some evidence from modelling that peak flow reductions could potentially extend into larger catchments.
2. Peatland surface and vegetation cover represent key controls on storm runoff, hydrograph and peak flow dynamics in peatland catchments.
3. The current evidence base for the NFM effects of key peatland restoration measures indicates that:
 - a) Re-vegetation of bare peat leads to delayed and reduced peaks flows in small catchments.
 - b) Initial data suggests the blocking of erosional gullies can delay and reduce peak flows at small catchment scales.
 - c) Field studies of drain blocking generally report decreased peak flows from peatlands, but model studies indicate that blocking could also increasing peak flows depending on drain orientations and other local factors.
 - d) Plot-scale and modelling studies predict that widespread re-introduction of *Sphagnum* to peatlands has the potential to reduce catchment flood peaks.
 - e) Evidence largely supports the assumption that severely burnt peatlands will have flashier hydrograph responses to rainfall events, with higher peak flows relative to unburnt peatlands or peatlands restored after severe fire.
 - f) Current understanding of forest hydrological processes predicts that the removal of conifer forest cover from peatlands could significantly increase flood peaks, and care will therefore be needed to minimise potential adverse effects of restoration of afforested peatlands.
4. The spatial location of restoration measures within peatland catchments will impact the potential NFM benefit.
5. There are still significant uncertainties in our understanding of peat restoration and NFM. We lack sufficient field data on the impact of several types of restoration measure on flow regimes, and we have limited data on hydrological responses to restoration over longer (>5 year) timescales. We also lack quantitative estimates of the scale of NFM effects of peatland restoration for flood events and catchments of different sizes.
6. Although we can enhance the current evidence base by further monitoring of the impacts of land management and restoration on peak flows through the use of plot and small-scale catchment experiments, direct observation of the impacts on floods at a larger catchment scale (>20 km²) is unrealistic due to confounding factors as scale increases.
7. More comprehensive modelling is therefore required both for catchment-specific assessments and for scaling-up to allow full quantification of the NFM benefits, and any possible adverse consequence, of peatland management and restoration at scales relevant to communities at risk of flooding. Appropriate modelling solutions are already available.
8. Ongoing projects and modelling programmes are addressing some of these uncertainties and evidence gaps, and substantial further progress in our understanding of peatlands and NFM is expected within the next 3-4 years.

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1. Introduction

This report represents a contribution to the Commission of Inquiry on Peatlands Update of the IUCN UK Peatlands Programme. The Commission of Inquiry was established to produce an authoritative set of reports assessing key areas of peatland research with relevance to policymakers. A summary assessment report was published in 2011 (Bain et al., 2011) and as part of this original Inquiry a detailed report was produced on Peat Hydrology (Labadz et al., 2010). The hydrology report summarised the understanding of controls and drivers of change in peat hydrology, with emphasis on issues of water quality. In 2017 the IUCN decided to produce an update of the Inquiry focussing on topics where new scientific information has emerged, including on the hydrology of peatland catchments. There are two important contexts to this topic. First, the scale and variety of peatland restoration projects in the UK has grown dramatically over the last decade and associated scientific studies have more clearly established the effects of restoration practice on peat hydrology (see Parry et al., 2014; Lindsay et al., 2016; Price et al., 2016). Second, and partly as a consequence of recent major flood events, there has been significant recent policy attention on Natural Flood Management (NFM) and the potential contribution NFM could make to fluvial flood risk reduction and management (e.g. SEPA, 2015; Dadson et al., 2017; Ngai et al., 2017).

The current report therefore considers scientific understanding of the effects of peatland restoration and management on peat hydrology, with emphasis on the evidence base for the impacts of restoration on water quantity regulation (i.e. river flow regimes and high flow events) and associated NFM benefits. The aims of the review are to:

- Summarise the recent science around peatland restoration and management and catchment-scale hydrology;
- Review the evidence base for the impacts of peatland restoration and management on river flows and runoff in peatland catchments;
- Assess the current evidence for Natural Flood Management (NFM) benefits from peatland restoration;
- Identify key remaining evidence gaps for the links between peatland condition and restoration and river flood dynamics;
- Make recommendations on future research and evidence gathering priorities for policy development.

The review process was as follows. The review was initiated in 2017 with the review authors conducting a literature review to identify relevant publications since Labadz et al. (2010). Emphasis is on peer-reviewed published literature and publicly available grey literature or reports. A pilot case study was also undertaken to provide a first-order evaluation of the potential for peatland restoration to contribute to NFM using mapping procedures (see Section 3). Initial key findings from the literature review and GIS pilot study were presented and discussed at a Stakeholder Workshop of invited academics, peatland practitioners and flood policy makers held at the University of Manchester in June 2018. This workshop focused on: (i) co-producing a consensus on the evidence base and key findings; (ii) identifying key knowledge gaps in the evidence base and associated priorities; and (iii) collaboratively developing an agenda to fill the gaps in policy relevant scientific information. Notes from the workshop are included in the appendix to this report.

2. The process-based case for peatland restoration and natural flood management

NFM is a form of catchment-based flood management (CBFM) drawing on the principle that downstream flood inundation can be manipulated by land-use and land management measures within the catchment, thereby reducing flood risk and providing an alternative or additional strategy to traditional flood management using hard engineering solutions (Lane, 2017). NFM seeks to restore or enhance catchment processes and hydrological functions that have been degraded by human intervention (Dadson et al., 2017). SEPA (2015) and Ngai et al. (2017) identify a wide variety of NFM measures including river and floodplain management, woodland management and run-off management. There have been several recent reviews of the NFM approach, its effectiveness for flood risk reduction and how it is currently being implemented (see SEPA, 2015; Dadson et al., 2017; Lane, 2017; Ngai et al., 2017; Rogger et al 2017; Stratford et al., 2017). The systematic review by Dadson et al. (2017) is particularly instructive as a summary of the science on the effectiveness of catchment based NFM in the UK. They conclude that the hazard associated with fluvial floods can be significantly reduced by CBFM and NFM measures, but current evidence shows this to be scale dependent. NFM appears effective for small floods in small catchments, but there is more limited evidence that NFM interventions can be effective for large catchments or for the most extreme rainfall events. Dadson et al. (2017) used the convention of areas <20 km² for 'small' catchments and >100 km² for 'large' catchments and this convention is followed in the current report.

Most UK peatlands are in a modified and degraded condition, with only around 20% of our peatland area in a near-natural ('intact') state (IUCN UK Peatland Programme, 2018). Restoration targets have been set as a matter of policy with, for example, the Scottish Government's Climate Change Action Plan aiming to restore 250,000 ha of degraded peatlands by 2030. Restoration of degraded peatlands is increasingly cited as providing natural flood management (NFM) benefits through the alteration of catchment runoff regimes (e.g. Bain et al., 2011; SEPA, 2015; Gao et al., 2016; Price et al., 2016; Ngai et al., 2017; Shuttleworth et al, 2019). This is on the premise that, in comparison to the original intact state, peatland degradation results in higher downstream peak flows and increased flood risk, and restoration practices will in turn alter the hydrology to reduce downstream flood risk.

It is therefore important to consider the processes by which NFM measures in general, and peatland restoration specifically, could contribute to reduction in downstream flood peaks. Lane (2016, 2017) identifies three relevant types of process control:

1. Increased storage of water in the catchment during high river flow events (within-event storage);
2. Reductions in how quickly overland runoff is generated on hillslopes (rapidity of flow generation);
3. Reductions in the rate of conveyance (velocity) of flow on hillslopes or in the channel network ('slowing the flow').

Increased within-event storage would result in reductions in the total volume of runoff during a high flow ('storm') event and corresponding decreases in flood hydrograph peak flow, but would not necessarily change the response time (time to peak flow or hydrograph lag time) of the catchment to the rainfall event (see Figure 1a). Conversely, reductions in the rate of overland flow production or in the rate of stormflow conveyance would not reduce the total volume of storm runoff but would reduce peak flow through hydrograph attenuation and the associated effect of increased lag time (Lane, 2007; see Figure 1b). This distinction between different types of process control is important in understanding the potential relationships between peatland restoration measures and NFM.

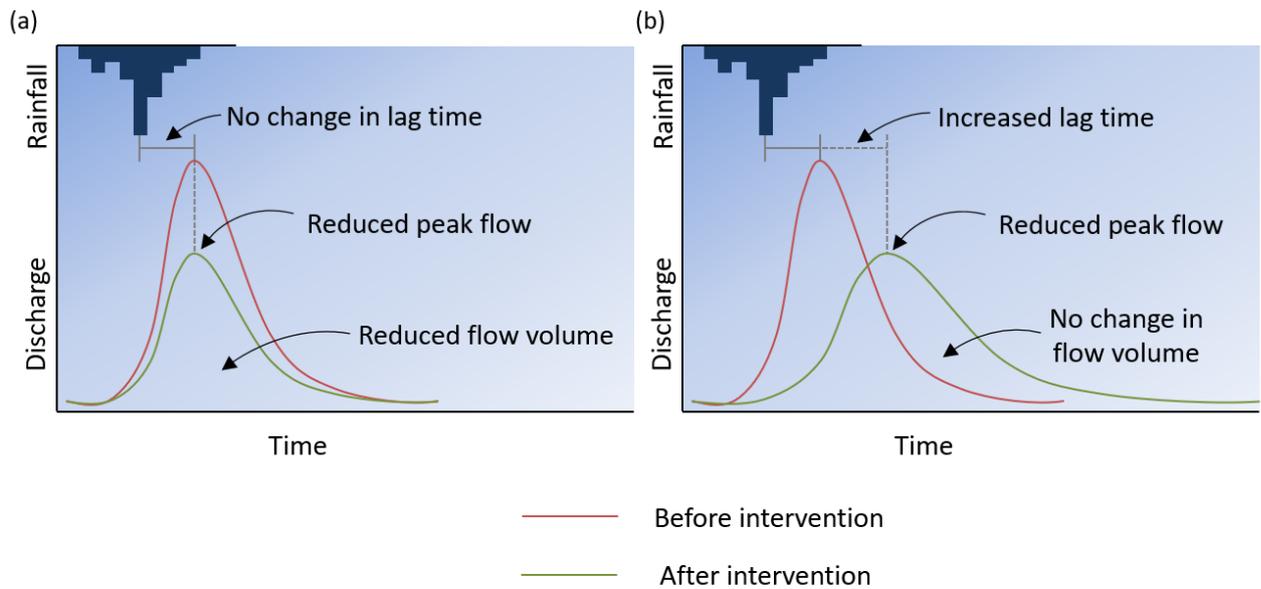


Figure 1: Hypothetical river flood hydrographs showing the impacts on hydrograph peak flows and lag times of natural flood management (NFM) measures which (a) increase within-event storage in the catchment and (b) delay the conveyance of stormwater into river channels.

This report does not present a comprehensive review of the current understanding of hydrological processes and functions and runoff generation within peatland ecosystems as a number of recent reviews are available (e.g. Rydim & Jeglum, 2006; Holden, 2009; Labadz et al., 2010; Acreman & Holden, 2013; Price et al., 2016). However, some consideration of key peatland hydrological processes relative to the three controls on NFM cited by Lane (2017) is necessary as a context for discussing the evidence base for the NFM benefits of peatlands and peatland restoration.

2.1 Within-event storage

The first potential process control on NFM benefits is through within-event storage. There is a common assumption that peatlands reduce downstream flood peaks by buffering rainfall due to greater soil water storage and subsequent slow release of the stored water. This is not the reality in most cases (Bragg, 1992; Bacon et al., 2017). In intact peatlands, water tables are typically within a few centimetres of the ground surface (Evans et al., 1999; Rydim & Jeglum, 2006). Consequently, the capacity for additional soil water storage is limited, and significant rainfall events result in rapid water table rise to the peatland surface and generation of saturation excess overland flow (Evans et al., 1999; Holden & Burt, 2003). In theory peatlands could still have a significant influence on flood peaks through storage effects, but these would be through surface water storage due to topography through the collection of water in depressions or hollows in the landscape (Acreman & Holden, 2013). For example, lowland fen peatlands can represent large-scale depressions in the landscape, often on floodplains or directly connected to river channels, and could therefore offer substantial water storage in high flow events. At a small-scale surface water storage effects can be associated with micro-topographic variation on peatlands, for instance associated with ephemeral pools, pool-hummock topography or hollows on the peatland surface. Such features are often missing in degraded peatlands (Evans & Warburton, 2007). However, the amount of within-event storage effects in peatlands will be subject to antecedent conditions. After wet periods topographic storage will fill, so within-event storage effects will be limited if high flow events occur after prolonged rainfall.

2.2 Overland flow generation

Lane's (2017) second process control on NFM is the rapidity of stormflow generation on hillslopes during a rainfall event. NFM benefits associated with this type of process could occur if hillslope runoff can be manipulated to increase the proportion of runoff following slower flow pathways. NFM interventions might increase infiltration rates into the soil and thereby route runoff into relatively slow throughflow within the soil matrix rather than into rapid overland flow pathways. Lane provides examples associated with changes in agricultural practice on mineral soils such as livestock density reductions and changes in tillage practice. However, runoff generation from intact peatlands is already dominated by rapid flow pathways either on the peat surface or in rapid near surface throughflow within the unsaturated acrotelm (Evans et al., 1999; Holden, 2009). The extent to which the generation of rapid near-surface flow in peatlands can be reduced is constrained by the high-water table conditions of intact peats. Another consideration would be peatland catchments where a significant proportion of stormflow is associated with rapid water transfer in soil pipes (Smart et al., 2013). Soil pipes are common in some blanket peat systems with the development of pipe networks enhanced by land management impacts (Holden, 2005). Such pipes can connect and rapidly transmit saturation excess overland flow through the peat into stream networks. However, Smart et al. (2013) indicate that storm water routing through pipe networks represents a relatively slower route than overland flow, so it is unclear whether the development of pipe networks results in flashier catchment responses.

2.3 Overland flow attenuation

The third key process control on potential benefits of NFM is the slowing of flow either on hillslopes delivering stormwater into channel networks or within catchment channel networks themselves (Lane, 2017). Given that stormflow in peatlands is dominated by overland flow, the rapidity of delivery of stormwater from hillslopes into stream networks is largely a function of the surface condition of the peat and specifically its hydraulic roughness (Roels, 1984; Holden et al., 2008). Changes in surface cover on peatlands, such as the type or structure of vegetation, would therefore be expected to change the rate of stormflow delivery. Other interventions could potentially increase the hydraulic roughness or create barriers to flow in channel networks or along flow lines, for example the drain or gully blocking techniques commonly employed in peatland restoration projects (Thom et al., 2016). These have the potential to delay stormflow runoff. In theory there is significant potential for NFM benefits through peatland restoration interventions that alter the peatland surface or channel conditions.

Two implications of these different process controls on the potential for NFM and peatland restoration are worth highlighting. The first is that, for large flood events, any NFM benefits resulting from increases in within-storm catchment storage are likely to be less effective than those based on hydrograph attenuation. This is because catchment storage will be limited by high magnitude rainfall events. Alternatively, interventions which slow the flow and promote hydrograph attenuation through the surface roughness effect could potentially contribute to peak flow reduction even after wet antecedent conditions and for higher flow events. A second key implication is the possibility of adverse effects of hydrograph attenuation on catchment peak flow if NFM interventions result in hydrograph synchronisation effects in the river network (Pattison et al., 2014; Lane, 2017). Delays in flood peaks through NFM in a small sub-catchment could theoretically cause an increase in downstream flood peaks if changes to the timing of delivery of peak flow results in coincidence with the peak flow in the main catchment channel hydrograph. These factors need considering when reviewing the evidence base for NFM benefits of peatland restoration.

3. The importance of peat catchments to communities at risk from flooding

Peat covers 9.45% of the land area in the UK (Lindsay et al., 2014) rising to more than 20% in Scotland (Scottish Natural Heritage, 2015). Most of this comprises blanket peat in the upland headwaters of river systems which flow through downstream settlements and other assets vulnerable to flooding including infrastructure (road, rail etc) and agricultural land. If peatland restoration is to make a meaningful contribution to natural flood management (NFM) one prerequisite is that the areas of peatland upstream of communities at risk from flooding are substantial enough to influence catchment flood hydrology. An important first-order evaluation of the potential for peatland restoration to contribute to NFM could be provided by mapping and quantifying areas of peatland and peat soils in the catchment of communities at risk from flooding. However, an analysis of this type is not currently available at a national scale although the datasets required are potentially readily available if license restrictions can be addressed.

As part of the current review a regional pilot study was conducted to evaluate the spatial extent of peatlands in the catchments of a set of 21 Communities at Risk (C@R) of flooding in the West Pennine fringes of the Greater Manchester, Merseyside and Cheshire (GMMC) region. These were identified by the Environment Agency due to either their history and frequency of flooding or their geographical proximity to uplands which make them vulnerable to sustained, heavy rainfall events.

The objectives of the pilot study were to use a Geographical Information System (GIS) to:

1. Create a map and associated graphical representation to demonstrate the relationship between peatland areas and Communities at Risk of flooding, and;
2. Establish catchment areas and proportions of peatland within these using outlets located immediately downstream of the C@R.

Three datasets were used: (i) locations and properties in the C@R from the Environment Agency; (ii) peatland extent and location from the National Soil Map held by Cranfield University; and (iii) a LiDAR derived digital elevation model (DEM) for the study area provided by the Environment Agency. The datasets were licenced to the Moors for the Future Partnership (MFFP) and the analysis conducted by Jorge Auñón of MFFP. Catchment areas of the 21 C@R were established in ArcGIS using the DEM. Peatland coverage and C@R maps were layered over the catchment outlines to allow extraction of relationships between C@R and the extent of peat soils. Two classes of soils from the National Soil Map were used; deep- (>40 cm depth) and shallow- (10-40 cm) peaty soils.

Three key observations can be made from the extracted data in Figure 1 and Table 1:

1. Just over half (12 of 21) of the C@R are situated in small catchments (<20 km²), a catchment size for which there is evidence that land-use intervention can reduce the flood response (see Dadson et al., 2017; Ngai et al., 2017).
2. There are six small catchments (<20km²) which contain more than 100 properties at risk. For example, Shaw and Crompton has over 1000 properties at risk in a catchment of <12km². Indeed, over 30% of the 11,500 properties at risk in the dataset occur in small catchments.
3. Most of the catchments contain high proportions of peaty soils; 20 of the 21 catchments contain >20% cover of peaty soils by area. However, in terms of potential for peat restoration related NFM it is more appropriate to consider only deep peat soils, as this class best represent the conditions where peat restoration is most likely to occur. 18 of the catchments have >10% deep peat, 9 have >25% deep peat and two small catchments (Carbrook and Grasscroft) are dominated by deep peat (>50%). Of the 11,500 properties at risk nearly 2000 (17%) occur in catchments where the cover of deep peat exceeds 25% of the catchment area.

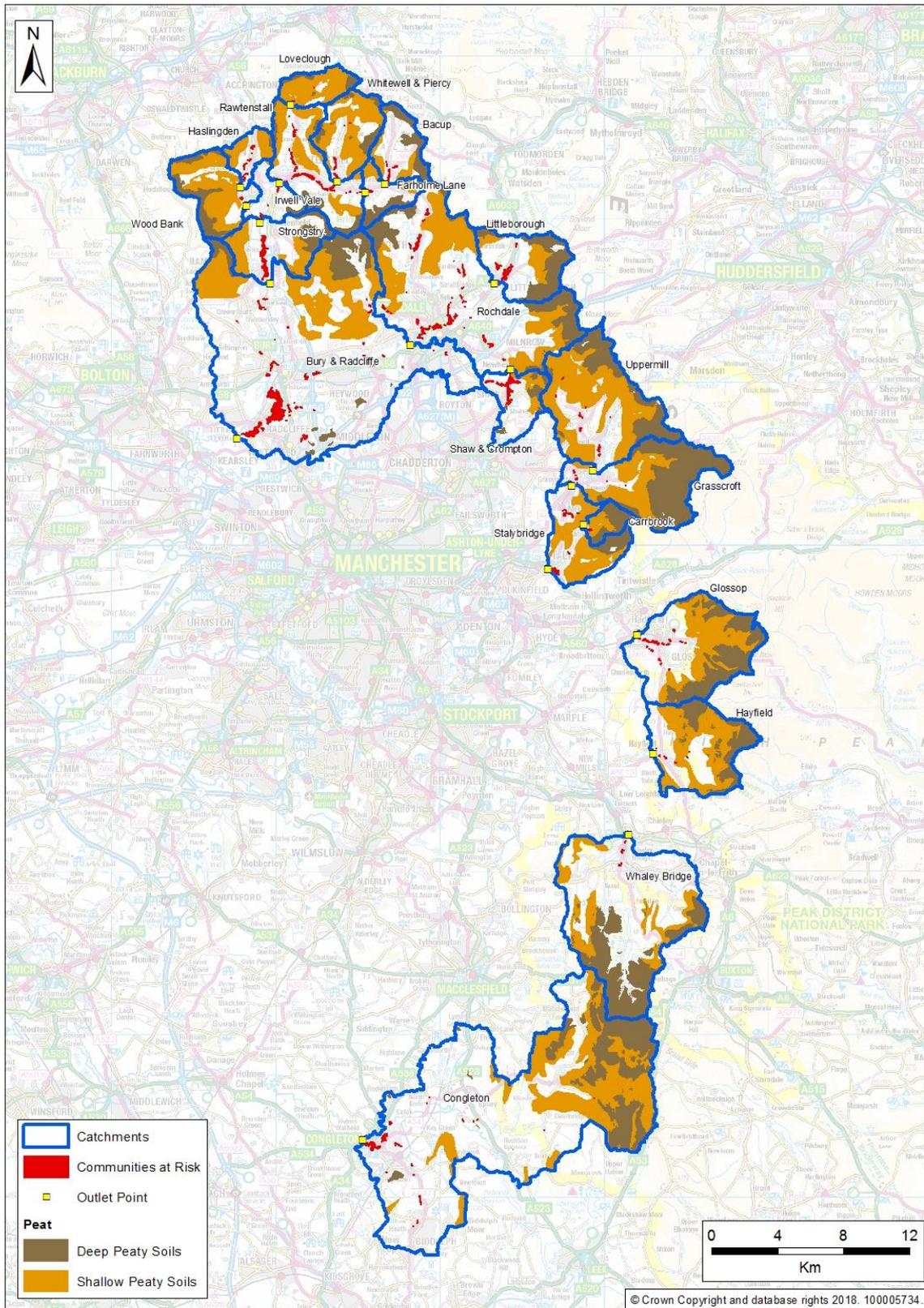


Figure 2: Map of 22 communities at risk from flooding in the Greater Manchester and Cheshire Environment Agency region, showing extent of peat soils in the catchments.

Catchment	Properties at Risk	Total Catchment Area (km ²)	Total Peatland Area %	Deep Peat Soils %	Shallow Peat Soils %
Bacup	115	11.9	47.7	30.9	16.8
Bury and Ratcliffe	3233	139.0	21.4	6.0	15.5
Carrbrook	65	4.6	96.2	60.9	35.3
Congleton	858	151.2	35.8	13.7	20.5
Farholme Lane	68	7.9	47.0	25.4	21.6
Glossop	602	38.6	61.0	31.9	28.5
Grasscroft	88	31.1	84.0	56.3	27.7
Haslingden	76	6.3	52.0	6.0	46.1
Hayfield	45	28.5	67.7	25.0	42.7
Irwell Vale	80	7.7	8.7	6.5	2.2
Littleborough	586	18.7	50.1	34.6	15.5
Loveclough	19	8.3	91.8	15.6	76.2
Rawtenstall	963	25.0	41.7	11.3	30.4
Rochdale	1710	79.5	35.8	12.7	23.2
Shaw and Crompton	1034	11.9	27.5	12.0	15.4
Stalybridge	773	18.7	59.4	12.5	46.9
Strongstry	521	19.0	45.7	16.8	28.8
Uppermill	259	41.2	73.9	24.9	49.1
Whaley Bridge	74	66.0	36.2	25.1	14.8
Whitewell & Piercy	266	16.2	67.4	13.1	54.3
Wood Bank	61	17.5	77.9	26.0	51.0

Table 1 Number of properties at risk, catchment areas and extent of peatlands in 21 catchments at risk of flooding in the Greater Manchester and Cheshire Environment Agency region.

The case study demonstrates the importance of peatlands within this set of C@R of flooding, emphasising the potential for peat restoration related NFM in this region. These figures are considered conservative estimates since they are amalgamations combining all properties at risk to the lowest point in the catchment. The compelling associations between communities at risk of flooding and catchment peat cover demonstrated for the GMMC region may not be representative for other parts of the UK even where C@R occur in upland catchments. Nevertheless, the method employed is straightforward and provides a valuable first-order analysis of the potential importance of peatlands for communities at risk. It would form a useful framework for a more comprehensive UK-scale assessment of the relationships between communities at risk, peatland cover and the potential for peatland restoration to contribute to flood risk management.

4. Impacts of peatland restoration and management on the hydrology and flow regimes of peatland catchments: The evidence base

Process understanding of peat hydrology indicates that management interventions in peatlands have the potential to impact the regulation of downstream river flows including peak discharges in flood events (Acreman & Holden 2003; Kadykalo & Findlay 2016; see section 2). We now review the evidence for the effects of peatland restoration and management on catchment flood hydrographs and on peatland hydrology more generally, where this is relevant to NFM and the understanding of peak flow behaviour. We also consider the impacts of restoration and peatland management on low flow regimes where evidence is available. The following widespread peatland restoration and management practices are included: peatland drainage and restoration by drain blocking; the revegetating of bare peat; blocking of erosion gullies; the re-introduction of *Sphagnum* moss to degraded peatlands; forestry, restoration of afforested peatlands, and woodland planting; and moorland burning and restoration following wildfire.

4.1 Peatland drainage and restoration by drain blocking

In the UK artificial drainage of peatlands using ditches has been extensive, with over 1.5 million hectares of blanket peat drained in the uplands (Holden et al., 2004; Parry et al., 2014). Although hydrological responses to drainage vary, in most reported cases the principal effects have been lowering of water tables, reductions in hydrograph lag times and increases in peak flows (see Holden et al., 2006; Labadz et al., 2010). The blocking of drainage ditches represents one of the most commonly reported techniques used by peat restoration projects, in most cases involving the placement of dams at regular intervals along drains (Parry et al., 2014). Ditch blocking of this type could be expected to significantly alter hydrological regimes and flow pathways (see Holden et al., 2004, 2006). Depending on the success of the installed dams, pools are created along the line of the former ditch representing water storage. Effective blocking of ditches to the height of the surrounding peatland surface will allow drainage water to spill out onto the surrounding peatland, creating new drainage routes and converting ditch flow to overland flow. The extent and importance of these changes in flow pathways will partially be controlled by the orientation of the ditches relative to the topography and hillslopes.

Recent studies evaluating the impacts of drain blocking on peak flows have been based on both: (i) field studies providing direct observational evidence, and; (ii) modelling approaches which simulate hydrological responses using process understanding and data from field experiments.

Several recent field experiments have evaluated the impacts of ditch blocking on peak flows. The Sustainable Catchment Management Programme (SCaMP) project funded by United Utilities

monitored flow regimes before and after drain blocking in four catchments in the Peak District and Forest of Bowland in England. Catchment sizes varied between 1.6 – 6.7 km² and Anderson et al. (2011) collated four years of data after intervention. They report that stream flow in all catchments maintained water yield characteristics and that there was some evidence that hydrograph responses had changed to a less flashy, more attenuated character. However, limited detail on the scale of these effects is provided by Anderson et al. and a more comprehensive analysis of the SCaMP stream flow data by Ewen et al. (2015) observed that it is difficult to draw general conclusions as the pre-intervention monitoring period was short. Wilson et al. (2010, 2011) present data on hydrograph change in both ditches and small streams following drain blocking of blanket peatlands in the Lake Vyrnwy catchment, mid Wales. Catchment sizes/contributing areas were generally not reported, but a value of c.12.5 ha is given for one of the ditch systems. The ditch systems at the sites were orientated across the catchment slopes. The study reports significant reductions in peak flow and hydrograph ‘flashiness’ (ratio of peak flow to total storm flow) following drain blocking, but no significant changes in lag times. The study also reports higher and more stable water tables following drain blocking, and that discharge from both drains and streams remained higher during droughts after blocking. The papers present only limited quantification of the observed changes, and the authors additionally caution that sample sizes for some of the hydrological analyses were limited.

Observational data on the hydrological effects of drain blocking have also been reported from the ‘Mires on the Moors’ experiment on Exmoor (Gatis et al., 2015; Grand-Clement et al., 2015; Luscombe et al., 2016; Ashe et al., 2017). This study represents a before-after comparison of the hydrology of two catchments characterised by relatively shallow (typically <1m), drained blanket peatland (Aclands, 19.5 ha; Spooners, 46.5 ha). In these catchments, ditches are predominantly aligned in downslope orientations. After ditch blocking the change in water tables was spatially complex, and overall evaluation of post-restoration change was confounded by a wet pre-intervention monitoring period. However, overall site water tables were stable between the before and after periods, implying some water table recovery given the difference in meteorological conditions between the monitoring periods. Rainfall-runoff relationships changed after ditch blocking. Total and peak discharges were reduced following restoration, with significant declines in peak flows (35% decline at Spooners and 22% at Acklands). However, there were no changes in the lag times of storm events (Gatis et al., 2015). Bower (2015) provided an initial evaluation of changes in baseflow (low flow), demonstrating evidence of higher baseflows (Q95 – the flow which occurs for 95% of the time) following restoration. The authors consider that the results to date for the experiment are preliminary and stress the need for analyses of further years of data to more fully establish and quantify the hydrological effects of the ditch blocking. However, their initial interpretation is that reductions in peak discharges in storm events are associated with increased short-term storage in ephemeral pools created by ditch blocking, which can drain down between storm events (D. Luscombe, personal communication). Given the shallow nature of the peats in these catchments, some of this drainage may be associated with connectivity to shallow groundwater systems underneath the peat.

Holden et al. (2017) present hydrological and discharge data from a ditch blocking experiment in the Migneint blanket peatlands, North Wales. The study monitored 12 ditches with downslope orientations over four years, using a before-after-control-impact (BACI) design. Topographic catchment areas for the ditches prior to blocking were 1-2.5 ha, although the authors recognise that significant changes in individual catchment (contributing) area can take place following ditch blocking. The study found an immediate step change in discharge in the ditches following blocking, with a five-fold reduction in flow, and runoff water displaced to overland flow or flow pathways away from the ditches. They also found that flows in the ditches were more continuous in later years of the study, indicating more sustained baseflow. Monitoring over a three-year post -restoration period showed a gradual trend of increasing ditch flow, indicating a lagged response to ditch blocking and an increase in baseflow in the ditches. Local water tables on the site were already

relatively close to the surface prior to ditch blocking, and there was limited evidence of increased water tables after ditch blocking (<2 cm rise). Although the study did not fully quantify storm hydrograph characteristics following ditch blocking, it demonstrates that storm discharge within ditches could potentially be significantly reduced following blocking. Importantly it also indicates that the immediate effects of blocking might not fully represent longer-term responses.

Ballard et al. (2011, 2012) developed a physics-based model to evaluate changes in hydrological regime at small spatial scales (2 ha) following drain blocking. They used this to produce a series of simulations exploring the hydrological and runoff response of intact, drained and blocked sites. The model indicated that drain blocking would usually decrease peak flows, but it also predicted that in some cases local conditions could lead to increased peak stormflows after blocking, most specifically where drains are already heavily vegetated or where drain angles are lower than the downslope flow paths created by drain blocking. Ballard et al. (2012) predicted that steep and smooth (i.e. non-vegetated) drainage ditches would show the greatest reduction in peak flows following drain blocking. Lane and Milledge (2012) developed a modelling approach to assess the impacts of ditch blocking on peatland storm hydrographs at a larger catchment scale based on the widely used TOPMODEL and applied this model to the Oughtershaw Beck, a 13.8 km² catchment in Yorkshire. The model assumes that ditching:

- (i) provides additional catchment storage due to drier antecedent moisture conditions (i.e. lower water tables) and;
- (ii) drains have higher flow velocities than overland flow thus potentially delivering flow more rapidly into to the drainage network.

Application of the model to the study catchment predicted that intact/restored conditions had higher flood peaks than drained catchments. This apparently counter-intuitive finding resulted from a prediction of decreased water storage in the catchment due to higher soil moisture (water table) conditions after blocking and the geometry of the ditch network where ditches were predominantly cross-slope in arrangement, therefore contributing relatively large travel times to the drainage network. Although the representativeness of this case study to other peatland catchments was not assessed, the importance of the research is in demonstrating that flow regimes could respond in different ways to ditch blocking depending on the arrangement and orientation of ditch networks.

The restoration of water tables is a major driver of drain blocking (Parry et al., 2014). Previous reviews have confirmed that most studies show drain blocking to create shallower water tables in the vicinity of blocked drains and effectively rewet the peatland, although on short timescales not to the levels of undisturbed bogs (Labadz et al., 2010; Haapalehto et al., 2011; Parry et al 2014; Anderson et al., 2017). Although water table data from the recent studies discussed in this section re-enforce these findings, they also demonstrate that water table responses to drain blocking are site specific, with more limited response observed in systems where drains are orientated in a downslope direction (e.g. Gatis et al., 2015; Green et al., 2017; Holden et al., 2017).

4.2 Peat erosion and re-vegetation of bare peat

Peatland erosion has been reported across some 10-30% of the total UK blanket peat area (Evans and Warburton, 2007). Severely eroded blanket peatlands are characterised by extensive areas of bare peat in the form of peat flats or exposed bare peat on the edges of erosion hagsgs or gullies. Over the past decade the stabilisation of eroding upland peatlands through bare peat re-vegetation has been a major focus of UK peatland restoration practice (Thom et al., 2016). A standard approach to re-vegetation of bare peat sites has been widely adopted and is referred to as the Lime-Seed-Fertilizer-Mulch (LSFM) approach (Anderson et al., 2009; Alderson et al., 2019). The treatment allows the rapid (<2 year) establishment of a nurse crop of non-native utility grass species that

stabilise the peat surface and prevents further erosion. This nurse crop facilitates the establishment and expansion of native moorland species over longer (i.e. 10 year) timescales (see Pilkington et al., 2015; Alderson et al., 2019). In the South Pennines over 2500 ha of peatland have been re-vegetated (stabilised) using LFSM by the Moors for the Future Partnership and the approach has been employed across other regions of the UK uplands (Alderson et al., 2019). A key feature of the re-vegetation success in the South Pennines has been the exclusion of grazers (sheep) by large scale fencing, reducing grazing pressure during the early years of vegetation establishment (Anderson et al., 2009). There have been reports from other regions (e.g. Cairngorms, Scotland; A. Cundill, personal communication) that re-vegetation success is more limited where grazers such as deer are not excluded, with subsequent grazing impacting newly planted or introduced vegetation.

Recent studies have provided extensive data on the impacts of the re-vegetation of bare peat on peat hydrology and catchment runoff (Grayson et al., 2010; Allott et al., 2015; Pilkington et al., 2015; Shuttleworth et al., 2019; Alderson et al., 2019). A fully controlled field experiment in the South Pennines provides clear evidence that re-vegetation by LFSM results in re-wetting of the peatland, with significant reductions in depth to water table (35 mm increase in water table at the treatment site four years after re-vegetation) and increased prevalence of overland flow generation during storm events (Shuttleworth et al., 2019). Alderson et al. (2019) demonstrate that this water table recovery continues well after the nurse crop is fully established, with trends to higher water table conditions still apparent 10 years after initial re-vegetation. The authors discuss the possible post-restoration controls on water tables, including the effects of changing energy balance or evapotranspiration associated with changing vegetation cover. However, the trends in water table are out of phase with the vegetation change. Alderson et al (2019) therefore argue they reflect long-term changes in peat structure and progressive recovery of soil hydrological function following restoration.

The impacts of bare-peat revegetation on catchment stormflow peaks and hydrograph response have also been evaluated. Grayson et al. (2010) analysed the effects of the long-term natural re-vegetation of eroding blanket peatlands within the 11.4 km² Trout Beck catchment in northern England, as an analogy for the restoration of bare peat. They evaluated a 40-year storm hydrograph record and found changes in the proportion of bare peat in the catchment were co-incident with changes in peak flow and lag time in the storm hydrograph record. Bare peat was at a maximum (>9% of the catchment area) in the 1970s and storm hydrograph peaks were higher per unit rainfall during this period and lower following re-vegetation (0.40 m³ mm⁻¹ compared to 0.27 m³ mm⁻¹). Mean peak storm discharge was also significantly higher during periods with high bare peat cover. Grayson et al. (2010) concluded that re-vegetation of bare peat could reduce flood peaks at the scale of the catchment studied (11 km²).

Evidence that revegetation reduces peak flows has been greatly re-enforced by an intensive study of restoration interventions in the blanket peats of the Peak District National Park (Allott et al., 2015; Pilkington et al., 2015; Milledge et al., 2015; Shuttleworth et al., 2019; Alderson et al., 2019). This took the form of a before-after-control-intervention (BACI) experiment of hectare-scale micro-catchments, using two treatments: re-vegetation alone and re-vegetation with additional gully blocking (see below). Re-vegetation resulted in significant changes in storm hydrographs, with significantly longer lag times relative to unrestored/bare peat control (106% increase) and reduced peak flows (27% decrease) and increased 'flashiness' of stormflow. Shuttleworth et al. (2019) also demonstrated that the effects persisted in the most extreme rainfall conditions within the dataset, albeit at a reduced level for some hydrograph metrics. Importantly, there was no change in storm runoff co-efficient (the proportion of rainfall leaving the catchment in a storm) associated with the restoration. This indicates that the post-restoration reductions in peak flow and associated hydrograph changes are not attributable to increased catchment storage. Low flow (baseflow) data have not yet been reported from this study.

Although the Shuttleworth et al. (2019) catchment experiment was conducted in micro-catchments of approximately hectare scale, Milledge et al. (2015) used data from the experiment to evaluate the implications of the observed changes in storm runoff for larger catchments. They used a modelling approach combining a hydrograph response unit (HSU) model with a spatially distributed unit hydrograph routing model to upscale the estimates of peak flow reductions to a catchment of c.9 km². Although highlighting uncertainties in the estimates, they concluded that: (i) restoration of 12% of the catchment by a combination of re-vegetation and gully blocking would produce an average reduction of peak discharge of 5%; (ii) suitable modelling approaches can be developed to upscale the results of empirical micro-catchment experiments to the larger catchment scale.

An important aspect of the research on peak flow and hydrograph stormflow response to re-vegetation is the evidence of the processes controlling these responses. Grayson et al. (2010) and Shuttleworth et al. (2019) conclude that reduced peak flows following re-vegetation are the results of retardation of surface (overland) flow during storm events and attenuation of hydrographs. The retardation results from increased roughness of peatland surface after re-vegetation and is consistent with both theoretical and experimental relationships between surface cover type and overland flow velocity (Holden et al., 2008). In detailed plot-scale experiments Holden et al. (2008) showed that overland flow velocity was significantly higher for bare surfaces on peatlands than for vegetated surfaces. Taken together with the Shuttleworth et al. (2019) observation that re-vegetation does not lead to an increase in within-storm storage, the evidence strongly supports the conclusion that increased surface roughness is the key control on peak flow reduction associated with re-vegetation of bare peat surfaces. A further implication is that other types of change in peatland surface roughness (e.g. transitions in vegetation type, vegetation change through grazing pressures, surface cover change associated with fire and burning) will also impact storm hydrograph response and peak storm discharges from headwater peatland catchments.

4.3 Peat erosion and restoration by gully blocking or reprofiling

Extensive erosional gully networks are common in upland peatlands across the UK (Evans and Warburton, 2007) and the blocking and/or reprofiling of erosion channels has become an increasingly important component of peatland restoration projects (see Anderson et al., 2009; Parry et al., 2014; Thom et al., 2016). Gully reprofiling is typically carried out where gully sides are steep and actively eroding. In these cases, techniques used to stabilise the erosion through re-vegetation would likely fail unless the slope angle is reduced. Reprofiling is therefore usually employed as a precursor to restoration by re-vegetation of eroded gully sides (Thom et al., 2016). A range of methods for blocking gullies have been used, the most prevalent of which are stone dams, wooden dams and plastic piling. Although there are some parallels between the blocking of artificial drainage ditches and the blocking of gully networks, a key difference is that restoration by ditch blocking is typically designed to fill the ditches right up to the level of the surrounding peatland, whereas blocks within gully networks generally only partially fill the gullies. Ditch blocking can therefore divert overland flow onto hillslopes whereas the drainage network (flow lines) provided by gullies is maintained even after blocking.

The stated aims of gully blocking have typically been to prevent further erosion loss, promote re-vegetation in the gullies and raise local water tables to increase peat saturation and carbon sequestration (Anderson et al., 2009). However, there are potential impacts of gully blocking or reprofiling on flow regimes through either increased water storage in the pools which can form behind gully blocks or through attenuation of stormflow peaks associated with re-vegetation of blocked or reprofiled gullies. However, the evidence base for these effects is still relatively limited. The only empirical data come from the micro-catchment study of Shuttleworth et al. (2019) discussed above, which in addition to evaluating stormflow responses to re-vegetation also

evaluated the effects of re-vegetation and gully blocking combined. They found the addition of gully blocking significantly extended lag times and increased the reduction of peak flows in comparison to re-vegetation alone. Storm hydrograph lag times increased by a further 94% and peak flows were reduced by an additional 24% relative to control data. Milledge et al. (2015) also used modelling techniques to demonstrate that the design of gully blocks can improve the efficiency of gully blocking in storing stormwater, and therefore reducing peak flows during storm events. These analyses and the Milledge et al. (2015) modelling of effects of combined re-vegetation and gully blocking in a c.9 km² catchment imply that gully blocking can contribute to reducing flood peaks at larger catchment scales. However, further quantifications of gully blocking effects are required as well as consideration of the changing impacts of gully blocking on peak flows as gully blocks mature and pool storage and revegetation effects evolve.

4.4 *Sphagnum* re-introduction to degraded peatland systems

Sphagnum is absent or restricted in spatial cover in many UK peatlands due to air pollution (sulphate or nitrogen deposition) or through other land management pressures (Lee, 1998; Holden et al., 2008) and there is growing emphasis on restoring *Sphagnum* cover to peatland landscapes such as the Pennines. In these heavily impacted upland regions levels of air pollution and atmospheric deposition have fallen, *Sphagnum* species and bryophytes generally are reappearing, but recovery is very slow (Carroll et al., 2009). Large-scale *Sphagnum* re-introduction to both bare peat sites and to peatland vegetation lacking bryophyte cover is therefore being widely trialled using plug plants from donor sites, bryophyte rich mulch or beads containing *Sphagnum* propagules (Thom et al., 2016).

There is growing evidence that large-scale *Sphagnum* re-introduction could significantly impact the hydrology and peak flow characteristics of peatland catchments where *Sphagnum* cover is currently absent or restricted. The key process involved is the retardation of overland flow and therefore the delay in the delivery of stormwater from hillslopes to stream and river channels. The plot-scale study of Holden et al. (2008) provides detailed data on overland flow velocity across different peatland surface types; bare peat, *Eriophorum* and *Sphagnum*. *Sphagnum* cover provides a significantly higher effective roughness to overland flow than the other surface types, with overland flow travelling c.10 times more rapidly across bare peat surfaces than those covered by *Sphagnum* moss (Holden et al., 2008). The same study predicted that large-scale *Sphagnum* reintroduction to bare peat or cotton grass dominated peatlands would reduce peak flows in high flow events. Gao et al. (2016, 2017) used a spatially distributed version of the widely applied TOPMODEL (see Gao et al., 2015) to evaluate the impact of different land cover scenarios at a larger catchment scale, including introduction of *Sphagnum* cover on flood peaks associated with a 1-in-10 year rainfall event. Gao et al. (2016) simulated flood response for three upland catchments with areas of 11.4 km², 10.6 km² and 21.5 km², predicting that high density planting of *Sphagnum* within riparian zones would result in reductions in flood peaks of 10.1%, 1.8% and 13.4% respectively. The study emphasised the importance of spatial location of any restoration intervention, with the revegetation of riparian areas most effective. Cover changes on shallow slopes were also more effective than those on steeper slopes. Gao et al. (2017) then used a comparable modelling approach to predict the impact of different land-use scenarios, including *Sphagnum* reintroduction, for a 1-in-10 year rainfall event in a larger scale (84 km²) upland catchment. Vegetation restoration with *Sphagnum* to the 5.8% of bare peatland in the catchment resulted in a 5.2% reduction in the flood peak, whereas riparian *Sphagnum* planting of the same sized area predicted a much larger (15%) decrease in river peak flow.

These modelling studies suggest that significant reductions in flood peaks at intermediate (i.e. >20km²) catchment scales could be achieved by large-scale *Sphagnum* reintroduction to peatland catchments, particularly if the planting is targeted to flow networks and riparian zones. However,

the models are based on a comprehensive but spatially limited plot-scale study, and the effects have not yet been confirmed or quantified at the catchment scale by field experiments. Greater confidence in the model predictions would be provided by field observation of *Sphagnum* re-introduction related flood hydrograph change at the small- or micro-catchment scale.

4.5 Forestry, restoration of afforested peatlands, and woodland planting

While the hydrological effects of forests and forestry have been much studied around the world, the complexities involved mean that it remains difficult to accurately predict the impact of land use change on catchment behaviour. This especially applies to the case of peatland catchments, where a multitude of factors influence the hydrological response, including peatland type, condition, climate, forest type, forest design, tree age and the nature of past and present management practices. Nevertheless, it is possible to make some general statements about the direction of change based on our understanding of forest hydrological processes informed by plot, hillslope and catchment studies. These are:

- a. Trees and forests generally evaporate more water than shorter types of vegetation, principally due to the interception of rainwater by their aerodynamically rougher canopies (Hudson et al., 1997; Nisbet, 2005). This typically results in drier soils under forests, reduced runoff and lower catchment water yields (McCulloch and Robinson, 1993). Studies show that 10-30% of storm rainfall may be lost by wet canopy evaporation from conifer forest (T. Page, personal communication).
- b. A forest cover can reduce flood peaks while its removal and conversion to open peatland will have the opposite effect. The impacts on peak flows are greatest for small and medium flood peaks, declining with increasing flood size but with potential to reduce large but probably not extreme floods (Ngai et al., 2017).
- c. A forest cover has the potential to reduce, have no effect or increase low flows, depending on local factors.
- d. Forest design and management practices such as cultivation, drainage and road construction can exert a major influence on the above effects, including potentially altering the direction of change. However, impacts can be controlled by the use of good practice measures.

Direct observations to inform the quantification of forest effects on peatland catchment hydrology are very limited in the UK. There is one flagship catchment study which is the long-term evaluation of the impact of upland afforestation on water resources at Coalburn in Northern England (Robinson et al., 1998). This comprises a 150 ha headwater peaty catchment (75% deep peat), around 90% of which was planted with conifer forest in 1973 after a five year period of baseline hydrological measurements. Measurements have continued to present and the recent start of forest felling and replanting. Key findings to date are:

- a. Land use change from moorland to conifer forest had marked effects on catchment hydrology, which varied through time. Initially, pre-planting deep ploughing increased peak flows by 15-20% and reduced time to peak by a third (Robinson, 2004). These changes declined over time and were then reversed, associated with a progressive increase in water use by the growing forest. Identification of significant trends was hampered by rising annual rainfall totals but use of modelling to decouple the effect of climate variability found evidence of peak flows decreasing by 5-20% with forest growth (Birkinshaw et al., 2014). The reduction decreased with increasing event size and appeared to be lost as the return period approached 100 years. The results indicate that forest growth reduced the frequency of discharge events by around 50%, e.g. an event with a return period of 13 years became a return period of 20 years. The findings are

supported by a separate analysis by Archer (2003), who found that afforestation led to an overall reduction in annual pulse/peak flow numbers by nearly 40% and increased peak flow duration by >20% over most of the flow range, compared to conditions under the original moorland cover.

- b. Deep ploughing also led to a marked rise in catchment base flows, increasing from 0.10 to 0.23 of the annual flow, equivalent to a 225% increase (Robinson et al., 1998). Despite a progressive decline during the first five years after planting, values remained at around 0.19 annual flow or 160% of the baseline value. Although there was evidence of a subsequent decline in base flows of 1-2% per year linked to forest growth, the results indicated that the cultivation effect would persist throughout the full forest rotation of 45-50 years (Robinson, 2004). The ability of forest drainage to increase low flows in the medium-long-term has been demonstrated in a number of studies (Seuna, 1980; Lundin, 1984; Nicholson et al., 1989; Sirin et al., 1991) but not everywhere, with others finding the opposite effect (Anderson et al., 2000).
- c. The observed catchment hydrological effects are supported by nested process studies. These found interception losses for established forest stands to average 25-30% of annual rainfall (Robinson, 2004). The effect of this 'biological drainage' combined with the mechanical drainage due to the pre-planting deep ploughing, resulted in a lowering of the peat water table by an average of 7-10 cm (Nisbet, *unpublished data*). Overall surface roughness originally declined with the cultivation of plough furrows, but this is likely to have been subsequently reversed and possibly exceeded by the development of a needle litter layer and surface rooting, inputs of deadwood and the gradual infilling of furrows by subsidence, *Sphagnum* regrowth and needle dams.

Another long-term afforestation study of note is that at Chiemsee in southern Germany. This involved four experimental catchments on a raised bog, two of which were completely afforested with Norway spruce in 1962 and 1969. The trees were planted on a previously drained site for agricultural usage but the initial effects of drainage and planting could not be assessed as measurements did not begin until 1971. The impact of forest growth to 22 years age was found to significantly reduce peak flows, with the volume/runoff coefficient for storm events decreasing from 50% to 27% (Robinson *et al.*, 1991). This was considered to be due to the rise in interception loss with canopy development and associated drier forest soils. The reduction was proportionately greater for small storms but still marked for larger ones. Time to peak was extended by about 20%. Lower flows also declined with tree age, with the 70% percentile exceedance flow reducing by 60%, although it was not possible to compare this with the original drainage enhancement effect measured in the neighbouring, older experimental catchments.

Forestry policy in the UK no longer supports afforestation of peatland soils driven by the need to protect peatland habitats and preserve carbon stocks (Forestry Commission, 2017). Instead, the focus has shifted to identifying forested peatlands where there is potential to restore functioning open peatland habitat. Restoration of afforested or forestry-drained peatlands is increasingly prevalent (Anderson et al., 2016), including on raised bog, blanket bog and fen peatlands in the UK, Ireland and Scandinavia (see Anderson et al., 2016; Anderson & Peace, 2017; Anderson, et al., 2017). Long term monitoring of restoration experiments on afforested peatlands (both raised and blanket bog) shows that felling the trees and damming the drains can effectively rewet the peatland (Anderson et al., 2016). Anderson and Peace (2017) found that in a forestry-drained peatland a combination of tree felling and blocking forest drainage ditches was the most successful restoration approach for raising peat water tables towards the surface. Studies of restoration of forested peatlands in Finland have also demonstrated that drain blocking significantly raises water tables in most cases.

Observational data on changes in catchment runoff following the restoration of afforested peatlands are sparse. However, since forest removal is likely to increase peak flows and accompanying

restoration measures such as drain blocking potentially reduce low flows, care is required to minimise any downstream impacts. The UK Forestry Standard (Forestry Commission, 2017) provides a number of controls through good practice measures, with a key measure being the need to phase clearfelling within catchments with a high flood risk. Research shows it is very difficult to detect changes to water flows when the extent of forest felling is <15-20% of a catchment (Ngai et al., 2017) and therefore a value of 20% is generally adopted as an appropriate threshold. While this measure is designed to reduce the temporary effect of forest removal until crops are replanted and return to canopy closure, it will have a limited benefit where deforestation is planned. In such cases, there should be an assessment of the likely impact on downstream flood risk and where this is significant, plans reconsidered, or additional measures selected to compensate for the loss of the forest effect.

4.6 Moorland burning and peat restoration following wildfire

Recent major peat wildfires in the UK have focused attention on the effects of wildfire, post-wildfire restoration and prescribed (managed) burn on the hydrology of peatland river systems (see Davis et al., 2016; Douglas et al., 2016; reviews in preparation by Natural England and DEFRA), and substantial efforts are now being made to restore fire affected peatlands through revegetation and associated restoration actions. The evidence of fire impacts on peatland hydrology and catchment runoff have been reviewed by Ramchunder et al. (2009), Worrall et al. (2010) and Labadz et al. (2010) and more recently by Brown et al. (2015). This latter synthesis considers the responses of peat hydrology and peatland-dominated river catchments to fires from both wildfire and prescribed vegetation burning. It notes that relatively little is known about fire effects on peatland hydrology with few studies directly examining the effects of burning on peatland river flows.

The evidence base for fire effects is therefore largely drawn from process studies of the near-surface hydrological properties of peat from small-scale or plot experiments, with subsequent inference of the implications for catchment runoff. On this basis the evidence largely supports the assumption that severely burnt peatlands will have flashier hydrograph responses to rainfall events, with higher peak flows relative to unburnt peatlands. This assumption is based on three key observations. First, hydrophobic crusts can develop on the surface of peats due to high intensity fires (Clymo, 1983) or on bare peat surfaces exposed after fire (e.g. Eggelsmann et al., 1993). These surfaces will promote rapid runoff by increasing infiltration excess overland flow in high rainfall events. Second, the clogging of peat pores by ash can also generate overland flow (see Worrall et al., 2010). Third, the removal of vegetation cover following severe fire leaves bare peat surfaces that persist for up to 7-8 years (Yallop et al., 2006) and so significantly reduces surface roughness. This will increase overland flow velocity in storm events, thereby increasing the rapidity of stormwater delivery through the catchment (see Holden et al., 2008). Further impacts of burning on runoff production could result from changes in peatland water tables following fire or due to post-fire peat shrinkage and cracking (Holden et al., 2014, 2015). Water tables could also be influenced by post-burn changes in energy balance and evapotranspiration, including reductions in vegetation water use. Changes to water table following fire would also impact surface runoff production, but there have been different reports of the responses of peatland water tables to burning. In studies of managed burning Clay et al., (2009; 2012) found that burnt and more frequently burnt plots are associated with shallower water tables whereas Holden et al. (2015) report significantly deeper water tables in recently burnt plots and a trend of decreasing depth to water table with increasing time from burn (to > 10 years). Higher water tables following burning would be expected to promote saturation excess overland flow in storm events (see Shuttleworth et al., 2019), so potentially increasing runoff volumes. However, Holden et al. (2014) discuss the possibility that peat shrinkage and cracking when exposed by fire could connect macropore flow and lead to increased infiltration, potentially reducing overland flow production. They also note this could be confounded by the development of peat

hydrophobicity noted above, and their empirical study showed a decline in macropore flow at recently burnt sites.

A key recent observational study on the effects of burning on river flows in a peatland catchment is the EMBER project (Brown et al., 2014; Holden et al., 2015). This study compared river flow hydrographs from a set of five catchments subject to prescribed burn with those from five unburnt catchments. Catchment size varied from 0.7 – 2.8 km². They observed nonlinearity in streamflow response to prescribed burning for small and large rainfall events. For the largest 20% of storms in the dataset they found no significant difference in storm lag times between burnt and unburnt catchments, but a significant difference in hydropath intensity (flashiness), and there was some evidence that river flows where managed burning had taken place were more prone to higher peak flows, although this was not conclusive (Brown et al., 2014). There was no before-after control comparison and the varying hydrograph response might have been due to underlying differences between the catchments rather than from burning alone.

In the absence of directly monitored impacts of prescribed burning in headwater peatlands on peak flows, modelling can play an important role. Gao et al (2017) modelled flow in the 84 km² Coverdale catchment in Yorkshire using a distributed variant of the widely applied TOPMODEL. Based on the assumptions that: (i) the surface roughness of recently burnt moorland is reduced by 50% compared to the normal surface characteristics; and (ii) the hydrological conductivity of burnt areas decreases by 50% (cf. Holden et al., 2014), the model predicted that prescribed burning of 8.8% of the catchment increased the peak flow for an approximately 10-year return period rainfall event by 3.2%.

To date, there have been no observational studies published which evaluate catchment-scale runoff changes associated with the natural recovery or restoration of peatlands following wildfire. However, Holden et al., (2014) presented data on the impacts of burning on near-surface peat hydrological conductivity and infiltration. The study indicated that fire has a significant impact on the hydrological functioning of near-surface peats, with a chrono-sequence of burnt sites of different ages indicating that recovery could take place within two decades if no further fires occur within this timescale. There is also increasingly clear empirical evidence that peatland wetness, as represented by the water table level, is a key control on the severity of wildfire impacts on peatlands. Turetsky et al (2011; 2015) used field observations following wildfire to show that deeper water tables due to drainage are associated with deeper burns and more carbon loss. Higher water tables therefore provide greater resilience to wildfire, which will be increased by restoration measures that lead to rewetting.

Although this review has considered the hydrological impacts of the burning of peatlands using both studies from wildfires and managed burns, Davis et al. (2016) stress the need to distinguish between the impacts of fires occurring with different severity and frequency. It is also clear from the evidence base that hydrological responses of peatland catchments to fire are dependent on a range of factors, in particular soil type, vegetation type and cover, peat surface structure and fire severity (Holden et al., 2014).

4.7 Restoration of lowland peatlands

Many current UK peatland restoration projects focus on lowland mire systems (e.g. Cumbria BogLife, Humberhead Peatland Project, Lancashire Mosslands, Flanders Moss, see <http://www.iucn-uk-peatlandprogramme.org/projects/>). Previous studies on the hydrology of lowland peatland systems, including both raised mires and fen peatlands, indicate they have a potential role to play in catchment runoff regulation (Bullock & Acreman, 2003; Acreman & Holden, 2013). For example, Bragg (2002) compared stormflow runoff from a raised lowland mire to runoff from a nearby shallow

mineral soil dominated system, finding that discharge response from the peatland was delayed by 3-6 hours even after wet antecedent conditions. It is important to note that NFM benefits of lowland peat restoration would be limited to sites draining to communities at risk (C@R), given that many lowland fens occur in the lower parts of catchment systems. There are few publications evidencing impacts on catchment hydrology and flow regimes associated with restoration of lowland peatland systems. This is perhaps unsurprising given (i) the current focus on greenhouse gas budgets (e.g. Artz et al., 2012; Graves & Morris, 2013; Evans et al., 2017) and (ii) hydrological monitoring in lowland peatland restoration projects is often restricted to water table measurements. Lowland raised bogs often cover only a small proportion of lowland catchments and/or their discharge can straddle catchment boundaries (Bragg 2002), so their potential influence on catchment flow regimes is more difficult to demonstrate than for upland blanket bogs which can cover a significant proportion of catchments with flood issues (cf. section 3). Flood protection has been cited as an objective of efforts to restore lowland fen systems through blocking of ditches to retain water in drained lowland landscapes (e.g. Great Fen Restoration project, www.greatfen.org.uk), but there is little empirical evidence of the impact on peak flows and flood reduction (Ngai et al., 2017).

4.8 Key observations and findings from the evidence base

A feature of the recent literature on peat hydrology as described above is that improved process understanding has led to more confident inference of the probable effects of peat restoration practice on peak river flows (e.g. Holden et al., 2008; Birkinshaw et al., 2014; Holden et al., 2015; Alderson et al., 2019; Shuttleworth et al., 2019). However, another crucial development has been the emergence of studies making direct, quantitative evaluations of the effects of restoration on peak flows at a catchment rather than plot scale (see Table 2). These studies include both:

- (i) Field studies where hydrological responses have been directly measured in comparative, before-after or before-after-control-intervention (BACI) studies, and;
- (ii) Modelling studies which predict hydrograph and peak flow responses based on current understanding of the processes which control peat hydrological function and runoff generation.

The field studies are generally based on very small (<1 km² scale) catchments whereas the modelling studies have been able to make evaluations at small to medium catchment scales (e.g. 10-100 km²). This is consistent with current understandings of the limitations of direct field observation of natural flood management benefits at larger scales (Dadson et al., 2017; Ngia et al., 2017). It is difficult or impossible to design experiments at larger catchment scales that exclude multiple-effects and additional non-experimental influences on hydrograph responses (Lane, 2017).

Four of the nine catchment studies in Table 2 evaluate the impacts of drain blocking on peak flows and although field studies demonstrate that drain blocking can reduce catchment peak flows (e.g. Gatis et al., 2015), taken together they show that the NFM potential for this type of restoration is site specific, given evidence of both positive and negative effects. An important finding is that drain conditions (degree of vegetation, gradient) and orientation relative to slope are key controls on the response of catchment runoff to drain blocking. The other five catchment studies evaluate restoration through revegetation or changes in vegetation cover on peatlands. These provide consistent evidence of positive effects on peak flows. Only one of the studies (Shuttleworth et al., 2019) considers the peak flow impacts of gully blocking. Although it concluded gully blocking is positive from an NFM perspective there was an inter-relation in the study with re-vegetation which made definitive evaluation of gully blocking difficult. There is evidence from both the drain blocking and revegetation studies that the long-term effects of restoration may be different to those

Study	Grayson et al. (2010)	Gatis et al. (2015)	Holden et al. (2017)	Shuttleworth et al. (2019)	Ballard et al. (2012)	Lane and Milledge (2013)	Milledge et al. (2015)	Gao et al. (2016)	Gao et al. (2017)
Location	Trout Beck, North Pennines, England	Exmoor, southwest England	Migneint, north Wales	Ashop, Peak District, England	Wharfedale, Yorkshire Dales, England	Wharfedale, Yorkshire Dales, England	Ashop, Peak District, England	Trout Beck, Pennines, England; Wye, Wales; Dart, southwest England	Coverdale, Yorkshire Dales, England
Approach	Empirical <i>(Before-After natural revegetation study)</i>	Empirical <i>(Before-After-Intervention experiment)</i>	Empirical <i>(Before-After-Control-Intervention (BACI) experiment)</i>	Empirical <i>(Before-After-Control-Intervention (BACI) experiment)</i>	Modelling <i>(Simulation of intact, drained and blocked drain scenarios)</i>	Modelling <i>(Simulation of drained vs intact catchment scenarios)</i>	Modelling <i>(Simulation of restored vs unrestored catchment scenarios)</i>	Modelling <i>(Simulation of revegetation scenarios)</i>	Modelling <i>(Simulation of revegetation and burning scenarios)</i>
Peatland Type	Blanket peat	Blanket peat	Blanket peat	Blanket peat	Blanket peat	Blanket peat	Blanket peat	Blanket peat	Blanket peat
Restoration Type	Natural revegetation	Drain blocking	Drain blocking	Revegetation of bare peat and gully blocking	Drain blocking	Drain blocking	Revegetation of bare peat and gully blocking	Land cover change (<i>Sphagnum</i> reintroduction)	Land cover change (vegetation restoration)
Catchment Size/s	11.4 km ²	19.5 – 46.5 ha	1 – 2.5 ha	0.5 – 0.7 ha	4 ha	13.8 km ²	c.9 km ²	10.6 – 21.5 km ²	84 km ²
Summary of changes in storm hydrographs and peak river flows	Revegetation is associated with significantly less 'peaky' storm hydrographs and lower flood peaks per unit rainfall.	22-35% reductions in peak flows. No change in storm hydrograph lag times.	Immediate 5-fold decrease in peak flows within drainage ditches, but subsequent lagged responses of increasing peak flow suggest this does not represent steady state.	Revegetation reduced peak flow by 27% and increased lag times by 106%. Additional gully blocking reduced peak flow by further 24% and increased lag times by further 94%.	Predicted drainage would generally increase peak flows, but effects of drain blocking dependent on local conditions and could increase or decrease peak flows.	Predicted the dominant effect of drain blocking in the study catchment would be to produce higher peak flows and lower base flows.	Predicted peat restoration in 12% of study catchment would reduce peak flow by 5%.	Predicted <i>Sphagnum</i> reintroduction would reduce peak flow of 1 in 10 year event by 12.8%, 1.8% and 19.6% in three study catchments.	Predicted <i>Sphagnum</i> reintroduction in study catchment would reduce peak flow of 1 in 10 year event by 5.2%.

Table 2 Summary of recent catchment-scale assessments of impacts of peatland restoration on storm hydrographs and peak flows.

measured over short timescales, emphasising the need for long-term hydrological monitoring (e.g. Holden et al., 2017; Alderson et al., 2019). Process understanding indicates that forest removal for peatland restoration could significantly increase peak flows and flood risk but data are lacking to quantify impacts at the catchment scale. It should be noted that most of the studies indicated in Table 2 investigated the effects of a single peatland restoration technique on NFM potential. It may be possible to use several techniques in combination to enhance NFM potential, but further research is required to demonstrate this.

The modelling studies are instructive in several ways. Firstly, they demonstrate that suitable methodologies are now available for upscaling the results of process and field measurement studies to evaluate potential NFM benefits at larger catchment scales. The use of a TOPMODEL framework (Beven & Kirkby, 1979) in most of the modelling studies is justified by process understanding of the controls on flow generation from peatlands and specifically the dominance of saturation excess overland flow. There is therefore significant scope for standardising model treatments for the evaluation of the NFM benefits of peat restoration. Secondly, the model studies show that upscaling of empirical data collected at plot or hectare scale can result in predictions of reductions in peak flows for small to medium sized catchments. The Gao et al. (2017) study is particularly interesting in predicting up to a 15% peak flow reduction from vegetation management in a relatively large (84 km²) catchment. However, it should be recognised that the modelling approaches do not yet extend to assessment of the impact of forest clearance or fire, or how meaningful the predicted peak flow reductions are to flood inundation within catchments at risk. They demonstrate potential of peatland restoration for NFM, most specifically through vegetation management, but require further development if they are to provide assessments of direct value to flood risk managers. Another important feature of the modelling studies relates to the potential for negative impacts of NFM intervention at larger catchment scales due to possible hydrograph synchronisation of sub-catchments within a catchment network (Pattison et al., 2014). This effect could occur if the restoration of a sub-catchment low in the network delayed delivery of the local flood peak, to the point where it then coincided with peak flow in the main channel. This would increase downstream flood risk. Although many peat restoration schemes are focused on headwater sub-catchments, and so unlikely to cause this problem, modelling approaches can be used to explicitly test for the synchronisation effect as they incorporate a channel network model component. The impacts of peak flow synchronisation in channel networks at the larger scale can therefore be evaluated through modelling.

Overall, consideration of the evidence base for the effects of peatland restoration and management on flow regimes results in the following findings:

- **Recent published research on peatland restoration and catchment hydrology in the UK is predominantly from blanket peats and upland catchments.** Recent publications on lowland and raised mires are limited, despite ongoing studies and restoration schemes on these systems.
- **There is increasingly robust and consistent evidence that peat restoration practices can effectively re-wet peatlands by raising water tables.** This has been demonstrated for restoration measures including ditch blocking, removal of afforestation and the revegetation of bare peat. Nevertheless, water table responses are site specific, with limited response observed in some studies. There is also increasing evidence of lagged or progressive responses of water tables to restoration over decadal timescales.
- **NFM benefits of peatland restoration will be associated with either (i) increased capacity of the peatlands to store stormwater in topographic depressions or surface hollows, or (ii) reductions in the rate of transfer of stormwater from the peatland into the river channel**

system. The former can lead to reductions in flood volumes, the latter would slow the delivery of stormflow into the catchment system.

- **There is increasing evidence from both field and modelling studies that peatland restoration measures can alter catchment runoff regimes, reduce peak flows and contribute to NFM at the small (<20 km²) catchment scale, with some evidence from modelling that peak flow reductions could potentially extend into larger catchments.** However, the evidence for these effects is not consistent for all restoration types and responses are often site specific.
- **Field studies of drain blocking generally report decreases peak flows from peatlands, but model studies indicate that blocking could also increasing peak flows depending on drain orientations and other local factors.** Field experiments have generally shown that drain blocking can reduce peak flows through either increased within-storm storage or increased runoff travel times, but modelling studies have indicated that the impact of drain blocking on flood peaks is dependent on the nature of the drains and the geography (density and orientation) of the drainage system. Put very simply, blocking drains orientated downslope is more likely to reduce flood peaks than blocking drains across slopes, and blocking steep, smooth drains is more likely to reduce peak flows than low angled, well vegetated drains, given current understanding of the effects of stormflow travel times.
- **It is firmly established that peatland surface and vegetation cover represent key controls on storm runoff, hydrograph and peak flow dynamics in peatland catchments.** The type and nature of vegetation cover on peatlands controls the velocity of overland flow through the roughness effect, and therefore the rapidity of delivery of stormflow into channel system and resulting storm hydrographs. This has been demonstrated in both plot and catchment scale studies. A key implication of the surface roughness effect is that any NFM benefit of restoration which increases surface roughness (e.g. bare peat to vegetated or cotton grass to *Sphagnum*) could be sustained even in large floods where any temporary storage effects would be overwhelmed, although the effect would be expected to decline with increasing depth of surface runoff for large events. An additional implication is that land cover changes which decrease surface roughness, such as impacts on vegetation cover through overgrazing, could reduce NFM benefits.
- **Revegetation of bare peat leads to both significant rewetting of the peat, reduced overland flow velocities and delayed and reduced flood peaks in small catchments. There is high confidence in these findings** which are consistent with conceptual models of peat hydrology (controls on overland flow) and have been quantified through both plot-scale experiments, catchment monitoring studies and before-after-control-intervention experiments.
- **Initial evidence suggests the blocking of erosional gullies can reduce flood peaks at small catchment scales.** However, this evidence is limited, and further data are needed.
- **Plot-scale and modelling studies predict that widespread re-introduction of *Sphagnum* to peatlands has the potential to reduce catchment flood peaks.** This effect is a result of the increased surface roughness provided by *Sphagnum* cover, and modelling studies predict the reintroduction of widespread *Sphagnum* cover to blanket peatlands could significantly reduce flood peaks in small to medium sized catchments. Importantly however, the effect has not yet been demonstrated by observational or experimental study at catchment scale.
- **Evidence largely supports the assumption that severely burnt peatlands will have flashier hydrograph responses to rainfall events, with higher peak flows relative to unburnt peatlands.**

Comparison of catchment runoff from burnt (prescribed burn) and unburnt catchments indicates more intense (flashier) hydrographs for large storms in burnt catchments. However, there is uncertainty over this finding given the small number of studies involved. We lack field studies of the impacts of severe wildfire on runoff regimes and on the recovery of severely burnt peatlands following restoration, although our current process understanding suggests the effects of severe wildfire on peak flows could be substantial.

- **Current understanding of forest hydrological processes predicts that the removal of conifer forest cover from peatlands could significantly increase flood peaks, and care will therefore be needed to minimise potential adverse effects of restoration of afforested peatlands.** However, observations of the impacts of restoring afforested and forest-drained peatland on catchment runoff are sparse and more data are needed to check predictions. Long-term monitoring of restoration experiments on afforested peatlands (both raised and blanket bog) shows that tree felling and drain blocking is effective at raising the soil water table closer to the peatland surface.
- **The spatial location of restoration measures within peatland catchments will impact the potential NFM benefit.** For example, reintroducing *Sphagnum* to riparian zones is predicted to be more effective than on hillslopes.
- **There is a larger evidence base for the impact of peatland restoration and management on high flows than on low flows.** There is also contradictory evidence on the impacts of drain blocking on baseflow regimes. Studies from forested catchments suggest drainage promotes higher baseflow, whereas restoration studies have indicated increased baseflow following drain blocking. More comprehensive reporting and analysis of the low flow effects of restoration are required.
- **There is evidence of lag and gradual, progressive responses following peatland restoration interventions** and so the timescales for detecting flood responses to interventions may be longer than many current monitoring programmes (often only 2-3 years duration), emphasising the need for long-term monitoring of key experiments.
- **An increasing number of case studies are available which evaluate the impacts of restoration on peak flows at the catchment scale. However, we still lack full quantification of the NFM impact of peatland interventions and quantitative estimates of the scale of any effect for flood events and catchments of different sizes.** The evidence for efficacy of NFM measures is limited for larger storms (> 1-in-10 year events) and for medium to large catchments (>20 km²), and this is also the case for catchments containing peatlands.
- **Although we can monitor and measure the impacts of land management and restoration on storm hydrology through plot or small-scale catchment experiments, direct detection of the impacts on floods at a larger catchment scale (>20 km²) is probably unrealistic.** This is due to the increased complexity of catchment processes and associated catchment changes with increased spatial scale, and the associated challenges of controlling for non-intervention effects in monitored data from large catchments.
- **Modelling is therefore required both for catchment-specific assessments and for scaling-up to allow full quantification of the NFM benefits, or adverse consequence, of peatland management and restoration at scales relevant to communities at risk. Appropriate modelling solutions are already available.** Models need to be carefully parameterised, calibrated and tested using empirical data on the hydrological process response of peatlands to different

restoration interventions. The recent literature demonstrates that models and modelling approaches are rapidly developing to allow more effective (and more accessible) quantification of potential NFM benefits of peatland management at catchment scales relevant to communities at risk. But the number of case studies and applications so far is limited.

- **Effective evaluation of the potential NFM benefits of peatlands and peatland restoration at larger catchment scales requires consideration of potential adverse hydrograph synchronicity effects.** The location of peatland restoration within the catchment network is crucial, and catchment specific assessments are therefore needed incorporating river channel network models.

5. Evidence gaps and recommendations for research priorities

The key findings from the literature review and GIS pilot study were presented and discussed at a Stakeholder Workshop of invited academics, peatland practitioners and flood risk managers held at the University of Manchester in June 2018. This workshop focused on:

- (i) co-producing a consensus on the evidence base and key findings (see above);
- (ii) identifying key knowledge gaps in the evidence base and associated research priorities, and;
- (iii) collaboratively developing an agenda to fill the gaps in policy-relevant scientific information.

Summary notes from the workshop listing the issues raised by workshop participants are presented in Appendix A. Policy relevant knowledge gaps were identified by participants and summarised in the form of five inter-related questions. These questions help focus key priorities for further research.

5.1 Evidence gaps identified

1. *Over what spatial scales will peatland restoration be effective as an NFM measure, and will these be relevant to communities at risk of flooding?*

This question was prompted by observations that restoration related peak flow reductions have been demonstrated by field experiments at the small or very small (hectare) catchment scale whereas communities at risk are often located in medium to large catchments (see section 3).

Two priorities result from this question. Firstly, more extensive upscaling is needed of the results of field experiments to allow larger scale catchment assessments. The evidence base demonstrates that modelling approaches are available for this upscaling. Secondly, to evaluate the spatial scales that matter we need a more comprehensive, national assessment of the catchment sizes of communities at risk of flooding (C@R), the importance of areas of peatland within these catchments and the potential for restoration of these peatlands. The case study in Section 3 presents a first-order approach that could be applied to this problem.

2. *What are the costs and benefits of NFM interventions by peatland restoration?*

This is a more complex but fundamental question. In order to invest in peatland restoration flood risk managers will require robust data to support cost benefit evaluations. The costs of peatland restoration measures are increasingly well established (e.g. Parry et al. 2016), but our ability to

quantify the NFM benefits of restoration for catchments containing communities at risk remains incomplete. We emphasise the point that the benefits of peatland restoration are not solely concerned with flood risk consequences. Nevertheless, the sort of evaluation currently required by flood risk managers and authorities can be exemplified by the following question:

“If you apply restoration measure X to Y% of catchment Z, what will be the reduction of peak flow for floods of different return periods, and by how much will this reduce the probability of inundation for downstream communities at risk?”

Such a very detailed level of assessment will require robust catchment modelling approaches. These models will need to draw on the increasingly available field data on the effects of restoration treatments, represent catchment specific factors that will influence these responses and have the ability to evaluate the influence of both catchment scale and event size (return periods) on associated flood peak reductions. The evidence base indicates that appropriate modelling approaches for such catchment assessments are increasingly available (e.g. Milledge et al., 2015; Gao et al 2017), but so far have been applied to a limited number of catchments and have represented the predicted flood peak reductions in different ways (i.e. used different return periods). They have also not yet been linked to flood inundation models to make a direct evaluation of the impacts of catchment restoration for properties and communities at risk of flooding.

We therefore require significant efforts to develop further modelling capacity and allow more widespread application of catchment models. This modelling will need to be supported by appropriate field data to both parameterise the model, test model outputs and evaluate model uncertainty. We also need to more fully integrate NFM benefits with the other established benefits of peat restoration and present cost-benefit evaluations of the multiple benefits to policy makers and planners. These cost-benefit analyses will also need to consider any longer-term maintenance costs for peatland restoration NFM measures.

3. *What are the timescales for the NFM benefits of peatland restoration?*

This question was prompted by two considerations. Firstly, the NFM contribution of some peatland restoration measures may not occur immediately after intervention. One example discussed was the widespread re-introduction of *Sphagnum* moss to blanket peatlands as a restoration treatment. The evidence base suggests this can make a positive contribution to NFM (e.g. Holden et al., 2008; Gao et al., 2016, 2017) but the timescales over which *Sphagnum* introduction will lead to a significant % cover of *Sphagnum* moss are largely unknown, although probably decadal given typical application rates within reintroduction projects and the likely rates of *Sphagnum* growth and spread. Secondly, the long-term effects of restoration on river peak flow might be different from those measured over short time periods, due to maturation of the restored peatland. These effects were discussed in relation to the post-intervention evolution of gully and ditch blocking which could lead to increases or diminutions to any short-term NFM benefits respectively (see Holden et al., 2017; Alderson et al., 2019).

We therefore require longer timescale (>5 year) monitoring of key field experiments to evaluate the long-term adjustment of flow regimes to peatland restoration. We also require research to establish any long-term maintenance requirements for the NFM benefits of restored peatlands (e.g. what actions, if any, are required to ensure that re-vegetated areas remain re-vegetated with the right species, gully and ditch blocks remain in place and undamaged, restoration is not hampered by other land use pressures such as overgrazing, etc.) .

4. *What type and level of evidence is required to change policy and promote peatland restoration as an NFM measure?*

This question was highlighted due to issues around values placed on different types and levels of evidence for the NFM benefits of restoration. The most compelling evidence would come from well

controlled before-after-control intervention (BACI) field experiments at catchment scales relevant to communities at risk which demonstrate significant measured reductions in peak flows for large events. However, this is an exceptionally challenging level of empirical evidence to obtain for several reasons. Field experiments must be restricted in spatial (catchment) scale to allow intervention effects to be isolated from confounding factors, so field experiments at the scale of communities at risk is usually unrealistic. The event size represented within field experiments is also dictated by the duration of the project, so large return period events are not reliably captured. Such experiments are also expensive so limited in number, and in the type of catchment and type of restoration interventions evaluated. It is therefore recognised that quantitative evidence for NFM benefits of peatland restoration at the scale of communities at risk will largely come from the upscaling of field and process observations through models. However, model assessments are sometimes perceived by lay-people and the policy community as less reliable than those based on observed data.

A priority is therefore to more effectively communicate the inter-relationships between field data and model assessments to practitioners and policy makers, translating model results for users and appropriately quantifying and explaining uncertainties in model predictions. We also need to provide more case studies demonstrating that models can reliably reproduce real observational data from storm events to build confidence in their value within lay and practitioner communities.

5. *How do we manage uncertainty due to lack of data and incomplete scientific understanding?*

This question was general to many of the workshop discussions on gaps in the evidence base. One response has been to identify the key knowledge gaps and recommend priorities for research to reduce uncertainty in our assessment of the role of peatland restoration in NFM (see below). However, it was also recognised that a significant expansion in the evidence base of peat restoration impacts on river flows and NFM will accumulate within a 2-4 year time period due to reports from ongoing studies (e.g. NERC PROTECT-NFM, NERC Yorkshire iCASP, EU-Moorlife 2020, Exmoor Mires Project and South West Water 'Upstream Thinking' project). There will therefore be opportunity to represent current and new evidence to more effectively communicate uncertainty in the links between peatland restoration and natural flood management (cf. SEPA, 2015).

5.2 Priorities for research

Review of both the evidence base and key policy relevant knowledge gaps identified through the workshop generated the following priorities for further research:

- a) A national- scale assessment is needed to locate and quantify areas of peatlands in the catchments of communities at risk of flooding, as well as to identify peatland catchments of relevance to other assets vulnerable to flooding (e.g. transport infrastructure), and to map the associated opportunities for peatland restoration. This will provide greater understanding of the potential for peatland restoration based NFM in both upland and lowland catchments.
- b) More evidence is needed to quantify the impacts of restoration of lowland peatlands (raised mire and fen) on runoff and peak flows and the potential reductions in flood risk for downstream communities.
- c) Additional field studies are needed to quantify the response of catchment flow regimes and peak flows for all relevant peatland restoration treatments. Data on the restoration treatments and scales where data are currently lacking should be prioritised, in particular:
 - a. Small catchment studies of *Sphagnum* re-introductions;

- b. Impacts of gully blocking;
- c. Impacts of severe wildfire plus restoration and recovery from wildfire;
- d. Small catchment studies of the restoration of afforested peatlands by tree removal and drain blocking.

We also need further studies of runoff regimes from intact (near natural) peatland catchments to provide reference data for peatland restoration.

- d) In all cases research design and data collection should be informed by (i) hypotheses of hydrological response derived from current process understanding and (ii) the evidence and parameters needed to improve and test hydrological models and to reduce uncertainty in model simulations of catchment responses.
- e) Longer term monitoring is required of key restoration experiments to more fully establish how NFM benefits of peatland restoration will evolve through time.
- f) We have an increasingly large evidence base for the impacts of drain blocking on flow regimes, but this indicates that responses are catchment specific and depend on the nature and geography of the drain networks. Modelling applications are therefore needed across a wider set of catchments with varying drain network characteristics to confirm the types of catchments where reductions in peak flow following drain blocking would be expected, and to identify catchments where there might be adverse effects.
- g) Further development and application of models are needed to improve quantification of the NFM impacts of peatland interventions and to check for possible negative hydrograph synchronisation effects within catchment systems. These need to be developed for and applied at catchment scales relevant to communities at risk. Model simulations should incorporate (i) more comprehensive evaluations of peak flow reductions and NFM benefits across a range of flood event sizes (return periods) including for extreme events and (ii) coupling of hydrological and inundation models to simulate impacts on communities at risk. Model applications need to be accessible to the practitioner community and should provide clear information on the uncertainty of model predictions.

6 Conclusions

This report has reviewed scientific understanding of the effects of peatland restoration and management on peat hydrology, with emphasis on the evidence base for the impacts of restoration on peak and low flow events. It has summarised key findings from the evidence base, identified evidence gaps and made recommendations on priorities for research to better inform policy on peatland management and restoration.

Several general conclusions can be drawn from the review.

- a) Within the last few years a lot of new data have become available on the relationships between peatland management and restoration and catchment flow regimes. We therefore have improved understanding of the processes by which restoration interventions can contribute to natural flood management.
- b) Significant advances have also been made in our ability to evaluate the impacts of peatland restoration on peak river flows using appropriate modelling techniques. Modelling has already provided quantitative evaluations of the NFM benefits of peat restoration treatments for

selected study catchments and should be further developed and made available to practitioner communities for wider application.

- c) There is increasing evidence from both field and modelling studies that peatland restoration measures can alter catchment runoff regimes and reduce peak flows at the small (< 20 km²) catchment scale, with some evidence from modelling that peak flow reductions could potentially extend into larger catchments. These findings are consistent with those of recent major reviews of NFM measures.
- d) However, there are still significant uncertainties in our understanding of the NFM contribution of peatlands and peatland restoration. We lack data on the impact of several key types of restoration measure on flow regimes. We also know that individual catchments can respond in different ways to intervention, so assessments are needed for different catchment types. We have limited data on hydrological responses to restoration over longer timescales. This is likely to be particularly important for restoration techniques that progress slowly over many years, for example *Sphagnum* reintroduction. Finally, more research is required into the effectiveness of using different restoration techniques in combination.
- e) Fuller assessments are also needed at the scale of communities at risk of flooding, and for events of different sizes (return periods), including for extreme events, to more fully establish the scales of NFM that can be achieved from peatland restoration.
- f) Further work is needed on the cost-benefits of NFM in a variety of scenarios so that effective investment decisions can be made by responsible authorities and landowners.
- g) Ongoing projects and modelling programmes are addressing some of these uncertainties and evidence gaps, and substantial further progress in our understanding of peatlands and NFM is expected within the next 3-4 years.

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8 References

- Acreman M., Holden J. 2013. How wetlands affect floods. *Wetlands* 33(5), 773–786.
- Alderson, D.M., Evans, M.G., Shuttleworth, E.L., Pilkington, M., Spencer, T., Walker, J. & Allott, T.E.H. 2019. Trajectories of ecosystem change in restored blanket peatlands. *Science of the Total Environment* 665, 785-796.
- Allott, T., Shuttleworth, E., Evans, M., Agnew, C., Pilkington, M.G., Spencer, T., Milledge, D., Gorham, J., Mellor, J., Jones, A., Richards, R., Maskill, R., & Walker, J. 2015. Annex 5: Flood Risk. In Pilkington M.G. et al. *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. Available from: https://www.moorsforthefuture.org.uk/_data/assets/pdf_file/0007/1460572/Annex-5.Flood-Risk_0.pdf. Last accessed 18 May 2019.
- Anderson, A.R., Ray, D. and Pyatt, D.G. 2000. Physical and hydrological impacts of blanket bog afforestation at Bad a' Cheo, Caithness: the first 5 years. *Forestry*, 73 (5) 467-478.
- Anderson, P. & Ross, S. 2011. United Utilities Sustainable Catchment Management (SCAMP) Programme. Volume 1: Executive Summary. Penny Anderson Associates Ltd. Available from www.pennyanderson.com/file_download/62/SCaMP+Vol_1_Executive_Report.pdf. Last accessed 18 May 2019.
- Anderson, P., Buckler, M. & Walker, J. 2009. Moorland restoration: potential and progress. . In Bonn, A., Allott, T., Hubacek, K & Stewart, J. (Eds) *Drivers of Environmental Change in Uplands*. Routledge, London
- Anderson, R. & Peace, A. 2017, Ten-year results of a comparison of methods for restoring afforested blanket bog. *Mires and Peat* 19, Article 06, 1-23.
- Anderson, R., Vasander, H., Geddes, N., Laine, A., Tolvanen, A., O'Sullivan, A. & Aapala. K. 2016. Afforestation and forestry-drained peatland restoration. In Bonn, A., Allott, T., Evans, M., Joosten, H., Stoneman, R. (Eds) *Peatland Restoration and Ecosystem Services: Science, Policy and Practice*, Cambridge University Press.
- Anderson, R., Farrell, C., Graf, M., Muller, F., Calver, E., Frankard, P., Caporn, S., & Anderson, P. 2017 An overview of the progress and challenges of peatland restoration in Western Europe. *Restoration Ecology* 25, 271-282.
- Archer, D., 2003. Scale effects on the hydrological impact of upland afforestation and drainage using indices of flow variability: the River Irthing, England. *Hydrology and Earth System Sciences Discussions* 7(3), 325-338.
- Artz, R.R.E., Donnelly, D., Cuthbert, A., Evans, C., Smart, S., Reed, M., Kenter, J. & Clark, J. 2012. Restoration of lowland raised bogs in Scotland: Emissions savings and the implications of a changing climate on lowland raised bog condition. Report to the Scottish Wildlife Trust. Available from https://scottishwildlifetrust.org.uk/docs/002_057_restorationoflowlandraisedbogsinscotland_jan2013_1359568030.pdf. Last accessed 18 May 2019.
- Ashe, J., Benaud, P., Carless, D., Dooling, G.P., Fensome, S., Freeman, G., Gatis, N., Grand-Clement, E., Luscombe, D.J., Puttock, A., Anderson, K., Gallego-Sala, A., Hartley, I. & Brazier, R. 2017. Mires monitoring results update March 2017. University of Exeter. http://www.beachlive.co.uk/media/pdf/b/9/Mires_Monitoring_University_of_Exeter_Annual_Report_2017web.pdf Last accessed 12 June 2018.

- Bacon, K.L., Baird, A.J., Blundell, A., Bourgault, M-A., Chapman, P.J., Dargie, G., Dooling, G.P., Gee, C., Holden, J., Kelly, T., McKendrick-Smith, K.A., Morris, P.J., Noble, A., Palmer, S.M., Quillet, A., Swindles, G.T., Watson E.J. & Young D.M. 2017. Questioning ten common assumptions about peatlands. *Mires and Peats* 19, Article 12, 1-23.
- Bain, C.G., Bonn, A., Stoneman, R., Chapman, S., Coupar, A., Evans, M., Gearey, B., Howat, M., Joosten, H., Keenleyside, C., Labadz, J., Lindsay, R., Littlewood, N., Lunt, P., Miller, C.J., Mosey, A., Orr, H., Reed, M., Smith, P., Swales, V., Thompson, D.B.A., Van de Noort, R. Wilson, J.D. & Worrall, F. 2011. IUCN UK Commission of Inquiry on Peatlands, IUCN UK Peatland Programme, Edinburgh.
- Ballard, C.E., McIntyre, N., Wheeler, H.S., Holden, J. and Wallage, Z.E. 2011. Hydrological modelling of drained blanket peatland. *Journal of Hydrology* 407, 81 - 93.
- Ballard, C.E., McIntyre, N. & Wheeler, H.S. 2012 Effects of peatland drainage management on peat flows. *Hydrology and Earth System Science* 16, 2299-2310.
- 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, 559-573.
- Bonn, A., Allott, T., Evans, M., Joosten, H. & Stoneman, R. 2016. *Peatland Restoration and Ecosystem Services: Science, Policy and Practice*. Cambridge University Press.
- Bower, K. 2015. The effect of peatland restoration on baseflows. Exmoor and Dartmoor Mires Project – Final Environment Agency hydrology report. Available from http://www.beachlive.co.uk/media/pdf/b/k/2015-07-22_Effect_of_peatland_restoration_on_baseflows_EA_hydrology_report_Final_July_2015.pdf. Last accessed 7 August 2019.
- Bragg, O.M. 2002. Hydrology of peat-forming wetlands in Scotland. *Science of the Total Environment* 294, 111-129.
- Brown, L.E., Holden, J. & Palmer, S.M. 2014. Effects of Moorland Burning on the Ecohydrology of River Basins. Key Findings from the EMBER project. University of Leeds. Available from <http://water.leeds.ac.uk/our-missions/mission-1/ember/>. Last accessed 18 May 2019.
- Brown, L.E., Holden, J., Palmer, S.M., Johnston, K., Ramchunder, S.J. & Grayson, R. 2015. Effects of fire on the hydrology, biogeochemistry, and ecology of peatland river systems. *Freshwater Science* 34, 1406-1425.
- Bullock, A. & Acreman, M.C. 2003. The role of wetlands in the hydrological cycle. *Hydrology and Earth System Science* 7, 358-389.
- Carroll, J., Anderson, P., Caporn, S., Eades, P., O'Reilly, C. & Bonn, A. 2009. Sphagnum in the Peak District: Current Status and Potential for Restoration. Moors for the Future Report 16. Moors for the Future Partnership, Edale. Available from https://www.researchgate.net/profile/Aletta_Bonn/publication/224807088_Sphagnum_in_the_Peak_District_Current_status_and_potential_for_restoration/links/53f4a7830cf2888a749111b2/Sphagnum-in-the-Peak-District-Current-status-and-potential-for-restoration.pdf. Last accessed 7 August 2019.
- Clay, G.D., Worrall, F., Clark, E. & Fraser, E.D.G. 2009. Hydrological responses to managed burning and grazing in an upland blanket bog. *Journal of Hydrology* 376, 486-495.

- Clay, G.D., Worrall, F. & Aebischer, N.J. 2012. Does prescribed burning on peat soils influence DOC concentrations in soil and runoff waters? Results from a 10 year chronosequence. *Journal of Hydrology* 448-449, 139-148.
- Clymo, R.S. 1983. Peat. In Gore, A.S.P. (Ed) *Swamp, bog, fen and moor*. Elsevier, Amsterdam, The Netherlands.
- Dadson, S.J., Hall, J.W., Murgatroyd, A., Acreman, M., Bates, P., Beven, K., Heathwaite, L., Holden, J., Holman, I.P., Lane, S.N. & O'Connell, E., 2017, A restatement of the natural science evidence concerning catchment-based 'natural' flood management in the UK. *Proceedings of the Royal Society A* 473(2199).
- Davis, G.M., Kettridge, N., Stoof, C.R., Gray, A., Ascoli, D., Fernandes, P.M., Marrs, R., Allen, K.A., Doerr, S., Clay, G.D., McMorrough, J. & Vandvik, V. 2016. The role of fire in UK peatland and moorland management: the need for informed, unbiased debate. *Philosophical Transactions of the Royal Society B* 371, 20150342.
- Douglas, D.J.Y., Buchanan, G.M., Thompson, P. & Wilson, J.D. 2016. The role of fire in UK upland management: the need for more informed challenge to conventional wisdoms: a comment on Davies et al (2016). *Philosophical Transactions of the Royal Society B* 371, 20160433.
- Eggesmann, R., Heathwaite, A.L., Gross-Braickmann, G., Kuster, E., Nauke, W., Schich, M. & Schweikle, V. 1993. Physical processes and properties of mires. In Heathwaite, A.L. & Gotlich, K.H. (Eds) *Mires: Process, Exploration and Conservation*. Wiley, Chichester, 172-262.
- Evans, C.D., Bonn, A., Holden, J., Reed, M.S., Evans, M.G., Worrall, F., Couwenberg, J. & Parnell, M. 2014. Relationships between anthropogenic pressures and ecosystem functions in UK blanket bogs: Linking process understanding to ecosystem service valuation. *Ecosystem Services* 9, 5-19.
- Evans, C.D and 34 others. 2016. Final report on project SP1210: Lowland peatland systems in England and Wales – evaluating greenhouse gas fluxes and carbon balances. Centre for Ecology and Hydrology. Available from <http://oro.open.ac.uk/50635/>. Last accessed 18 May 2019.
- Evans, M.G. & Warburton, J. 2007. *Geomorphology of Upland Peat: Pattern, Process, Form*. Blackwell, Oxford.
- 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.
- 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. Environment Agency Report SC060092/R1. Available from <https://www.gov.uk/government/publications/long-term-land-use-changes-and-flood-risk-multiscale-experimentation-monitoring-and-analysis>. Last accessed 7 August 2019.
- Forestry Commission 2017. *The UK Forestry Standard*. Forestry Commission, Edinburgh, UK.
- Gao, J., Holden, J. & Kirkby, M. 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. 2016. The impact of land-cover changes on flood peaks in peatland basins. *Water Resources Research* 52, 3477–3492.

- Gao, J., Holden, J. & Kirkby, M.J. 2017. Modelling impacts of agricultural practice on flood peaks in upland catchments: An application of the distributed TOPMODEL. *Hydrological Processes* 31, 4206-4216.
- Gatis, N., Grand-Clement, E., Luscombe, D.J., Anderson, K., Hartley, I., Ashe, J., Benaud, P. Jenkins, T. & Brazier, R.E. 2015. Mires Monitoring Results: Final Report March 2015. Report by the University of Exeter to South West Water.
- Goulsbra, C., Evans, M. & Lindsay, J. 2014. Temporary streams in a peatland catchment: pattern, timing, and controls on stream network expansion and contraction. *Earth Surface Processes and Landforms* 39, 790-803.
- Grand-Clement, E., Anderson, K., Smith, D., Angus, M., Luscombe, D.J., Gatis, N., Bray, L.S. & Brazier, R.E. 2015. New approaches to the restoration of shallow marginal peatlands. *Journal of Environmental Management* 161, 417-430.
- Graves, A.R. and Morris, J. 2013. Restoration of Fenland Peatland under Climate Change. Report to the Adaptation Sub-Committee of the Committee on Climate Change. Cranfield University, Bedford. Available from: https://www.theccc.org.uk/wp-content/uploads/2013/07/Report-for-ASC-project_FINAL-9-July.pdf. Last accessed 18 May 2019.
- Grayson, R., Holden, J. & Rose, R. 2010. Long-term change in storm hydrographs in response to peatland vegetation change. *Journal of Hydrology* 389-343.
- Green, S.M., Baird, A.J., Holden, J., Reed, D., Birch, K. & Jones, P. 2017. An experimental study on the response of blanket bog vegetation and water tables to ditch blocking. *Wetlands Ecology and Management* 25, 703-716.
- Haapalehto, T. O., Vasander, H., Jauhiainen, S., Tahvanainen, T., Kotiaho, J. S. 2011. The effects of peatland restoration on water-table depth, elemental concentrations, and vegetation: 10 years of changes. *Restoration Ecology* 19, 587–598
- Holden, J. 2005. Controls of soil pipe frequency in upland blanket peat. *Journal of Geophysical Research* 110, F01002, doi:10.1029/2004JF000143.
- Holden, J. 2009. Flow through macropores of different size classes in blanket peat. *Journal of Hydrology* 364, 342-348.
- Holden, J. 2009. Upland hydrology. In Bonn, A., Allott, T., Hubacek, K & Stewart, J. (Eds) *Drivers of Environmental Change in Uplands*. Routledge, London.
- Holden, J. & Burt, T.P. 2003. Runoff production in blanket peat covered catchments. *Water Resources Research* 39: 1191. doi: 10.1029/2002WR001956.
- Holden, J., Chapman, P.J. & Labadz, J.C. 2004. Artificial drainage of peatlands: hydrological and hydrochemical processes and wetland restoration. *Progress in Physical Geography* 28, 235-249.
- Holden, J., Evans, M.G., Burt, T.P. & Horton, M. 2006. Impact of land drainage on peatland hydrology. *Journal of Environmental Quality* 35, 1764-1778.
- Holden, J., Kirkby, M.J., Lane, S.N., Milledge, D.G., Brookes, C.J., Holden, V. & McDonald, A.T. 2008. Overland flow velocity and roughness properties in peatlands. *Water Resources Research* 44, W06415. doi: 10.1029/2007WR006052.
- Holden, J., Wallage, Z.E., Lane, S.N. & McDonald, A.T. 2011. Water table dynamics in undisturbed, drained and restored blanket peat. *Journal of Hydrology* 402(1), 103-114.

- Holden, J., Wearing, C., Palmer, S., Jackson, B., Johnston, K. & Brown, L.E. 2014. Fire decreases near-surface hydraulic conductivity and macropore flow in blanket peat. *Hydrological Processes* 28, 2868-2876.
- Holden, J., Palmer, S.E., Johnston, K., Wearing, C., Irvine, B. & Brown, L.E. 2015. Impact of prescribed burning on blanket peat hydrology. *Water Resources Research* 51, 6472–6484.
- Holden J, Green S.M., Baird A.J., Grayson R.P., Dooling G.P., Chapman P.J., Evans C.D., Peacock M. & Swindles G. 2017. The impact of ditch blocking on the hydrological functioning of blanket peatlands. *Hydrological Processes* 31, 525–539.
- Hudson, J.A., Crane, S.B. & Blackie, J.R. 1997. The Plynilimon water balance 1969-1995: the impact of forest and moorland vegetation on evaporation and streamflow in upland catchments. *Hydrology and Earth System Science* 1, 409-427.
- International Union for Conservation of Nature UK Peatland Programme. 2008. UK Peatland Strategy 2018-2040. Available from <https://portals.iucn.org/library/node/47692>. Last accessed 7 August 2019.
- Kadykalo, A.N. & Findlay, C.S. 2016. The flow regulation services of wetlands. *Ecosystem Services* 20, 91-103.
- Labadz, J., Allott, T., Evans, M., Butchr, D., Billett, M., Stainer, S., Yallop, A., Jones, P., Innerdale, M., Harmon, N., Maher, K., Bradbury, R., Mount, D., O'Brien, H. & Hart, R. 2010. Peatland Hydrology. Scientific Review commissioned by the IUCN UK Peatland Programme's Commission of Inquiry on Peatlands. <http://www.iucn-uk-peatlandprogramme.org/publications/commission-inquiry/work-commission/peatland-hydrology> Last accessed 19 May 2019.
- Lane, S.N. 2017. Natural flood management. *WIREsWater* 2017, 4:e1211. doi: 10.1002/wat2.1211.
- Lane, S.N. & Milledge, D.G. 2012. Impacts of upland open drains upon runoff generation: a numerical assessment of catchment scale impacts. *Hydrological Processes* 27, 1701-1726.
- Lee, J.A. 1998. Unintentional experiments with terrestrial ecosystems: ecological effects of sulphur and nitrogen pollutants. *Journal of Ecology* 86: 1–12
- Lewis, C., Albertson, J., Zi, T., Xu, X. & Kiely, G. 2013. How does afforestation affect the hydrology of a blanket peatland? A modelling study. *Hydrological Processes* 27, 3577-3588.
- Lindsay, R., Birnie, R. & Clough, J. 2014. Peat bog ecosystems: key definitions. IUCN UK Committee Peatland Programme Briefing Note No. 1. Edinburgh: International Union for the Conservation of Nature UK Peatland Programme. Available from <http://www.iucn-uk-peatlandprogramme.org/resources/iucn-briefing-notes-peatlands>. Last accessed 18 May 2019.
- Lindsay, R., Birnie, R. & Clough, J. 2016. Peatland restoration. IUCN UK Committee Peatland Programme Briefing Note No. 11. Edinburgh: International Union for the Conservation of Nature UK Peatland Programme. Available from <http://www.iucn-uk-peatlandprogramme.org/resources/iucn-briefing-notes-peatlands>. Last accessed 18 May 2019.
- Luscombe, D.J., Anderson, K., Grand-Clement, E., Gatis, N., Ashe, J., Benaud, P., Smith, D. & Brazier, R.E. 2015. How does drainage alter the hydrology of shallow degraded peatlands across multiple scales? *Journal of Hydrology* 541, 1329-1339.
- Lundin, L. 1994. Impacts of forest drainage on flow regime. *Studia Forestalia Suecica*, 192, 1-23.

- Menberu, M. W., Tahvanainen, T., Marttila, H., Irannezhad, M., Ronkanen, A.-K., Penttinen, J. & Kløve, B. 2016. Water-table-dependent hydrological changes following peatland forestry drainage and restoration: Analysis of restoration success, *Water Resources Research* 52, 3742–3760.
- McCulloch, J.S.G. and Robinson, M. 1993. History of forest hydrology. *Journal of Hydrology*, 150 (2-4), 189-216.
- Milledge, D., Odoni, N., Allott, T., Evans, M., Pilkington, M. & Walker, J. 2015. Annex 6: Flood risk modelling. In Pilkington M.G. et al. 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. Available from: https://www.moorsforthefuture.org.uk/_data/assets/pdf_file/0007/1460572/Annex-5.Flood-Risk_0.pdf. Last accessed 18 May 2019.
- Ngai, R., Wilkinson, M., Nisbet, T., Harvey, R., Addy, S., Burgess-Gamble, L., Rose, S., Maslen, S., Nicholson, A., Page, T., Jonczyk, J. & Quinn, P. 2017. Working with Natural Processes – Evidence Directory. Appendix 2: Literature Review. Environment Agency, Bristol. Available from <https://www.gov.uk/government/publications/working-with-natural-processes-to-reduce-flood-risk>. Last accessed 18 May 2019.
- Nicholson, I.A., Robertson, R.A. and Robinson, M. 1989. The effects of drainage on the hydrology of a peat bog. *International Peat Journal* 3, 59-83.
- Nisbet, T., 2005. Water Use by Trees. Forest Research, Information Note FCIN065.
- Nisbet, T., Silgram, M., Shah, N., Morrow, K., & Broadmeadow, S. 2011. Woodland for Water: Woodland measures for meeting Water Framework Directive objectives. Forest Research Monograph, 4, Forest Research, Surrey, 156pp.
- Parry, L.E., Holden, J. & Chapman, P.J. 2014. Restoration of blanket peatlands. *Journal of Environmental Management* 133, 193-205.
- 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(7) 5444-5458.
- 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. Available from <https://www.moorsforthefuture.org.uk/our-work/our-projects/making-space-for-water/making-space-for-water-in-detail>. Last accessed 18 May 2019.
- Price, J., Evans, C., Evans, M., Allott, T. & Shuttleworth, W. 2016. Peatland restoration and hydrology. In Bonn, A., Allott, T., Evans, M., Joosten, H., Stoneman, R. (eds) *Peatland Restoration and Ecosystem Services: Science, Policy and Practice*, Cambridge University Press.
- Robinson, M., Moore, R.E., Nisbet, T.R. and Blackie, J.R. 1998. From moorland to forest: the Coalburn catchment experiment. I H Report No. 133., Institute of Hydrology, Wallingford.
- Robinson, M. 2004. Coalburn catchment hydrological review. CEH Report to United Utilities. Centre for Ecology & Hydrology, Wallingford.
- Robinson, M., Gannon, B. and Schuch, M. 1991. A comparison of the hydrology of moorland under natural conditions, agricultural use and forestry. *Hydrological Sciences Journal* 36 (6), 565-577.

- Rogger, M. et al. 2017. Land use change impacts on floods at the catchment scale: Challenges and opportunities for further research. *Water Resources Research* 53, 5209-5219.
- Roles, J.M. 1984. Flow resistance in concentrated overland flow on rough slope surfaces. *Earth Surface Processes Landforms* 9, 541-551.
- Rydin, H. & Jeglum, J.K. 2006. *The Biology of Peatlands*. Oxford University Press, Oxford.
- Scottish Environmental Protection Agency 2015. *Natural Flood Management Handbook*. Scottish Environmental Protection Agency, Stirling.
- Scottish Natural Heritage 2015. *Scotland's National Peatland Plan: Working for our Future*. Scottish Natural Heritage. Available from https://www.nature.scot/sites/default/files/2017-07/A1697542%20-%20150730%20-%20peatland_plan.pdf. Last accessed 7 August 2019.
- Seuna, P. 1980. Long term influence of forestry drainage on the hydrology of an open bog in Finland. *IAHS Publ. No. 130*, 141-9.
- Sirin, A., Vompersky, S. and Nazarov, N. 1991. Influence of forest drainage on runoff - main concepts and examples from central part of the USSR European territory. *Ambio*, 20, 334-339.
- Shuttleworth, E.L., Evans, M.G., Pilkington, M., Walker, J., Milledge, D. & Allott, T.E.H. 2019. Restoration of blanket peat moorland delays stormflow from hillslopes and reduces peak discharge. *Journal of Hydrology X* 2 (2019) 100006. DOI: 10.1016/j.hydroa.2018.100006.
- Smart, R.P., Holden, J., Dinsmore, K.J., Baird, A.J., Billett, M.F., Chapman, P.J. & Grayson, R. 2013. The dynamics of natural pipe hydrological behaviour in blanket peat. *Hydrological Processes* 27, 1523-1534.
- Stratford, C., Miller, J., House, A., Old, G., Acreman, M., Dueñas-Lopez, M. A., Nisbet, T., Newman, J., Burgess-Gamble, L., Chappell, N., Clarke, S., Leeson, L., Monbiot, G., Paterson, J., Robinson, M., Rogers, M. & Tickner, D. 2017. Do trees in UK-relevant river catchments influence fluvial flood peaks? Wallingford, UK, NERC/Centre for Ecology & Hydrology, 46pp. (CEH Project no. NEC06063).
- Thom, T., Evans, M., Evans, C. & Allott, T. 2016. Blanket peat restoration and its impact on ecosystem services. In Bonn, A., Allot, T., Evans, M., Joosten, H. & Stoneman, R. (Eds) *Peatland Restoration and Ecosystem Services: Science, Policy and Practice*. Cambridge University Press, Cambridge.
- Turetsky, M.R., Donahue, W. & Benscoter, B.W. 2011. Experimental drying intensifies burning and carbon losses in a northern peatland. *Nature Communications* 2:514.
- Turetsky, M.R., Benscoter, B.W., Page, S., Rein, G., van der Werf, G.R. & Watts, A. 2015. Global vulnerability of peatlands to fire and carbon loss. *Nature Geosciences* 8, 11-14.
- Wallage, Z.E. & Holden, J. 2011. Near-surface macropore flow and saturated hydraulic conductivity in drained and restored blanket peatlands. *Soil Use and Management* 27, 247-254.
- Williamson, J., Rowe, E., Reed, D., Ruffino, L., Jones, P., Dolan, R., Buckingham, H., Norris, D., Astbury, S. & Evans, C.D. 2017. Historical peat loss explains limited short-term response of drained blanket bogs to rewetting. *Journal of Environmental Management* 188, 278-286.
- Wilson, L., Wilson, J., Holden, J., Johnson, I., Armstrong, A. & Morris, M. 2010. Recovery of water tables in Welsh blanket bog after drain blocking: Discharge rates, timescales and the influence of local conditions. *Journal of Hydrology* 391, 377-386.

- Wilson, L., Wilson, J., Holden, J., Johnson, 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 sample scale. *Journal of Hydrology* 404, 198-208.
- Worrall, F., Clay, C.D., Marrs, R. & Reed, M.S. 2010. Impacts of burning management on peatlands. *Peatland Hydrology. Scientific Review* commissioned by the IUCN UK Peatland Programme's Commission of Inquiry on Peatlands. <http://www.iucn-uk-peatlandprogramme.org/publications/commission-inquiry/work-commission/impacts-burning-management-peatlands>. Last accessed 19 May 2019.
- Yallop, A.R., Thacker, J.I., Thomas, G., Stephens, M., Clutterbuck, B. & Brewer, T. 2006. The extent and intensity of managed burning in the English uplands. *Journal of Applied Ecology* 43, 1138-48.

APPENDIX A
IUCN UK Peatland Programme
Workshop on Peatland Catchments and Natural Flood Management
Summary Notes

25th June 2018
Humanities Bridgeford Street Building, University of Manchester

To aid the University of Manchester in the delivery of a Technical Review report on the hydrology and value Natural flood Management (NFM) of peatland catchments for the IUCN Peatland Programme's Commission of Inquiry, Moors for the Future Partnership facilitated a workshop to enable the wider community of practitioners and academics to contribute to the content of the report.

The five hour workshop, attended by 21 participants, aimed to:

- Gain consensus on materials for inclusion in the IUCN UK Peatland Programme Technical Review report on Peatland Catchments and Natural Flood Management, including the state of understanding of:
 - the evidence base from peer reviewed and grey literature on the hydrology and NFM value of Peatlands;
 - known knowledge gaps in the evidence base from peer reviewed and grey literature on the hydrology and NFM of Peatlands;
- Gain consensus on the priorities of the above
- Collaboratively develop an agenda to fill gaps in policy relevant scientific evidence.

The workshop provided the opportunity for participants to:

- Prioritise what evidence regarding the hydrology and NFM value of peatlands could be included in the Technical Review - providing case studies or reference to evidence bases where possible.
- Prioritise evidence gaps regarding the hydrology and NFM value of peatlands that could be highlighted in the Technical Review, with specific reference to policy relevant scientific evidence gaps.
- Discuss how we can fill the evidence gaps prioritised above in terms of timescale, actions and possible resources.

The results of this workshop are summarised here.

Session 1: What do we know about the hydrology and NFM value of peatlands? – Of these which are prioritised to be included in the Commission of inquiry report?

The following topics were identified as the current state of understanding of the hydrology and NFM value of peatlands. They are presented in order of prioritisation for inclusion in the Technical Review. [Square brackets denote case studies, references or contacts to follow up with]. (Round brackets denote the number of votes attributed to this comment by all participants).

- Condition is important - re vegetation / gully blocking has impact on dynamics [MFFP MS4W] (9)
- Surface condition is crucial to determining how NFM relates to peatland roughness and vegetation (4)
- Surface roughness / how this responds in smaller peaks [Haweswater RSPB/UU case studies] (3)
- We know that models are limited - peatland empirical data is limited (3)
- We know where peatlands are but large scale mapping of state of peatlands missing currently (3)
- We know re-conditioning of peatlands (mostly) leads to (slight) water table rises (3)
- Mapping Communities at Risk & peat has been interesting and useful. It is partially relevant, but the impact of the peat is unknown (2)
- Channel network – gullies/grips/ditches – has significant effect on hydrology i.e. Orientation/speed of peak/connectivity [modelling observation?] (2)
- Confident we can change the behaviour of flow in small scale headwater catchments [MS4W, Exmoor, Ashop] (2)
- Evaporation losses of trees not well represented - what is the nature of the effect relative to nature of trees? (2)
- Peatlands occur in high rainfall areas (2)
- Majority of our peatlands are degraded in some way, including through drainage or erosion channels (1)
- We underestimate the impact of erosion on hydrology - cut drains are recognised but eroding ones are not (1)
- Plot scale and catchment scale effects of surface roughness (1)
- We understand the society is used to hard engineering solutions but also that NFM as a concept is achieving increasing acceptance (1)
- We do know about negative impact of heather burning as management on small catchment scale – hydrophobicity/erosion/doc storage [Plot scale studies, academic papers, Moorhouse/Hardhill] (1)
- Natural undamaged peatlands provide a very different hydrological environment and response to flooding [Lack of evidence of intact peatlands and stages] (1)

Session 2: What do we not know about the hydrology and NFM value of peatlands? – What are the policy relevant scientific evidence gaps?

- What is the cost benefit of NFM interventions (13)
 - How do we value the benefits? What are the timescales for benefits?
- Time; how long does peatland restoration take – how long does it take for interventions to have NFM benefit? (12)
- Can we demonstrate it's worth the wait 'for policy / investments?
 - e.g. 10 years (e.g. sphagnum reintroduction:
 - Roughness – how does a sphagnum rich catchment behave compared to non-sphagnum dense catchment in terms of storage capacity

- What evidence is required to change policy? (10)
 - Is a BACI design required?
 - How much 'Before' data is required?
- Scale – good evidence of larger scales needed both for spatial scale and for magnitude scale of event/hydrograph (9)
- How do we manage the uncertainty associated with a lack of data? How do we extrapolate? (6)
- We don't know if there is national data for Communities at Risk of flooding (5)
 - Where are the Communities at Risk that can benefit from NFM intervention on peatland?
 - Modelling into the future to inform longer term decision making & future proofing. How are we doing this?
- How does the cost/benefit impact of using peatlands for NFM compare to other NFM measures? (2)
- How big an effect does NFM work have downstream? (1)
- What is the relationship between peat and peat condition and communities at risk? (1)
- What is the optional vegetation structure...? (1)
- What is the hydrological connectivity...? (1)
- How do we better integrate our approaches to flood risk management NFM & traditional approaches (1)
- Upland bias to peatlands less known about raised bogs communities at risk below them. E.g. Humberhead levels (1)

Session 3: How do we fill the evidence gaps prioritised above? What might be an agenda to so?

Please see accompanying document: IUCN UoM Session 3 timeline.docx

Additional comments from this session not captured in the summary above but for note were:

- Clarity and expression of uncertainty
 - How sure are we of the answers that were experiencing?
 - What confidence do we have in the evidence
- Data repository
 - What data is available?
 - How can we share it?

Attendees:

Jillian Hoy (IUCN), Dave Chandler(MFFP), David Brown (EA), Ella James (Pendleton Hydrology Ltd), Emma Shuttleworth (UoM), Emma Goodyer (IUCN), Fraser Leith (Scottish Water), Ginny Hinton (UU), Jillian Labadz (NTU), Jon Walker (NRW), Jorge Aunon (Sheffield Hallam University), Paul Lunt (University of Plymouth), Linsey McLean (SEPA), Martin Evans (UoM), Michael MacDonald (RSPB), Mike Pilkington (MFFP), Nick Chappell (University of Lancaster), Steve Rose (JBA Consulting), Tim Allot (UoM), Tim Thom (YPP), Tom Nisbet (FC).

Facilitated by Matt Buckler, Kate Morley, Sarah Proctor & Matt Scott-Campbell
Moors for the Future Partnership
June 2018