Land cover and management activities across the moorlands in the Bamford Water Treatment Works Catchment and their implications for water colour and run-off.

Funded by:

SEVERN TRENT WATER

Prepared by

MOORS FOR THE FUTURE PARTNERSHIP

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2012

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Suggested citation:
Walker, J., Crouch, T, Proctor, S., Brown, M. and Maskill, R. (2012) Land cover and management activities across the moorlands in the Bamford Water Treatment Works Catchment and their implications for water colour and run-off. Moors for the Future Partnership, Edale.

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1 INTRODUCTION

Upland areas are significant water supply sources, providing over 70% of fresh water in Great Britain (Bonn *et al.* 2010; Watts *et al*. 2001). This ecosystem service is related to high rainfall amount, low evapotranspiration and upland landscape position. A major problem associated with water supply from upland areas is dissolved organic carbon (DOC) which affects water colour.

Upland peat soils are 50% carbon and as water passes through peat, a dominant soil type in upland areas, particulate organic carbon (POC) and DOC can enter the water. The amounts of these types of carbon entering the water depends on a range of factors, importantly vegetation cover, management and condition. In degraded moorland, with exposed bare peat and or lowered water tables, enhanced bacterial decomposition of organic material during aerobic conditions increases the availability of humic and fulvic acids which, when washed out result in increased water colour (Watts *et al.* 2001). Typically higher levels of POC and DOC are generated in the 'autumn flush' associated with storm events and movement of carbon from peat that has been decomposing during the summer. Iron can also contribute to water colour during stable warm summer conditions. O'Brien *et al*. (2008) identified elevated water colour within summer months within the Upper Derwent Catchment (Doctors Gate Clough and Red Clough) to be a result of the export of iron. The mobilisation of heavy metals (from historic atmospheric pollution) from degraded blanket peats is closely related to DOC concentrations which may be a result of metals complexing with the dissolved carbon (Rothwell *et al*. 2008).

Much upland water drains to reservoirs which store our potable water supply. As with peatland condition, processes within reservoirs can mitigate or exacerbate colour levels. For example, colour is decreased due to photo-oxidation near to the reservoir surface during spring and summer and increased due to the decomposition of organic matter which is exposed when reservoir levels fall, and washed out when reservoir levels rise again (Watts *et al.* 2001).

Water companies must comply with the EC maximum colour standard for treated water of 20 Hazen Units (DWI 2000); therefore, before drinking water can be supplied, water colour must be removed. Coloured water is not considered to be a direct health risk and no health-based guidelines are proposed (WHO 2006). However, it may pose indirect risks to health through the treatment process. For example, the process of chlorinating coloured water is believed to produce carcinogens such as trihalomethanes (Watts *et al.* 2001 and references therein).

For a summary of the current status of three ecosystem services affecting water quality and regulation across Peak District National Park peatlands and potential changes under different land-use scenarios see Appendix 1.

1.1 Aims and Objectives

The Bamford Water Treatment Works catchment is affected by high raw water colour during the autumn flush. This is difficult to treat due to the present inability to dose the appropriate amount of coagulant (Ferric Sulphate), leading to the production of disinfection by-products. Of particular concern is the increasing trend in raw water colour since 1989 (Personal communication K. Cherry, 2012).

The aim of this report is to provide spatial data for the land cover and management activities of the moorlands in the Bamford Water Treatment Works (WTW) catchment and briefly discuss their implications for water colour and run-off. This includes spatial data and discussion on the following land cover and management activities – see Table 1.

Table 1: Land cover and management activities and their justification for inclusion in the report

Land cover / management activity	Justification for inclusion
1. Land owner boundaries	Different land owners have different management objectives, which may affect dissolved organic (DOC) and particulate organic carbon (POC) export.
2. Areas of peat and mineral soil	DOC and POC enter water as it passes through peat soils.
3. Peat depth	DOC and POC enter water as it passes through peat soils; therefore, some areas may contribute more DOC / POC than others.
4. Land cover Audit	Different vegetation types are associated with different DOC concentrations.
5. Location of grips and gullies	Gullies lead to increased erosion and export of DOC and POC.
6. Burning areas, location, age and intensity	Vegetation changes associated with managed burning may impact DOC production.
7. Wildfire risk	Wildfires may trigger erosion, resulting in higher POC export.
8. Areas of restoration	Recovery of vegetation limits soil erosion and consequently reduces POC loss.
9. Grazing	Vegetation changes associated with grazing may impact DOC export.
10. Monitoring points for water level and water quality	Identify potential impact from land cover / management activities.

We draw these spatial data together to look at the cumulative potential impacts on DOC and run-off and make recommendations for addressing issues within the catchment.

1.2 The Bamford Water Treatment Works Catchment

The Bamford WTW catchment is 20,159 ha in area of which 12,302 ha (61%) is classified as moorland. In this project we use the Moorland Line[1] as a working boundary for the moorlands within the Bamford WTW catchment. The Moorland Line encloses land within England which has been defined as predominantly semi-natural upland vegetation, or predominantly of rock outcrops and semi-natural vegetation, used primarily for rough grazing. The version we use is 1.0 (version date: 01/06/2010).

The Bamford WTW is fed by three reservoirs (Howden, Derwent and Ladybower) with a combined capacity of 46,345 Ml. Howden reservoir (8998 Ml) is located at the head of the Derwent Valley. It receives inflows from its natural catchment and it flows by gravity to the WTW. Derwent reservoir (9478 Ml) is located immediately downstream of Howden reservoir. It also receives inflows from its natural catchment as well as flows diverted from the Alport and Ashop catchments (via the Ashop diversion) and flows discharged from Howden reservoir. Similarly, Derwent flows by gravity to the WTW. Ladybower reservoir (27,869 Ml) receives inflows from its natural catchment (including the Ashop) as well as flows from the Noe catchment (via the Noe Diversion) and any water discharged from Derwent reservoir. Water from Ladybower is pumped to the WTW. Bamford WTW receives water via three lines: Bamford Raw Line 1, containing water from Derwent and Ladybower reservoirs; Bamford Raw Line 2, containing water from Derwent reservoir; and Bamford Raw Line 3, containing water from Derwent and Howden reservoirs. Treated water is supplied to much of Derbyshire and to parts of Nottinghamshire and Leicestershire. There are also separate supplies to the Buxton area and a small local supply to the Hope Valley. The Derwent Valley reservoirs also provide a raw water supply to the Rivelin reservoirs of Yorkshire Water (Personal communication K. Cherry, 2012).

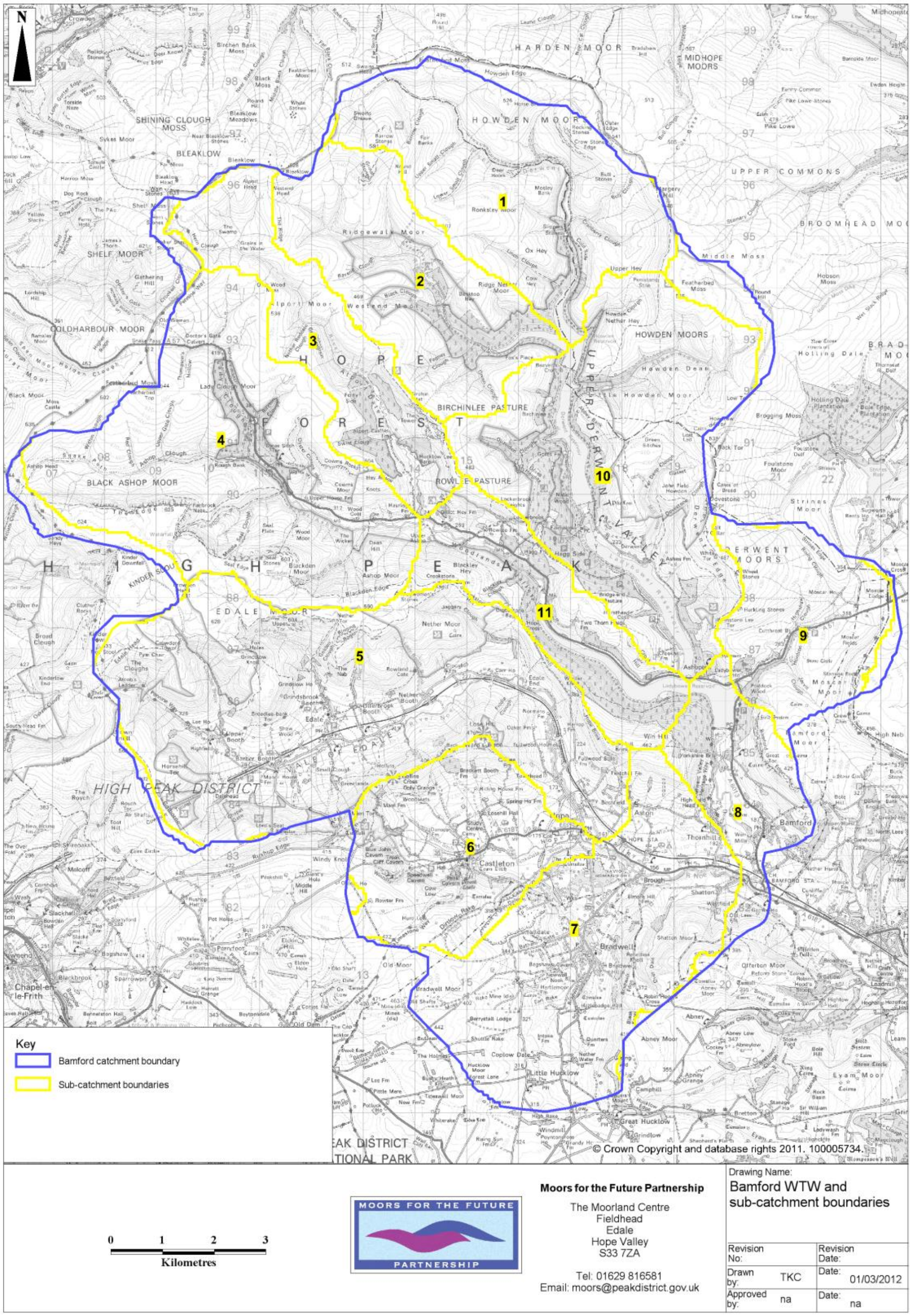
The Bamford WTW catchment comprises 11 separate sub-catchments (see Table 2 and Map 1). To define the boundaries of these sub-catchments we use Environment Agency (EA) GIS data. Note there are some discrepancies as to the catchment boundaries between Severn Trent water and the EA data – see Map 1.

[1] http://magic.defra.gov.uk/datadoc/metadata.asp?dataset=37

Table 2: Names of sub-catchments within the Bamford WTW Catchment (see Map 1) and Severn Trent Water colour results (28/07/2011 – 22/03/2012)

No. of sub-catchment	Name of sub-catchment (EA name)	Average colour / hazen
1	River Derwent from Source to River Westend	78.8
2	River Westend from Source to River Derwent	71.5
3	River Alport from Source to River Ashop	57.1
4	River Ashop from Source to River Alport	65.9
5	River Noe from Source to Peakshole Water	31.2*
6	Peakshole Water from Source to River Noe	No data
7	River Noe from Peakshole Water to River Derwent	No data
8	River Derwent from River Ashop to River Wye	55.1
9	Highshore Clough Catchment (tributary of River Derwent)	126.4
10	River Derwent from River Westend to River Ashop	93.1
11	River Ashop from river Alport to River Derwent	No data

* Average colour for sub-catchment 5 calculated from three sample sites: River Noe at Netherhall Bridge (17.9), River Noe near Barber Booth (32.7) and Grindsbrook near Grindsbrook Booth (42.9).



Map 1: The Bamford WTW Catchment and its 11 sub-catchments

2 DISCUSSION

2.1 Land owner boundaries

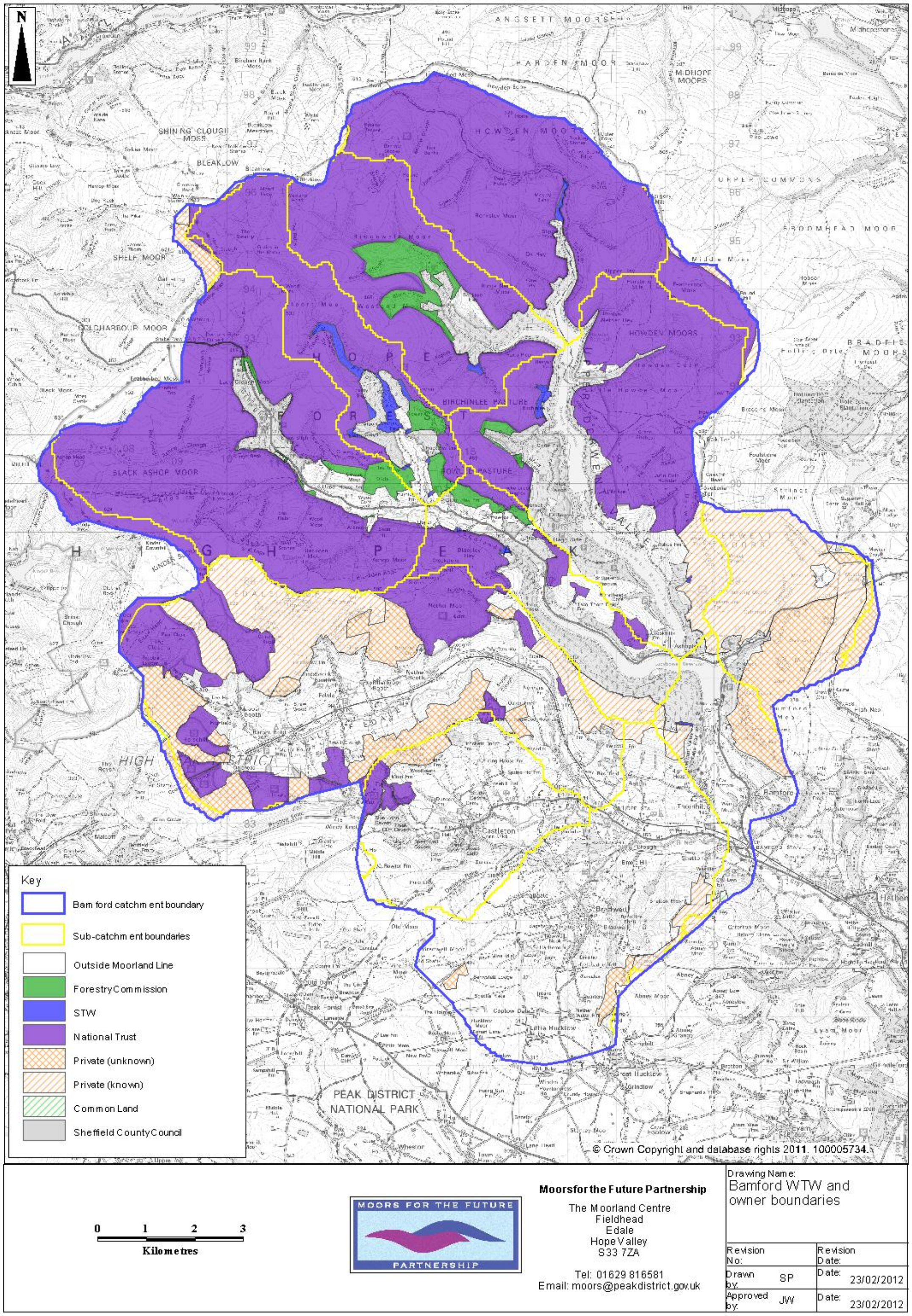
Data were collated from existing Peak District National Park Authority (PDNPA) / Moors for the Future spatial data on land ownership. Gaps in this dataset were addressed through interviews with local PDNPA rangers and the National Trust. Nearly three quarters (72.5%) of the moorlands within the catchment are owned by the National Trust with 2,896 ha (23.5%) in private ownership – see Table 3 and Map 2.

Table 3: Ownership of moorland with the Bamford WTW Catchment

Moorland land owner	Area (ha)	% of moorland within Bamford catchment
National Trust	8,924	72.54
Private	2,896	23.54
Forestry Commission	372	3.02
Severn Trent Water	109	0.89
Common Land	13	0.11
Sheffield City Council	2	0.02
Peak District National Park Authority	1	0.01

Land ownership - Implications for DOC and run-off

The National Trust is by far the major moorland owner in the catchment. The National Trust has proactive strategies for the sustainable management of their land holdings, particularly in relation to water. They state that "water is essential to the National Trust in our role in caring for and promoting the importance of nature and heritage" and that they "have a clear responsibility to both maintain and enhance the water environment." These commitments are set out in their 2008 report "From source to sea: working with water". Other (minor) public sector land owners (Peak District National Park Authority and Forestry Commission) have similar environmental aims which should lead to positive impacts on water quality and run-off. On National Trust land, outside of moorland restoration sites that are fenced off to exclude grazing (see section 2.8), the major land management activities are grazing and burning for sheep and grouse production respectively; see sections 2.6 and 2.9 for information on potential impacts of these activities on water colour and run-off.



Map 2: Moorland land ownership within the Bamford WTW Catchment boundary

2.2 Areas of peat soils

The National Soil Resources Institute (NSRI) maintains this extensive geographic database of land related data, covering England and Wales (accessible through LandIS[2]). It contains soil and soil-related information for England and Wales including spatial mapping of soils at a variety of scales as well as corresponding soil property and agro-climatological data. LandIS is the largest system of its kind in Europe and is recognised by UK Government as the definitive source of national soils information.

We do not hold comprehensive NSRI soils data for the entire Bamford WTW Catchment; although we are confident we hold data on all 'deep' peat areas within the catchment. A database licence agreement between Cranfield University and Severn Trent Water (Datalease code: L0096/00599) permits the reproduction of Map 3.

We classified peat soils into two groups blanket / deep peat and peat / shallow peat soils. Deep peat soil categories within Bamford Catchment: blanket peat, seasonally wet deep peat to loam; and shallow(er) peat soil categories within Bamford Catchment: peat to loam over sandstone, peat to loam over sandstone, shallow peat over sandstone.

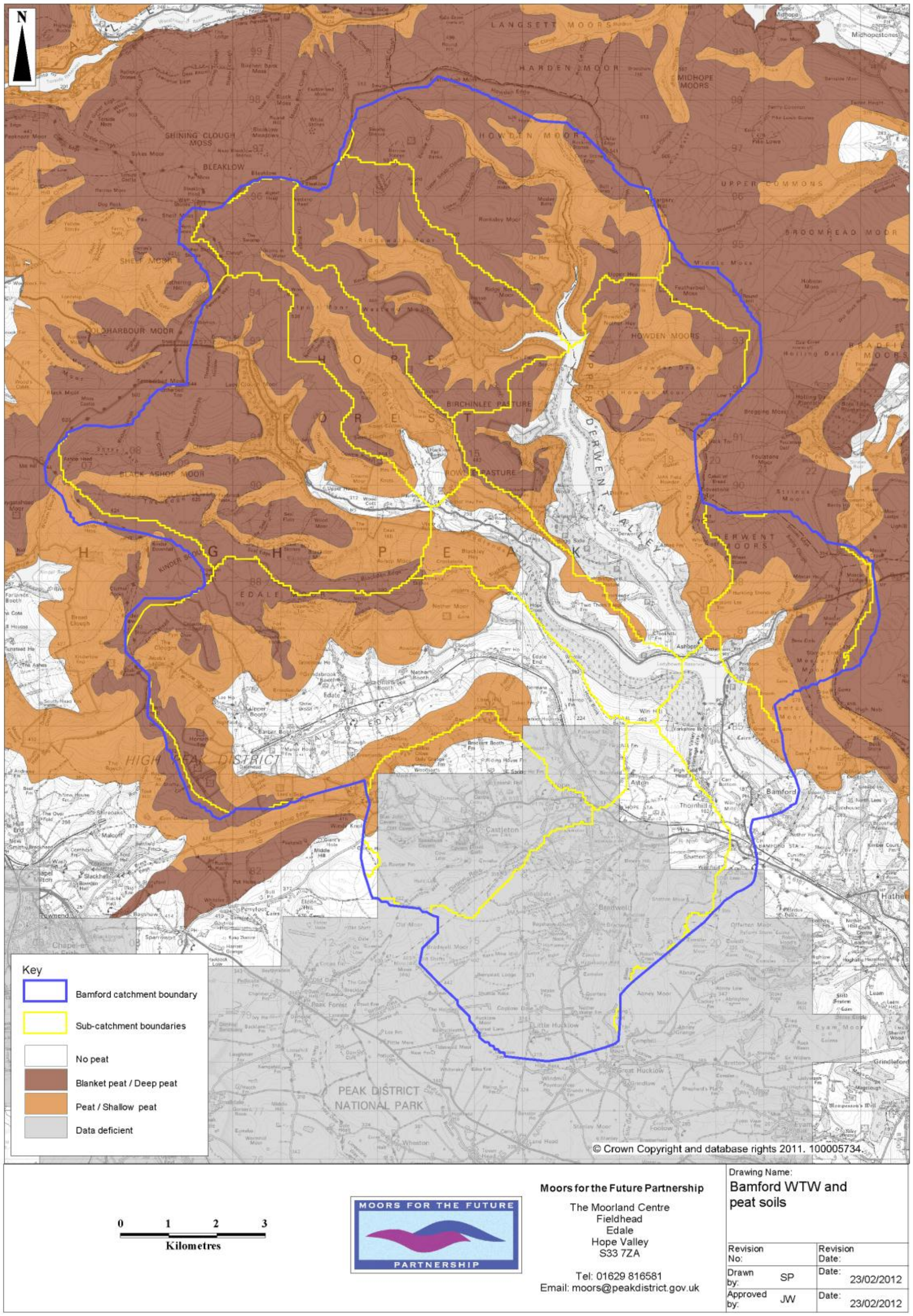
Based on the data we currently have access to we calculate that peat soils cover 12,677 ha (63 %) of the Bamford catchment, of which blanket / deep peat soils represent 6,700 ha (33 %) and peat / shallow peat represent 5,977 ha (30 %) – see Map 3.

Extent of peat soils - Implications for DOC and run-off

Peats naturally produce large amounts of DOC due to incomplete organic matter composition under waterlogged conditions. DOC concentrations have increased markedly in recent decades, which have been interpreted as evidence of peat degradation; however, research suggests that decreasing acid deposition may have contributed to these increases. Degraded peat soils generate higher levels of DOC and particulate organic carbon (POC) through increased microbial activity breaking down the peat and subsequent erosion.

As nearly two-thirds of the Bamford WTW Catchment are peat soils, half deep peat soils, these areas are therefore naturally likely to generate elevated levels of DOC (compared with mineral soils areas), especially when in a degraded or bare condition or under inappropriate management regimes.

[2] LandIS is the 'Land Information System', a substantial environmental information system operated by Cranfield University, UK. http://www.landis.org.uk



Map 3: Distribution of peat soils across the moorlands within the Bamford WTW Catchment

2.3 Peat depth

2.3.1 Introduction

In autumn / winter 2012 Moors for the Future carried out a peat depth survey across the deep peat areas of the Bamford WTW Catchment. The aim of the peat depth survey is to provide baseline data on peat depth across the peat soils within the Bamford catchment.

2.3.2 Methods

The survey area was generated using NATMAP (National Soil Map of England and Wales) to determine the extent of blanket and deep peat in the Bamford catchment. A buffer of 20 m was generated around the areas of 'deep' peat to capture the transition from peat to other soil types. It also included the gradient from the edge of the peatlands to the plateau centres, as well as different Biodiversity Action Plan Priority habitats. The spatial design of the survey was developed in discussion with Penny Anderson Associates (PAA) who is working with Peatscapes to deliver Natural England's Mapping Peat Depth and Carbon Storage in England Project[3]. The decision to align this survey with a contemporaneous project that is developing a national peat depth monitoring protocol meant that we would derive greater value from the data and contextualise peat depths across the Bamford WTW catchment in the national map.

A triangular grid configuration was adopted as it provides a slightly more efficient design in terms of sampling cost, and provides slightly better spatial predictive results. Based on the resources available to deliver the survey a 400 m equilateral triangular grid was chosen. The triangular grid of survey points was generated within MapInfo Professional 10.5 using the GRIDS.mbx tool. This created a 400 m x 400 m equilateral triangular grid, consisting of 513 peat depth sampling points. In terms of fieldwork this represented over 206 km of surveys excluding daily walks onto and off the moors. At each sampling point peat depth was measured by pushing a metal peat rod into the peat until the mineral base was reached; this was easy to identify using metal peat depth rods given the distinctive noise they make when hitting the bedrock. At each sampling location the predominant vegetation class was recorded, according to the Landscape Audit Classification (see Section 2.4) and the status of the peat being sampled in terms of - see Figure 1:

a) intact peat, intact vegetation
b) intact peat, no vegetation
c) gully side
d) gully bottom
e) peat dome top, vegetated
f) peat dome top, bare peat
g) peat dome bottom, vegetated
h) peat dome bottom, bare peat

[3] **Mapping Peat Depth and Carbon Storage in England (RP0437) Natural England.**
This project, run by the North Pennines AONB Partnership's Peatscapes initiative, will: i) collate and analyse all available peat depth/C data ii) develop a survey methodology to assess peat depth/C iii) conduct some new targeted peat surveys iv) coordinate with NPAs, NGOs etc. on new surveys v) produce a improved and easily updateable peat depth/C storage map for England vi) supply a report, database & licence-free map.

i) hag, vegetated
j) hag, bare peat
k) mineral/rock, vegetated
l) mineral/rock, bare peat
m) mineral/rock, mineral base

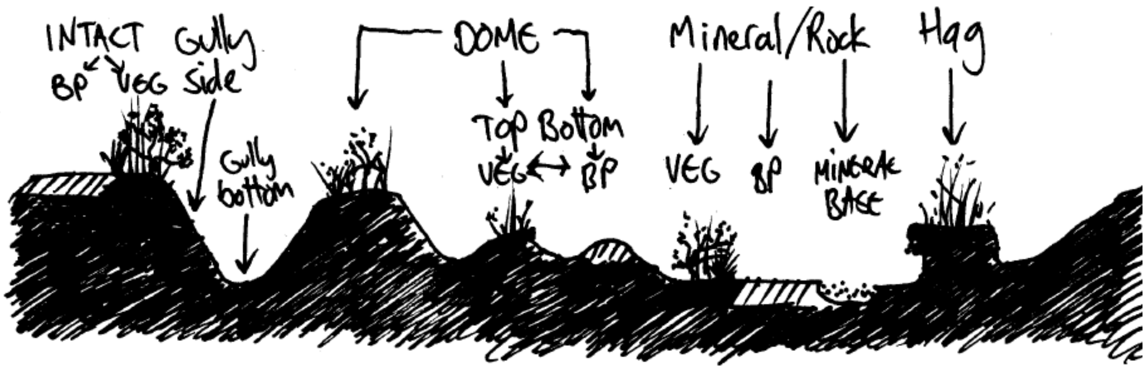


Figure 1: Diagram illustrating status of the peat (M. Brown, 2011)

To produce the peat depth map presented in this report (Map 4) we imported available peat depth measurements into MapInfo Professional 10.5. Using a ‘grid template’ (Map > Create Thematic Map) the peat depth point data were interpolated to produce a continuous raster grid. This displays the peat depth data as a continuous colour gradient across the map – see Map 5.

2.3.3 Results

In total 513 peat depth measurements were taken across the peatlands of the Bamford WTW Catchment. The mean peat depth recorded was 1.37 m (±0.08 95%CI). The distribution of the peat depth measurements across the areas surveys are presented in Figure 2; 75 % of measurements recorded peat depths between 0 and 2 m, the rest (25%) recorded depths >2 m.

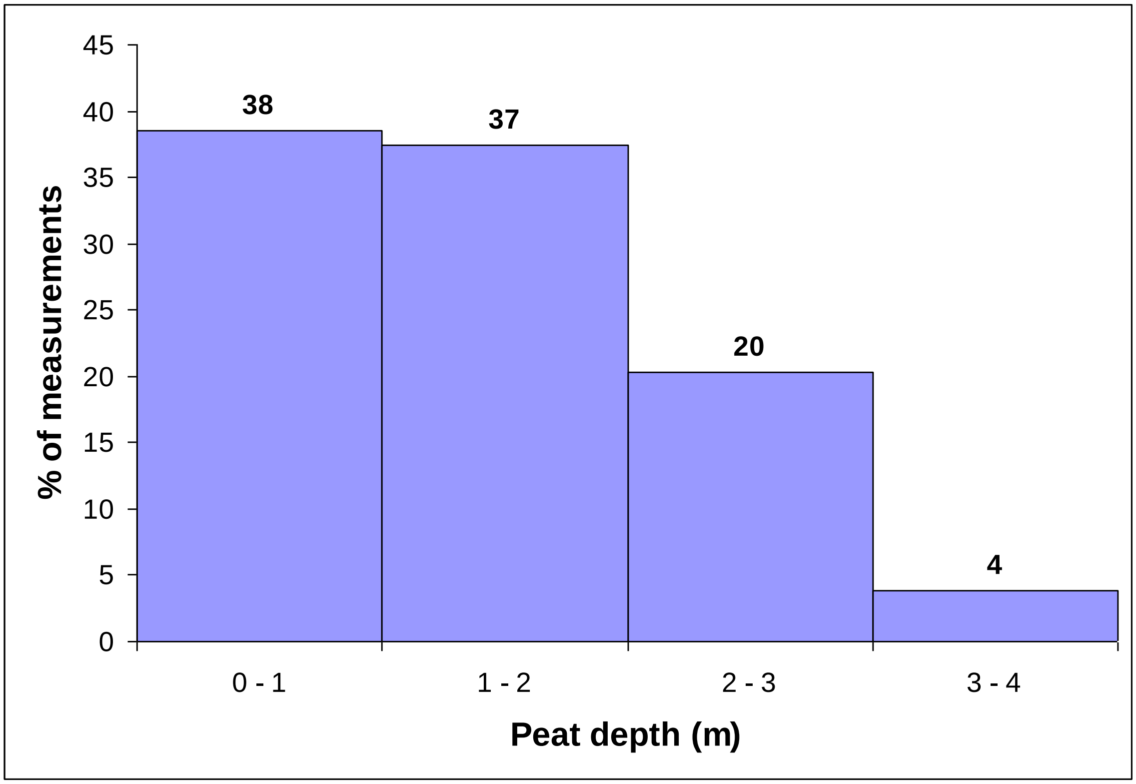


Figure 2: Distribution of the 513 peat depth measurements taken across the peatlands of the Bamford WTW Catchment. Values above bars represent percentage of measurements recorded within the peat depth bands.

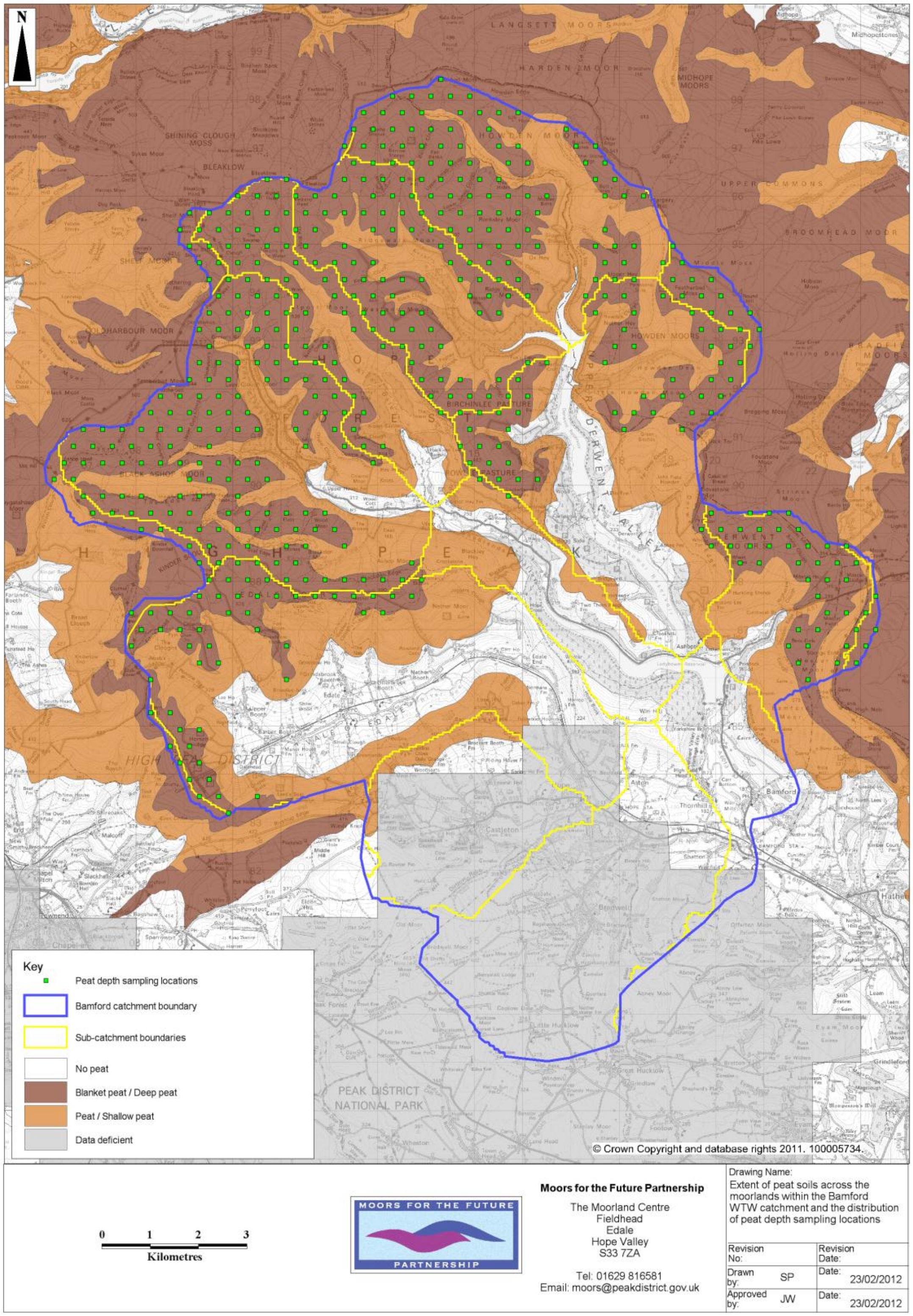
Table 4 shows the mean peat depth for each landscape location category (see also Map 6 for the distribution of these). From this data it is possible to observe reductions in peat depth of approximately 60 cm at some locations; for example the difference between gully side and bottom, or peat dome top and bottom) over time.

Table 4: Mean peat depth for each landscape location category

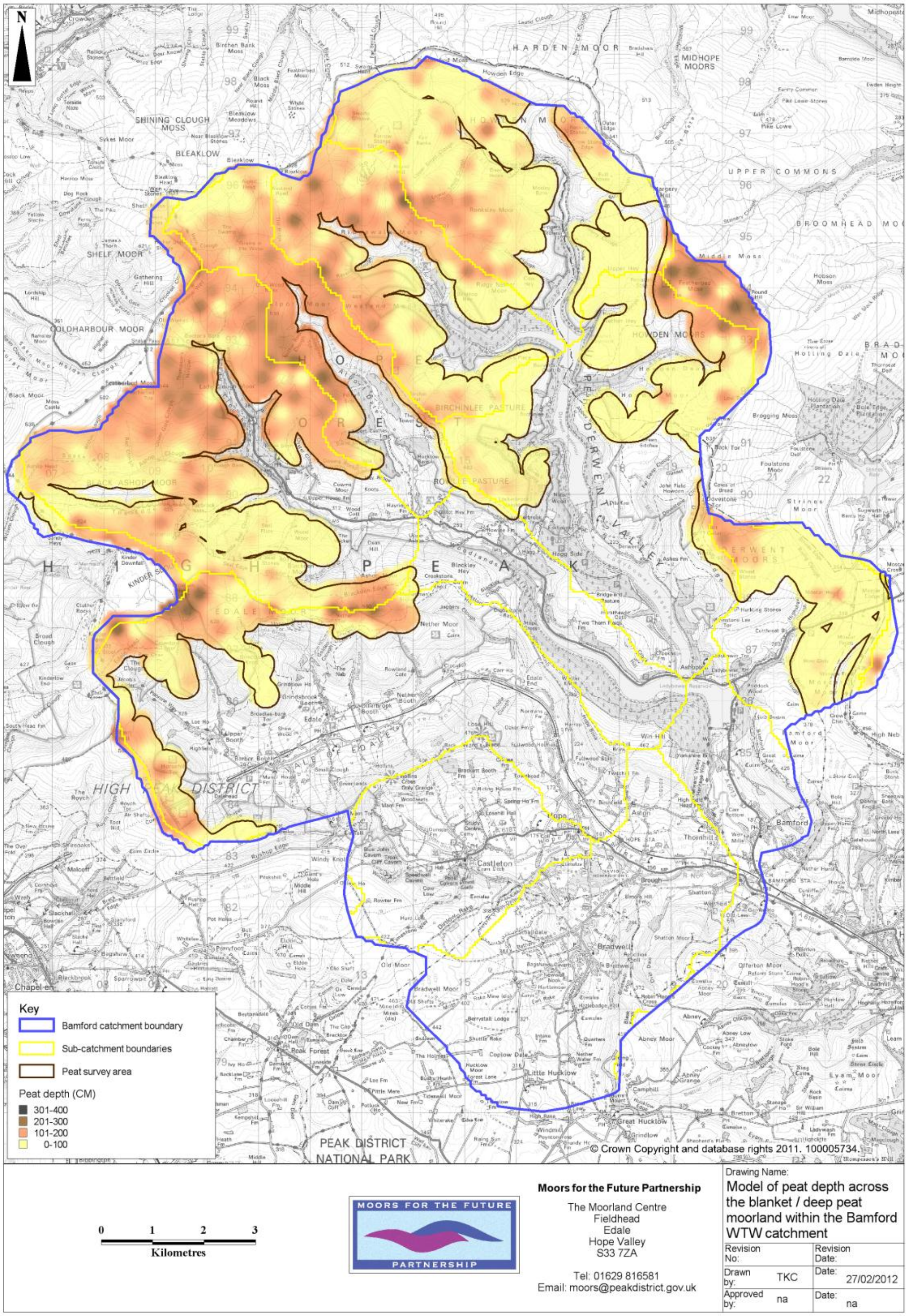
Landscape location	No. measurements	Mean peat depth (m)
Gully bottom	23	0.67
Gully side	19	1.21
Hag	24	2.25
Intact bare peat	2	2.50
Intact vegetation	399	1.37
Mineral/rock bare peat	1	0.11
Mineral/rock mineral base	3	0.00
Mineral/rock vegetation	3	0.33
Peat dome bottom vegetation	3	0.62
Peat dome top bare peat	5	1.28
Peat dome top vegetation	31	1.29

Peat depth - Implications for DOC and run-off

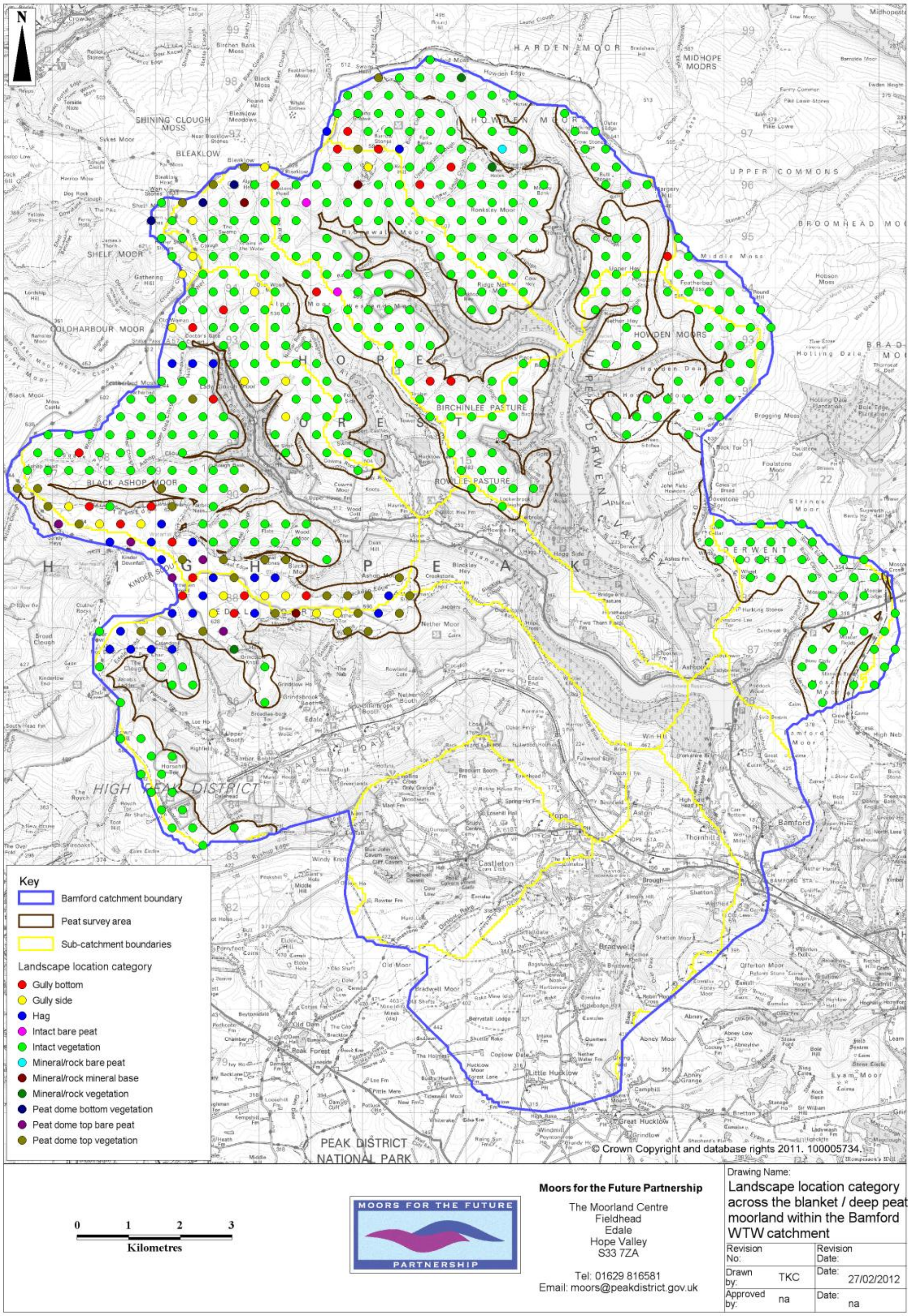
At a coarse scale DOC levels are directly related to the volume of peat / carbon located within a catchment. Consequently these data may identify areas from where greater sources of POC and DOC may be generated and where management / restoration action might be targeted to reduce present and potential future peat erosion (for example gully and peat dome locations; see Map 6).



Map 4: Extent of blanket peat soils across the moorlands of the Bamford WTW catchment and the distribution of the 513 proposed peat depth sampling locations



Map 5: Model of peat depth across the deep peat soil moorland areas within Bamford WTW catchment



Map 6: Model of landscape location category across the deep peat soil moorland areas within the Bamford WTW catchment

2.4 Landcover Audit

2.4.1 Introduction and Methods

Moors for the Future and the University of Leeds have produced a 'Landscape Audit' of land cover of the moorland areas of the PDNP (Chapman *et al.* 2010). Colour and infrared aerial photographs were classified into seven dominant land-cover classes across the unenclosed moorland in the PDNP using the Random Forest classification tree methodology (Chapman *et al.* 2010). In addition, heather (*Calluna vulgaris*) was further differentiated into growth phases, including sites that were newly burnt (see Section 2.6). Classification accuracy was ~95% and produced a 5-m pixel resolution map. The classification revealed the spatial distribution of managed burning and suggested that relatively steep areas may be disproportionately burnt.

Cloud-free aerial photographs (Infoterra Ltd, Leicester, UK) were taken in September 2005. Images consisted of 25-cm resolution true colour photographs (RGB) and 50-cm resolution false colour infrared images (CIR, also with three bands), all orthorectified to a 1-m accuracy. For vegetation classification, a pixel size of 5 x 5 m was selected as the finest practical resolution. The mean and standard deviations of each reflectance ratio throughout each 5-m cell were calculated as measures of the overall level and variation in reflectance. All operations were performed using ArcMap 9.2 (ESRI Inc. 2006).

To supervise classifications, stratified sampling was employed across the Peak District to record the locations of stands of dominant vegetation or areas of other cover types with radii ‡ 5 m at 1540 points using a hand-held differential GPS. Most of the data were collected in February and March 2006, although a small number of points were recorded after this. Seven land-cover classes were selected:

(1) heather;
(2) non-heather dwarf shrubs (mostly bilberry *Vaccinium myrtillus,* also some crowberry *Empetrum nigrum*;
(3) bracken *Pteridium aquilinum*;
(4) grasses (mostly purple moor grass *Molinia caerulea,* also some wavy-hair grass *Deschampsia flexuosa* and mat grass *Nardus stricta*;
(5) sedges and rushes (mostly common cotton grass *Eriophorum angustifolium*, hare's tail cotton grass *E. vaginatum* and *Juncus* spp., also some deer sedge *Trichophorum cespitosum*);
(6) bare peat;
(7) exposed rock, scree or shale.

2.4.2 Results

The results of the Landscape Audit are shown in Table 5 and Map 7 (bare peat land cover) and Map 8 (vegetation land cover classes). Bare peat is additionally considered in restoration section - Section 2.8. Bare peat covers 483 ha within the Bamford Catchment, some 2 % of the catchment. This is prominently distributed within the Ashop (#4), Alport (#3) and Upper Noe (#5) catchments but by far the majority of this is located within the Ashop and Alport catchments - 13 % bare peat. Exposed bedrock and rock outcrops account for 311 ha or 1.5 % of the catchment. Within the Bamford catchment heather represents the dominant land-cover class covering 3,470 ha (17 %). This is followed by sedges and rushes (2,663 ha or 13 %), bracken (2,008 ha or 10 %); grasses (1,880 ha or 9 %) and non-heather dwarf shrubs (1,801 ha or 9 %).

Table 5: Area (ha and %) of each land cover class

Land cover class	Area (ha)	Area (%)
Heather	3,470	17
Non-heather dwarf shrubs	1,801	9
Bracken	2,008	10
Grasses	1,880	9
Sedges and rushes	2,633	13
Bare peat	483	2
Exposed rock, scree or shale	311	1.5

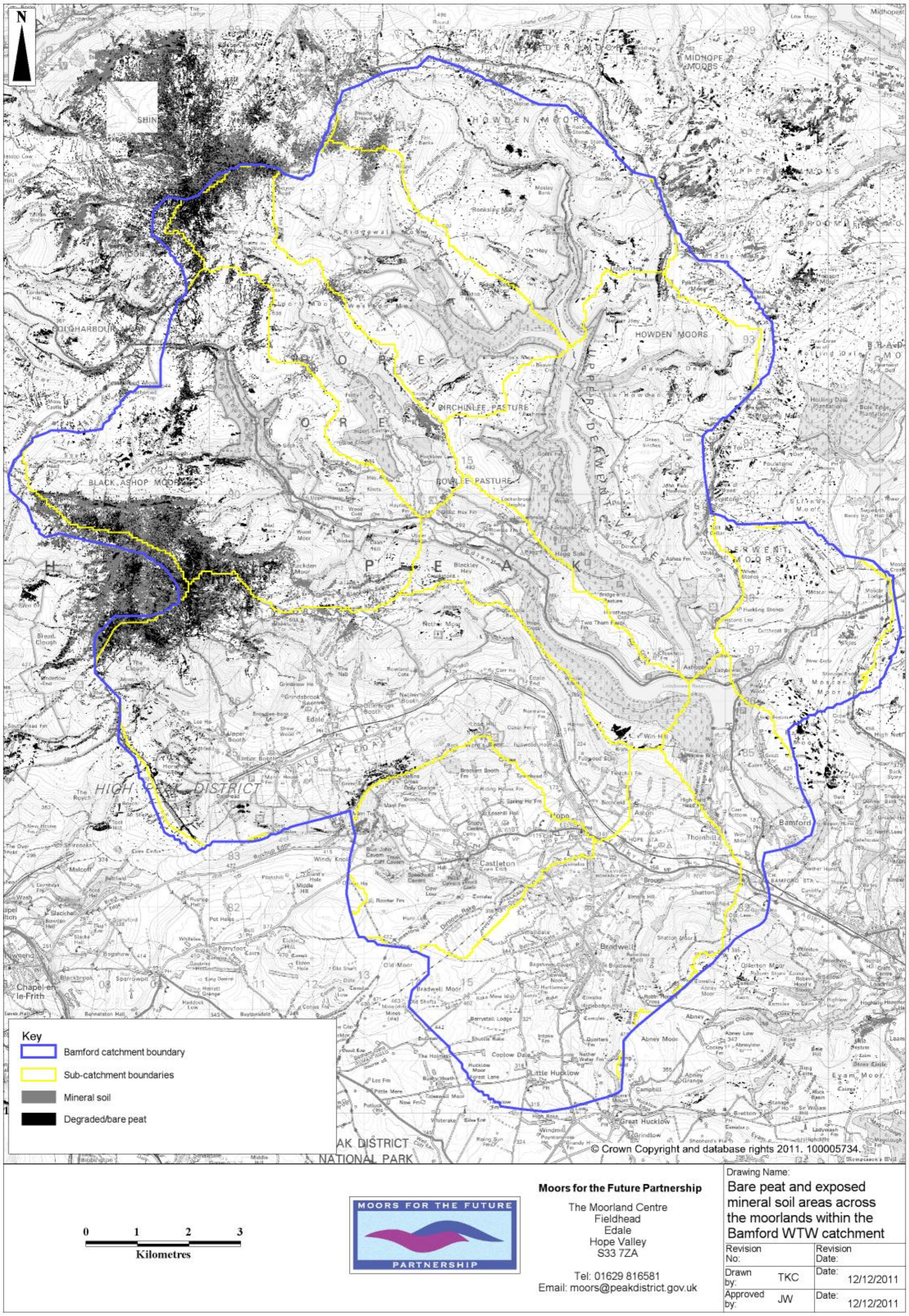
Vegetation cover - Implications for DOC and run-off

Worrall *et al*. (2011) report that the degree of vegetation or revegetation of a peatland is the dominant control on DOC flux, either through its role in limiting sediment production on intact surfaces or in reducing slope-channel linkages (breaking the pathway eroded sediment would take before reaching a stream in eroding but revegetating systems). Furthermore, they report that *Sphagnum* (not a vegetation class included in the Landscape Audit) and purple moor grass seem to be associated with low concentrations, while heather is associated with higher concentrations of DOC (see also Armstrong *et al*. (in review) and Lindsay (2010)). Thus if management, e.g. prescribed burning, alters the vegetation cover of sites then this might alter the carbon fluxes in the long term, and especially the DOC flux (Worrall *et al.* 2011). For POC, generation by wind (Aeolian) erosion is also important. Holden *et al.* (2008) investigated the velocity of flow over bare peat and different types of vegetation on slopes with blanket peat 2 m deep. They found average velocities over cotton grass to be 70% slower than over bare peat (0.034 m s^{-1} compared with 0.05 m s^{-1} respectively) but *Sphagnum* cover showed significantly greater hydraulic roughness, with the increased friction slowing flow to an average velocity of around 0.015 m s^{-1} or ~30 % slower than bare peat, ~44 % slower than cotton grass.

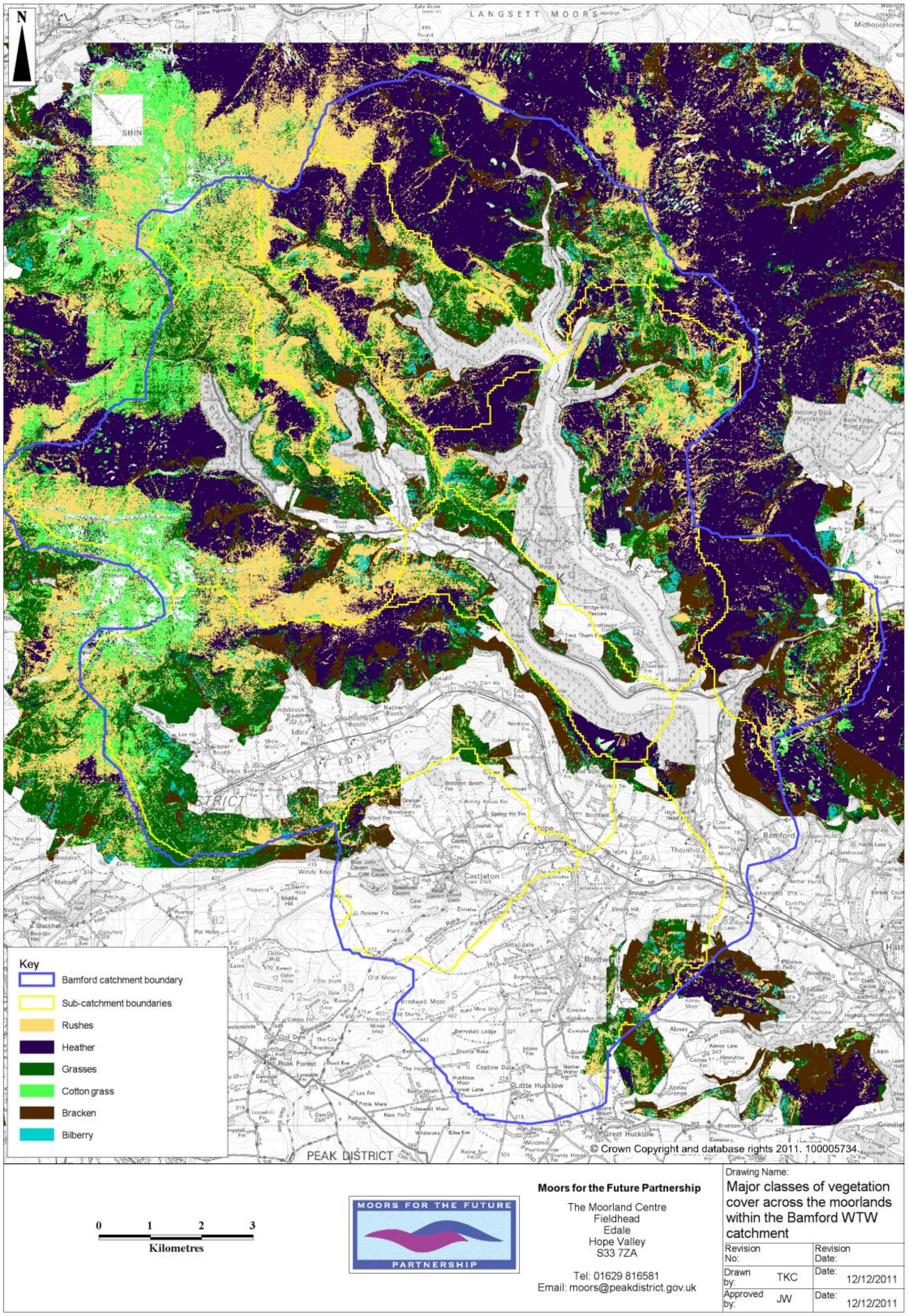
Sphagnum

Sphagnum mosses are the key species in the formation of peat on blanket bogs (Hinde *et al*. 2010); however, have been largely lost from the moorlands of the Peak District as a result of historic air pollution, fire and grazing pressure (Carroll 2009). *Sphagnum* species and bryophytes generally are now returning to the Peak District but recovery is slow and conditions may still not be suitable for many species. Reestablishment of Sphagnum on degraded (especially bare) peatlands may therefore be important for reducing the potential for sheet erosion and downstream flood peaks more than cotton grass or cotton grass-*Sphagnum* mixes (Holden *et al* 2008).

Just in terms of vegetation cover, areas of extensive heather cover (sub-catchments #1, #2, #9, #10 – see Maps 1 and 11) potentially are likely to generate higher levels of DOC compared with areas dominated by other vegetation classes. Establishment / increasing the cover of Sphagnum mosses across all vegetation and land cover classes should provide benefits in terms of increased water storage, reduced flow velocities and therefore potentially reduced peat erosion.



Map 7: Bare peat and exposed mineral areas across moorland within Bamford WTW catchment



Map 8: Major classes of vegetation cover across the moorlands of the Bamford WTW catchment

2.5 Location of grips and gullies

Using 2005 airbourne Light Detection and Ranging (LiDAR) data provided by the Environment Agency (see Map 9), Holden *et al*. (2005; see Evans *et al.* (2005)) created a map of gullies using an automated process based on a Multiple Criteria Evaluation (MCE) methodology. A digital terrain model (DTM) was generated and subsequently interpolated to account for areas of missing data. From this DTM flow accumulation, reflecting drainage networks and allowing differentiation between active and passive gullies, and a topographic Index, showing the likely distribution of saturation, were developed. Gullies were mapped using flow accumulation values of between 3,000 and 30,000 to minimise errors and exclude streams respectively. Gullies identified to have flow accumulation scores below 3,000 were manually digitised from the aerial imagery. The second dataset identifies gullies outside of the original modelled area which were mapped using an alternative approach. These gullies were manually digitised from aerial photographs of the Bamford Catchment area at a scale of 1:2000 (UK Perspective) – see Map 10. No grips we identified within the Bamford Catchment from available imagery.

Using these data, we estimate there are ~602 km of gullies within the Bamford Catchment. The majority of these are located within the Ashop Catchment (#4, 194 km; 32% of all gullies), with the River Derwent Source sub-catchment (#1, 98 km, 16%) and River Westend sub-catchment (#2, 73 km, 12 %) – these three catchments account for 60 % of all the gullies in the Bamford Catchment moorlands.

Gullies - Implications for DOC and run-off

Gullies cause the peat to dry out, resulting in accelerated peat decomposition, which leads to discolouration of local water sources and release of greenhouse gas emissions into the atmosphere (Bonn *et al.* 2010). They result in more rapid runoff and typically have a positive feedback leading to increased erosion and export of particulate and dissolved organic carbon (Evans and Warburton 2007). Gully edge peats provide a key linkage between the hillslope hydrological system and channel flow so that their influence on the hydrological functioning of the peatlands is disproportionate to their aerial extent within the catchment (Daniels *et al*. 2008). Future climate change may lead to further degradation of the bogs and a reinforcement of the importance of erosion gullies to runoff generation and water quality (Daniels *et al*. 2008). Blocking eroded gullies; however, may decrease annual flux of DOC from a site (O'Brien *et al.* 2008).

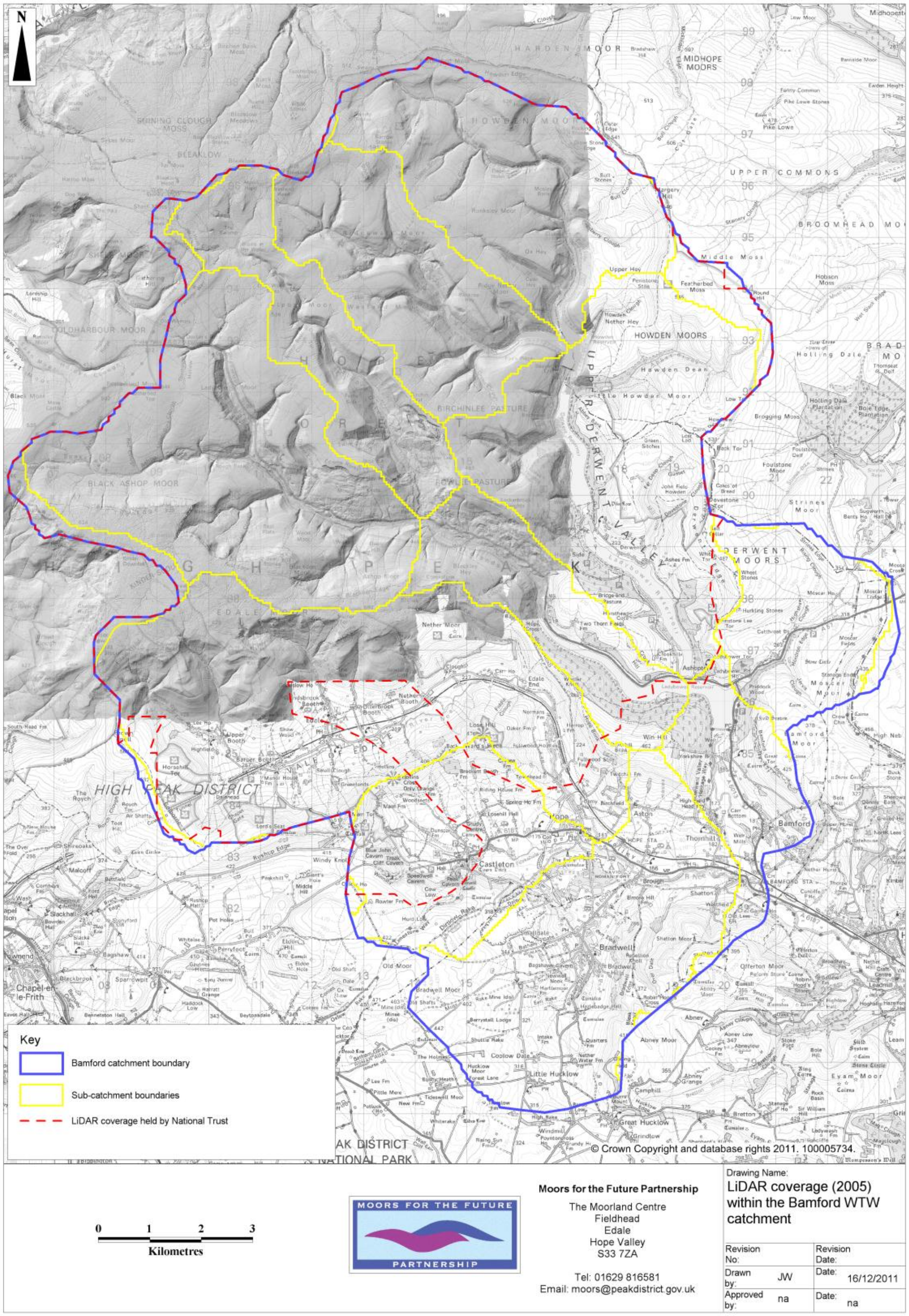
On the gullied system, the Bleaklow plateau, Worrall *et al*. (2011) found bare peat gullies to have the largest POC flux across all experimental sites. More recently, a related two year study by Clay *et al.* (2012b) of carbon pathways (DOC and CO_2) from gullies subject to different restoration treatments was carried out. They found that a 'control' natural channel had the lowest DOC concentration (median = 44.5 mgL^{-1}), followed by a blocked gully (median = 58.5 mgL^{-1}), a bare peat gully (median = 66.1 mgL^{-1}) and a re-vegetated gully (median = 66.4 mgL^{-1}). DOC concentrations in naturally re-vegetating gullies were the highest, 72.5 mgL^{-1}. Bare peat gullies had lower DOC concentrations but export much greater POC; Clay *et al*. (2012) suggest that the low DOC concentrations is due to the lack of an active vegetation layer; therefore little soil microbial community driving DOC production. Further, if gullies are to become net carbon sinks, management of the vegetation present is a significant factor.

Peat Pipes

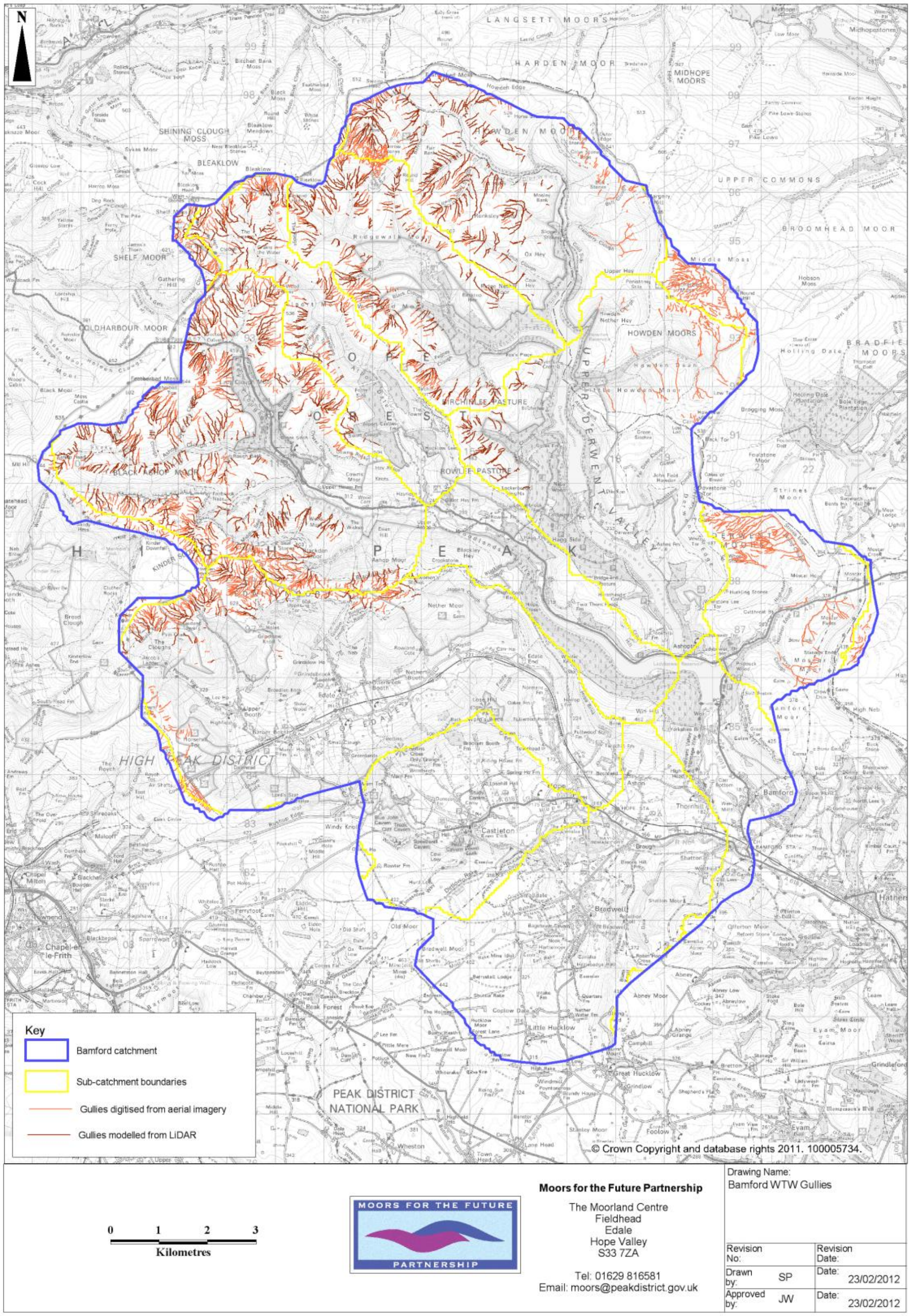
Peat pipes are large macropores, often many centimetres in diameter, via which water, sediment, solutes and dissolved gases may move through the soil (Holden *et al.* 2012). These pipes, or tunnels, can often be several hundred metres in length and typically form branching networks. In a survey of British blanket peat catchments, Holden (2005a) found land management (moorland gripping) to exert the most important control on hillslope pipe frequency in blanket peats, and that management practice in peatlands may therefore induce more rapid subsurface erosion and carbon loss. Further, Holden (2005b) demonstrated that heather (*Calluna*) species are one causative factor of piping in blanket peat catchments; pipe occurrence was significantly higher where bare peat (149 pipes/km) and heather (87 pipes/km) were present compared to other plant species (67 pipes/km). What is unknown from available data is the extent and potential role peat pipes play on the transport of water and carbon from the across the Bamford Catchment.

Jones (2004) reviewed evidence for the impact of natural soil piping on water quality in blanket bogs and suggested that it can be an important source of “dirty water”, with very marked brown colour especially during the first rains of autumn following a dry summer. It can lead to increased acidity (low pH) of surface water streams because it contributes water that has had only a short residence time and has been in contact with the upper organic soil horizons (peat) rather than weathered mineral surfaces. Evidence suggested that some water flowing from pipes may be relatively “old”, having spent time residing in the peat matrix, whereas some water also flows very rapidly through the pipes with little time for chemical interaction with the peat.

In the blanket bog of the Moor House NNR, North Pennines, Holden and Burt (2002) found pipes to have a prolonged recession limb such that they maintain low flow for longer periods than most other runoff production processes, that pipeflow contributed ~10% of the streamflow but did, at times, contribute up to 30%.



Map 9: LiDAR coverage (2005) within the Bamford WTW Catchment boundary



Map 10: Gullies on deep peat moorland within Bamford WTW catchment; red = automated mapping from LiDAR; orange = manually mapped from 2005 aerial imagery

2.6 Burning areas, location, age and intensity

Heather pixels within the Landscape Audit (based on 2005 aerial photographs – see Section 2.4) were classified into one of the four age classes, roughly corresponding to growth phases commonly used to describe heather:

1a) newly burnt - burnt for grouse moor management in the last 2 years
1b) age class 1 - corresponding to the pioneer or early building stages
1c) age class 2 - late building or mature stage
1d) age class 3 - degenerate stage.

Since heather burns are created in strips ~30 m wide within heather moorland, any patches with areas <900 m^2 were assumed to be misclassified. The aerial photographs corresponding to 500 randomly selected patches larger than this were examined visually to determine whether they were indeed true new burn patches. Based on this, it was also determined that patches with >90% of their pixels at the edge (defined as having at least one of their four-pixel neighbours outside the patch) or with their edge cells having on average <30% heather cover within a circular buffer of radius 50 m (excluding supposed new burn pixels) were also always misclassified.

Potential misclassifications were identified and these pixels were reclassified and then overlaid onto the map produced previously. See Map 11 for modelled map of heather burning areas using the 2005 imagery. Heather dominated vegetation accounts for 3,470 ha or approximately one quarter of the moorlands in the Bamford Catchment.

Additionally, we have digitised the boundaries of heather burns areas (all ages classes) manually from the 2005 aerial photographs – see Map 12. From these data it is estimated that one third of the moorlands within the Bamford Catchment or 14% of the entire catchment are subject to managed burning. Three quarters of the moorlands that are managed by burning with the Bamford Catchment are within just three sub-catchments, (Derwent Source (#1; 38 %), Ashop (#4; 20 %) and Highshore Clough (#9; 12%).

Burning - Implications for DOC and run-off

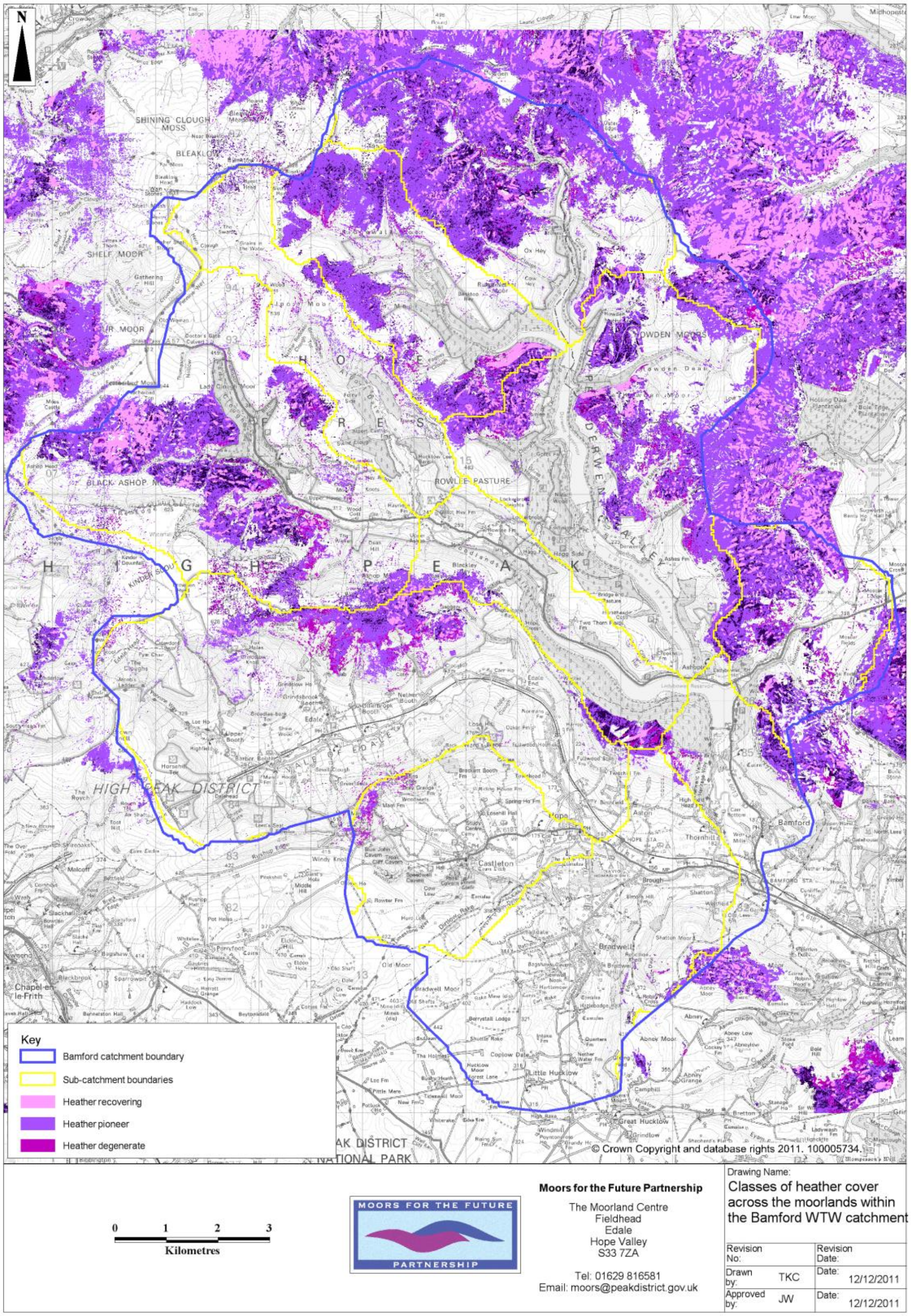
One of the main land management activities across the moorlands in the Bamford WTW Catchment is prescribed, or managed burning. This management tool is used to produce heather age mosaics to support red grouse (*Lagopus lagopus scotica*) production (Holden *et al.*, in press; Worrall *et al*., 2010). In recent years the area of land subject to managed burning in some areas of northern England is thought to have increased. This is thought to include areas of blanket bog, despite guidelines that recommend no burning on blanket peat (Holden *et al*. (in press) and references therein). As a result there is currently an interest in understanding the impacts of burning management on peatlands (see Holden *et al*. (2012), Worrall *et al*. 2010).The principle effect of managed burning is to change the vegetation from *Sphagnum* and cotton grass dominated to that dominated by common heather, or where burning is more frequent, and in some circumstance, purple moor grass (Worrall *et al*. 2011a). These vegetation changes may have a strong impact on DOC production and, as noted previously (Section 2.4), certain vegetation types are associated with certain levels of DOC concentration. Conway and Millar (1960) showed that, in this semi-intact blanket bog, rainfall input produces a rapid stream runoff response, especially where the catchment has a dense gully network or where the peat has been burnt. Water balance calculations showed that a relatively uneroded *Sphagnum*-covered drainage basin retained significantly more water than another basin which had been both drained and burnt (for grouse management).

Holden *et al.* (2012) have critically reviewed research on the impacts of managed burning on water colour. They found that research has taken place at three scales: laboratory studies, plot scale studies and catchment scale studies. The research findings from laboratory and catchment scale studies suggest burning will increase colour production, while findings from plot scale studies suggest colour production may either decrease or remain unchanged with burning. While evidence to date is equivocal, Holden *et al.* (in press) conclude that the balance of evidence suggests burning is related to increased colour / DOC in stream waters but that further research is required. Worrall *et al.* (2011a) point out that no study has measured POC fluxes from managed burnt areas, and that what may be critical in carbon and GHG balances from managed burns is understanding them in relation to variations in actual burning practice as data to date have come from well managed sites; the impact of burning might be dependent on how much “bad” burning occurs where bad is defined in carbon / GHG terms. Further research is required to investigate whether managed burning is a direct driver of enhanced colour and DOC in upland water bodies. If burning is conclusively found to impact on water quality and run-off, a reduction in burning or longer duration between burns could help reduce the impact of burning on water colour (Holden *et al*. (2012), Worrall *et al*. 2010) or alternative management methods to provide new heather growth adopted, for example cutting.

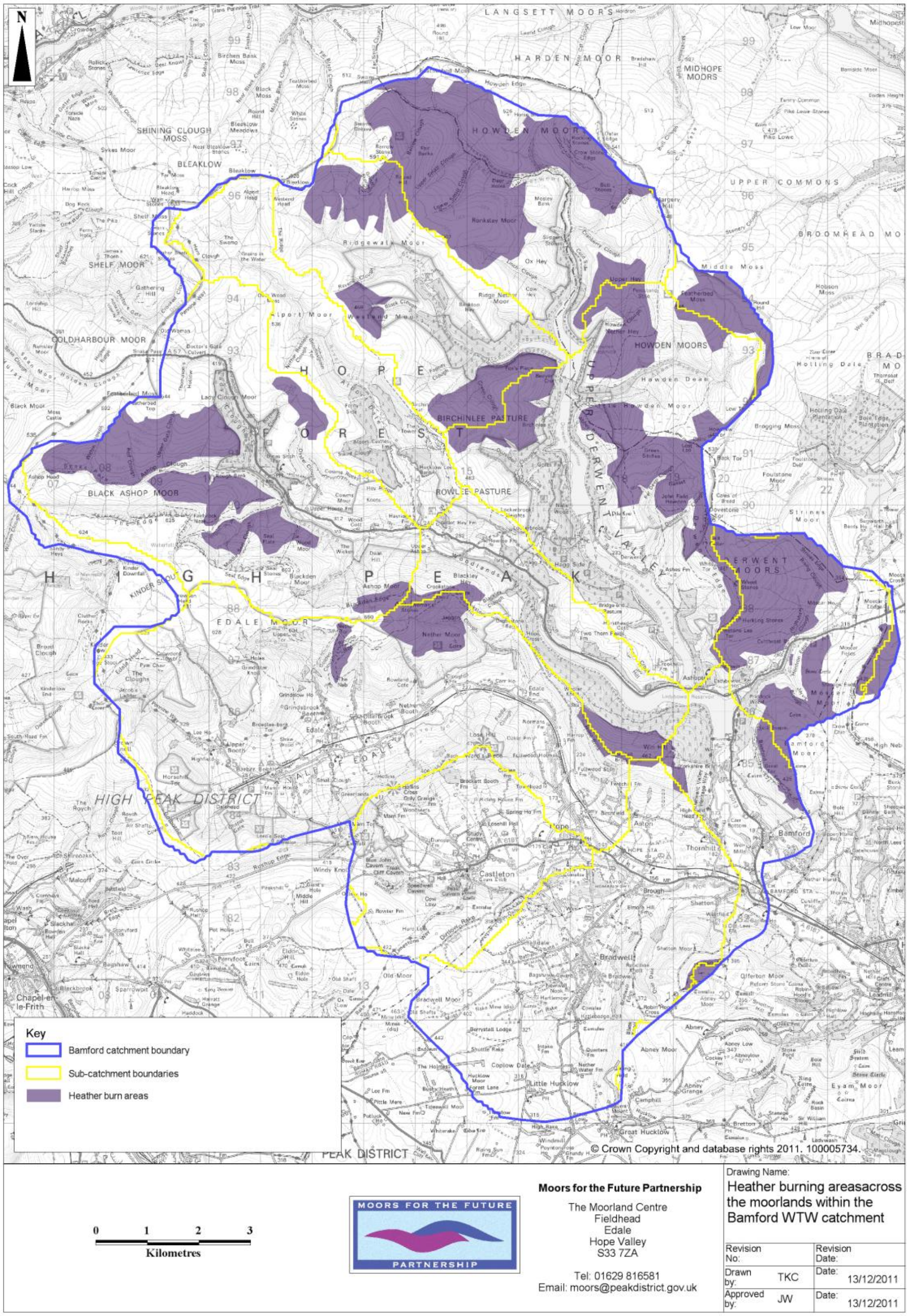
In a study of DOC concentrations in soil and run off waters over a 10 year period, Clay *et al*. (2012a) found elevated water colour in the 4-5 years immediately following burning, but this was not matched by a rise in DOC concentration. They propose that burning appears to affect the composition of the DOC rather than absolute DOC concentrations. The mechanism for increased colour but not DOC is thought to be hydrologically controlled as water table position has been shown to influence DOC dynamics in peat (e.g. Webster and McLaughlin, 2010), possibly as destruction of above-ground vegetation leads to a decrease in evapotranspiration and decreased drawdown of the water table (Worrall *et al*. 2007).

Clay *et al*. (2012a, 2009a) found water tables to be ‘shallower’ in newer burn sites. There are potential implications for water treatment as changes in DOC composition may affect the ‘treatability’ of water.

As a third of the moorland in the Bamford Catchment is subject to a prescribed burning management, the impacts of burning, both in the short and long term, are likely to be a major factor to investigate. Reductions in the spatial extent and temporal patterns of burning, and development and adoption of alternative management methods may be beneficial in terms of water quality and run-off.



Map 11: Classes of heather cover across the moorlands of the Bamford WTW catchment (no colour = no heather)



Map 12: Summary of heather burning areas as manually digitised from 2005 aerial imagery

2.7 Wildfire Risk

2.7.1 Introduction

The PDNP Rangers have kept a spatially accurate record of wildfires since 1976 (see Map 13). In total, between 1976 and 2011 (35 years) there have been 72 fires within the Bamford Catchment, 50 (69 %) of which have occurred on the moorlands. The major 'hotspot' area is the Kinder Plateau and its slopes, as shown on Map 13.

Using these data (1976 – 2004) the University of Manchester have developed a wildfire risk map (Map 14; Albertson *et al*. 2009). As this risk map is based on reported historical wildfires this map represents a retrospective, spatially distributed assessment of wildfire risk (of reported fires) across the moorlands of the Peak District.

2.7.2 How the model was built

There were five stages to building the multi-criteria evaluation (MCE) model:

- Incorporating expert opinion;
- Selecting layers;
- Scoring factors;
- Weighting the factors; and
- Mapping wildfire risk.

These are discussed below.

Incorporating expert opinion
There was an initial consultation with members of the PDNP Fire Operations Group (FOG) in March 2006. This consultation helped to identify a set of factors to use as the basis for subsequent analysis and to determine the nature and form of stakeholder involvement in subsequent stages of the project. Stakeholder involvement was undertaken in two stages, firstly through an online questionnaire open to a wide number of stakeholders and other experts, followed by a dedicated one day workshop where the issues were explored in more detail.

Selecting layers
Initial consultation with stakeholders identified a set of potential factors affecting wildfire distribution. Each factor considered for the MCE model was represented as individual map layers. There were two groups of factors: vulnerability to ignition hazard (physical factors) and accessibility (human factors). Not all of the suggested factors were eventually used in the final model due to: inconclusive findings regarding the influence of each factor on wildfire distribution; perceived low importance in subsequent weighting exercises; and/or time constraints. In generating a set of models, emphasis has been given to the most important layers affecting wildfire distribution, generated from stakeholder input and/or empirical analysis.

Scoring factors
Two types of scoring mechanisms were used, based on the way in which factors were represented as map layers.

(i) *Area-weighting principle*. This was used for factors where map layers were area based, for example habitat

(ii) *Distance decay.* This was used for factors where map layers were based on distances from point or line features, for example, paths

The first part of the process involved generating a distance surface containing distance values from particular features of interest to each 50 m cell in the data layer. Next, distance values were extracted for each cell containing a training fire. Finally, distance values were plotted as frequency distributions with different sized distance classes to assess the most appropriate distance bands and scores in each case. The process of deciding distance bands and scores also referred back to stakeholder input. In some cases, no relationship between distance and wildfire frequency could be established, necessitating the omission of some of the layers.

Weighting

Weighting was required in order to combine individual map layers into a single model to estimate the spatial risk of wildfire. The primary source of information concerning model weights was taken from stakeholder input. Weights were used to generate a formula to apply within the ArcGIS Spatial Analyst Raster Calculator to combine the scores associated with individual cells in each layer and create a final risk score as an output. Open water areas were set to zero in the final risk maps.

Mapping

There are numerous different methods for presenting the results of the data in map form and each method will influence the apparent distribution of high and low risk zones. There are also practical considerations, such as the number of categories which should be used when mapped output is to be used in operational contexts. Opinions were gathered using the online survey with further discussion at the June workshop. The use of three categories for mapped results received broad approval.

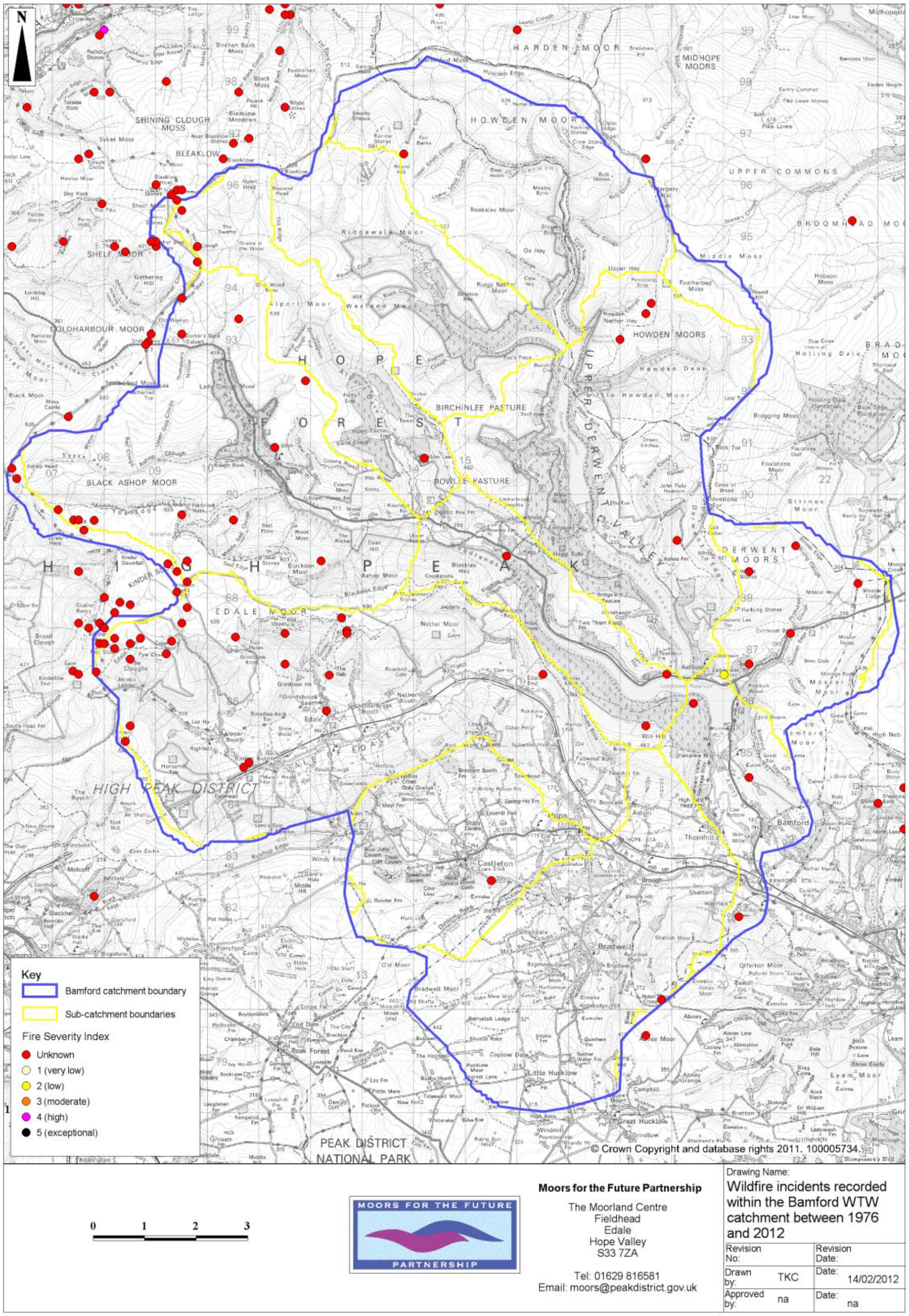
2.7.3 Results

Map 13 shows that the spatial distribution of wildfires is not random. Wildfires were mostly found on statutory Section 3 moorland. This is not surprising given that the fire database was compiled by PDNP rangers. Spatial bias may exist because wildfires close to access routes are seen more easily and are more likely to be reported; however, it probably also reflects the true distribution according to participants at the Climate Change and the Visitor Economy risk workshop (CCVE, 2005). The study was only concerned with section 3 moorland and within this, wildfires are more common in the west of the Park, especially in the Dark Peak on blanket peat, and where the long-distance footpath, the Pennine Way, is located. Few wildfires are found on managed heather moor in the east; this is likely to be because prescribed burning successfully manages fuel load. In the Dark Peak, it appears to be the combination of peat, especially exposed peat, and major footpaths which favour high fire risk.

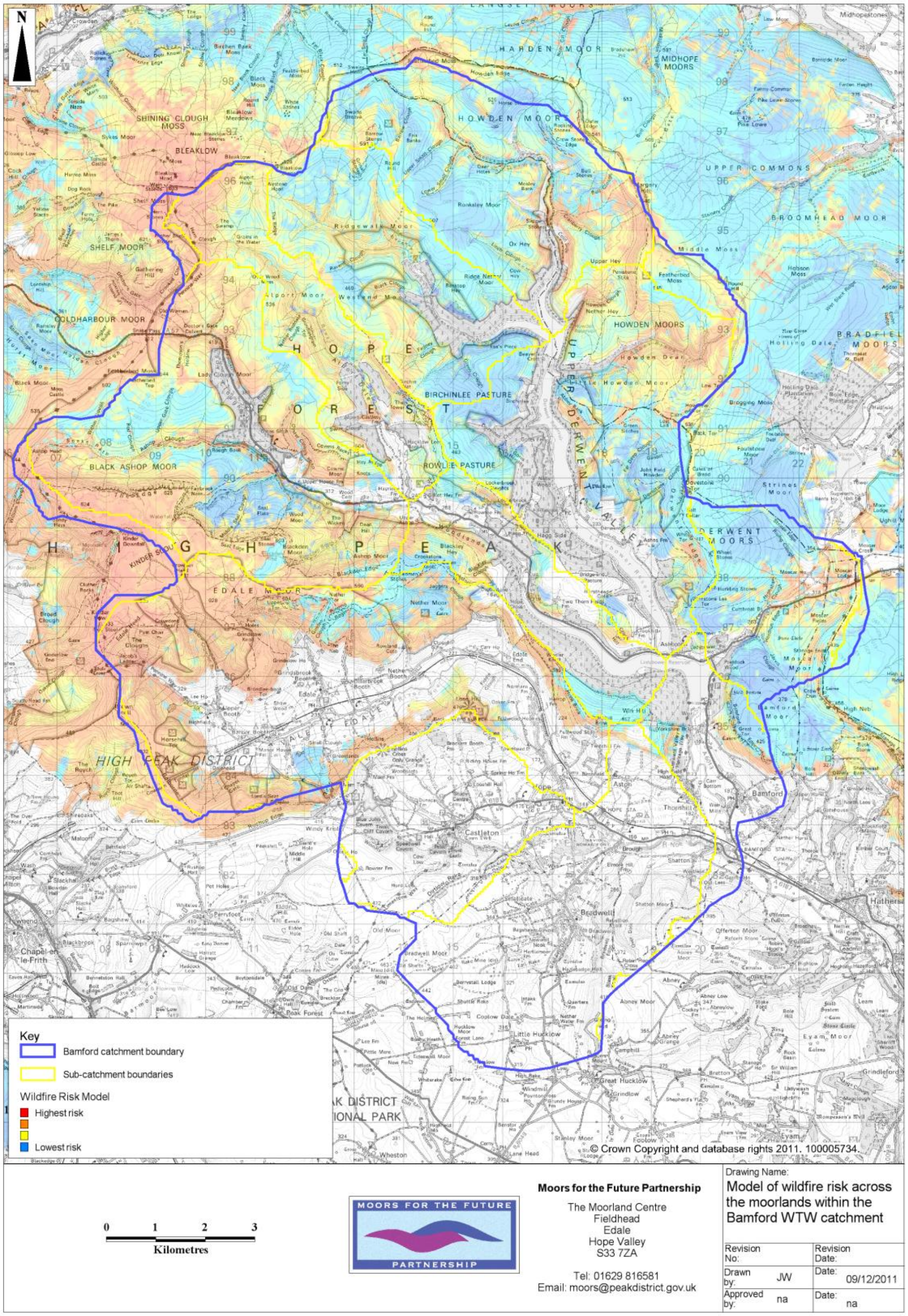
Wildfire - Implications for DOC and run-off

The environmental Impacts of wildfires depend on the efficiency and effectiveness of the fire fighting response, environmental conditions (vegetation types, weather - wind) and location / logistics. Major wildfires have been shown to trigger erosion. Wildfires commonly burn deeper and hotter than well managed burns so that plant roots are killed leading to break up of the surface, physical erosion and even damage to the peat itself (Worrall *et al.* 2011). There are many documented examples of extreme erosion associated with UK wildfire events. Rapid erosion means high POC export from these systems. Wildfires destroy vegetation creating large areas of bare peat and deep burning fires destroy roots. During the dry summer of 1976 fire burnt over 120 ha of moorland on Burbage Moor and subsequent heavy rainfall led to removal of over a metre depth of surface peat. This constitutes a catastrophic input of POC to the system and the subsequent chronic erosion of fire sites leads to long term increase in POC flux. Under conditions of increasing drought frequency the aggregation of fire scars across peatland surfaces and the associated POC losses represent a significant threat to long term peatland stability (Worrall *et al.* 2011). See section 4 (bare peat) for potential long-term impacts of major fire events and / or repeated events on a site are manifested. Clay *et al.* (2009) in a study of the impacts of a wildfire on Grindsbrook Knoll, Edale (within the Bamford Catchment) found its impact to be similar to that of a managed burn with little impact on DOC and little apparent long-term impact; however, this event did have the potential to become a 'major' event in the absence of a successful fire fighting response.

Both burning and grazing reduce fuel loadings on moorlands and therefore play a significant role in reducing the potential impact of wildfires. In the absence of these vegetation management methods suitable alternatives are required, particularly within high wildfire risk areas to mitigate the occurrence of catastrophic fire events.



Map 13: Wildfire incidents recorded within the Bamford WTW Catchment by Peak District National Park Rangers between 1976 and 2012. Data on fire severity are only available for wildfire incidents between 2009 and 2012



Map 14: Model of wildfire risk across the moorlands of the Bamford WTW Catchment

2.8 Areas of restoration work

This dataset was compiled from a GIS layer held by the conservation works team at Moors for the Future and from spatial data collected from the National Trust. Map 15 shows that approximately 1,900 ha of restoration are live or planned within with Bamford catchment. This represents ~16 % of the moorland. This work is being carried out on both National Trust and private land holdings. The works are primarily bare peat stabilisation works (revegetation and gully blocking); see Table 6.

Table 6: Summary of restoration works within the Bamford WTW Catchment

Site name (see Map 15)	Date	Project	Restoration works	Organisation
Stainery Clough	2008-2010	Conservation Plan	Gully blocking	National Trust
Bleaklow 1	2003-2012		Bare peat restoration (brash, lime, seed & fertiliser)	National Trust
Bleaklow 2	2003-2012		Bare peat restoration (brash, LSF)	National Trust
Bleaklow 3	2003-2012		Bare peat restoration (brash, LSF)	National Trust
Bleaklow 4	2003-2012		Bare peat restoration (brash, LSF)	National Trust
Swains Greave & Grinah	2008-2010	Conservation Plan	Gully blocking	National Trust
Hern Clough	2008-2010	Conservation Plan	Gully blocking	National Trust
North Grain	2005		Gully blocking	National Trust
Nether North Grain	2008-2009		Gully blocking	National Trust
Mirey & Ravens Clough	2008-2010		Gully blocking	National Trust
Seal Edges	2011		Gully blocking	National Trust
Red Clough	2008		Gully blocking	National Trust
Within Clough	2007		Gully blocking	National Trust
Upper Gate Clough	2009		Gully blocking	National Trust
Madwomans Stones	2009-2012		Stone gully blocking, reprofiling & planting	National Trust
The Edge	2010-2012	Making Space for Water	Gully blocking, plug planting, Sphagnum seeding & monitoring	MFF
Grindsbrook	2010-2012	NE Conservation Plan	Bracken control, pathworks, bare peat restoration, fencing	MFF
Crowden Moor	2010-2012	NE Conservation Plan	Bracken control, pathworks, bare peat restoration, fencing	MFF

The Roych	2010-2012	NE Conservation Plan	No restoration works took place	MFF
Mossy Lea	2010-2012	NE Conservation Plan	Brash	MFF
Whinstone Lee Tor	2010-2012	NE Conservation Plan	No restoration works took place	MFF
Woodhead	2010-2012	NE Conservation Plan (MoorLIFE)	Vegetation establishment & maintenance (brash, LSF), gully blocking, plug planting, Sphagnum seeding & monitoring	MFF
Howden Moors	2012-2015	Nature Improvement Area	Gully blocking, peat stabilisation and sphagnum inoculation	Dark Peak NIA
Derwent & Howden Moors	2012-2015	Nature Improvement Area	Gully blocking, peat stabilisation and sphagnum inoculation	Dark Peak NIA

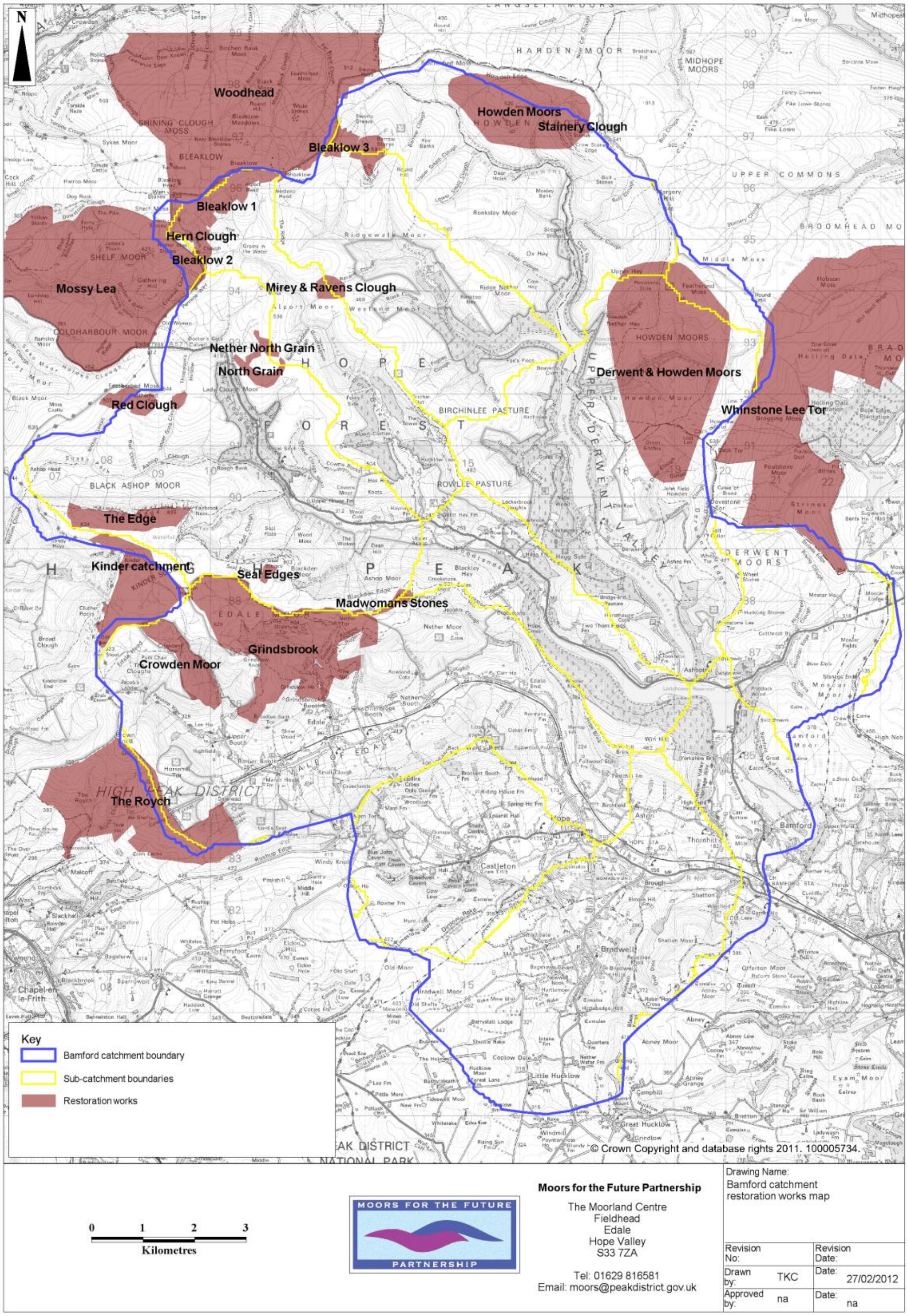
Bare peat restoration - Implications for DOC and run-off

The recovery of vegetation limits soil erosion and so POC flux declines but evidence for a change in DOC is equivocal (Worrall *et al*. 2011). On Bleaklow bare peat sites have significant carbon losses (DOC, POC; dissolved CO_2, primary productivity, net ecosystem respiration and CH_4) as high as 522 tonnes C km^{-2} y^{-1}; and that revegetation resulted in an improvement in carbon budgets, with one site displaying a carbon budget that was more negative than that of vegetated reference sites. These carbon benefits are largely a result of avoided losses; i.e. the effect of changing a large source (loss) to a small source (loss) rather than 'new' sequestration.

POC losses in the form of fluvial suspended sediment and turbidity represent the largest carbon loss pathway from these degraded upland peat catchments. Three years after large-scale restoration of highly bare peat blanket bog in North Longdendale, Peak District, Anderson and Ross (2011) found turbidity to have declined slightly (but statistically significantly) even with only a small proportion (5%) of the catchment restored. Colour levels in streamflow remain high and increased slightly over the monitored period. Water table levels in the peat mass responded positively to the re-vegetation of the bare peat surface but a deeper, more variable aeration zone in the peat body exists relative to control 'intact' areas. This will always produce more DOC and therefore more colour. It remains to be seen if the increasing trend in water colour production slows, or is stopped (Anderson and Ross 2011).

As noted in Section 2.4 (Landscape Audit) vegetation greatly affects surface run-off with *Sphagnum* displaying the greatest 'surface roughness' and consequently water velocity times through this vegetation are the slowest. While revegetation slows the passage of overland flow, Grayson *et al.* (2010) found little impact on the total discharge in streams. This may be in part because most of the discharge occurs in only a small fraction of the time on peatland catchments, and in part because bare peat has two separate effects on evapotranspiration: it is reduced because there is no vegetation, but increased because the dark surface has a high albedo and will warm up more than a vegetated surface. The impact on river flows may be greater than evidenced because the hourly flow records available are not sufficiently detailed to capture all the detail of quickflow responses in blanket peatland catchments.

Much of the large contiguous areas of bare peat are receiving restoration attention of some kind; however, on these sites there is a trajectory of restoration that needs to be maintained through follow-on or top up treatments. There are also areas of fragmented small-scale bare peat patches that have yet to be addressed but that would improve water quality. Additionally, there are vegetated areas that need to be restored to more appropriate blanket bog / upland heathland communities which may have temporal impacts on water quality - notably the conversion of purple moor grass (which is 'good' for water quality).



Map 15: Restoration areas within and immediately surrounding the Bamford WTW Catchment boundary

2.9 Grazing

Bonn *et al.* (2010) report that upland peatlands naturally have a low agricultural productivity due to soil properties, water logging, access, topography and climatic conditions. Upland peatlands are therefore generally classed as very poor quality agricultural land, i.e. land with very severe limitations that restrict use to permanent pasture or rough grazing (Agricultural Land Classification, MAFF 1988). In most English uplands, decades of subsidies led to steady intensification of farming with grants available for improvement of land and infrastructure, and subsidies or guaranteed payments for livestock. In 1987-1991, the first agri-environment schemes were launched with the Environmentally Sensitive Area (ESA) scheme, which rewards farmers for caring for the environmental, historical and cultural features on their land, while reducing stocking numbers. Today, stocking densities in the Peak District peatlands are much reduced. This may be attributed to the level of degradation of Peak District moorlands and therefore encouragement to take part in ESA schemes, socio-economic or cultural preferences by farmers, which may also be determined by alternative income sources, as opportunities for additional incomes for farming families through farm diversification (e.g. tourism) or jobs in surrounding conurbations may be more prevalent in the Peak District due to its geographical location.

For mapping levels of grazing we have used data from ESA agreements. These are linked to the individual landholdings and provide details on maximum grazing densities for agreement areas, but data do not accurately determine the exact location of grazing animals. In total, 11,215 ha (57 %) of land within the Bamford Catchment is under ESA agreements. ESA agreements within the Bamford WTW catchment include Tier 1B i-iii (4 %); 1C (12 %); 2A (37 %); 2B (4 %) and N/A (0.1 %), as summarised in Table 7. See Map 16 for their locations within the Bamford Catchment.

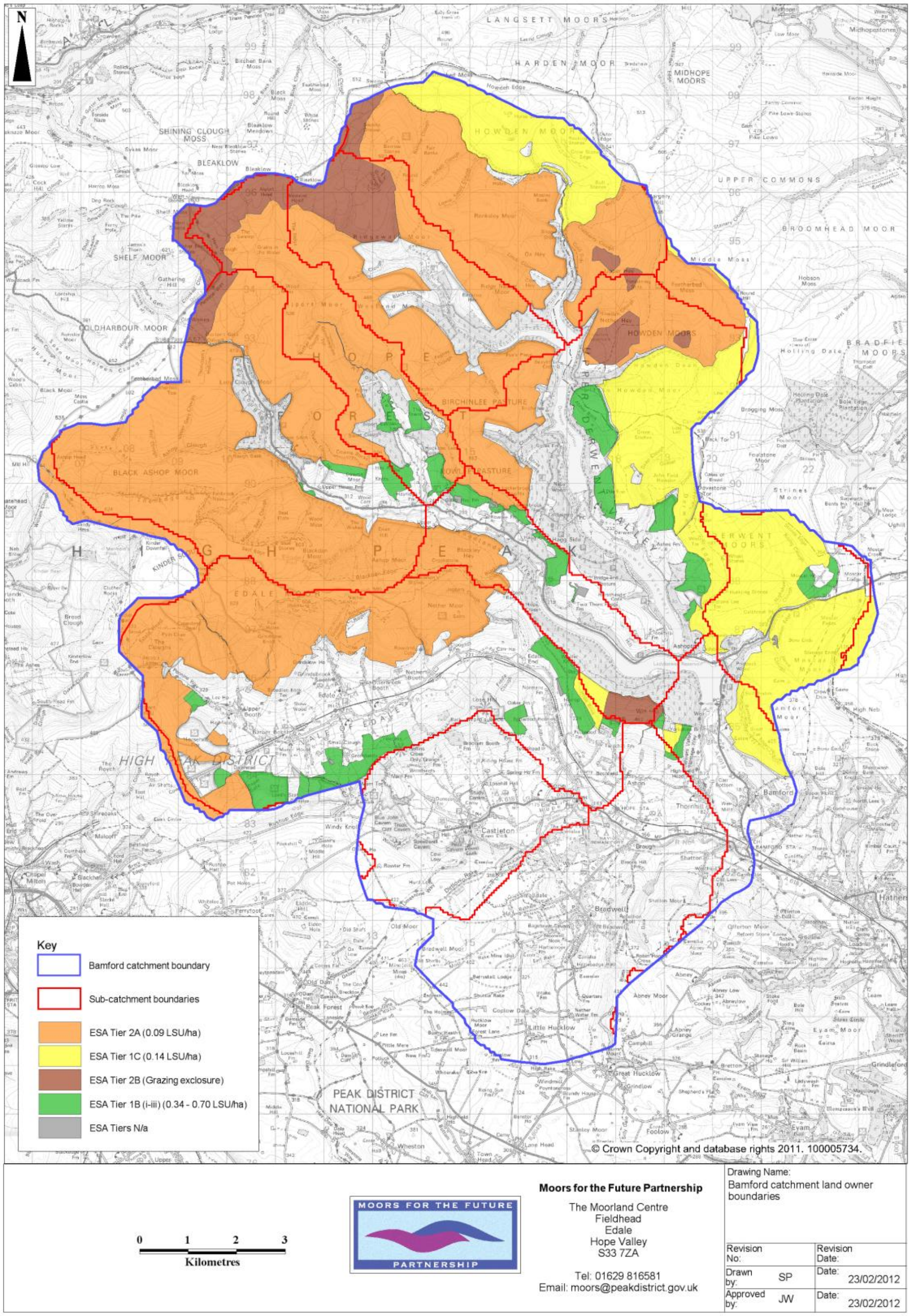
Table 7: ESA Agreement tiers, description and livestock units (LSU)

ESA Tier	Habitat	LSU/ ha
1B (i-iii)	Semi-improved permanent grassland; unimproved rough grassland; enclosed rough grazing	0.34-0.70
1C	Moorland	0.14
2A	Moorland (extensification)	0.09
2B	Moorland (exclosure)	0
N/A	Woodland; water; other ineligible land	N/A

Grazing - Implications for DOC and run-off

Sheep grazing is recognised as an important driver of vegetation change (Worrall *et al*. 2011). It directly affects vegetation composition and indirectly affects the activity of decomposer organisms and thus has the potential to alter ecosystem carbon fluxes. The key changes from grazing are defoliation, trampling and changes in the nutrient status of the soils. Changes in plant species have been reported as a result of grazing; the changes observed vary depending on the stocking densities of the sheep. Reductions in infiltration rates have been reported as a result of trampling and possibly stocking densities that are too high, which have also been cited as a cause for erosion in the uplands. Cessation of grazing and reduced grazing (in combination with restoring water tables) have led to changes in vegetation community, particularly increased *Sphagnum* cover within the SCaMP moorland restoration project (Anderson and Ross 2011). Overall there is a dearth of studies that have investigated the impact of grazing intensity on carbon dynamic and fluxes from peatlands (Worrall *et al*. 2011).

Restoration sites are fenced to exclude stock to enable vegetation to become established / recover. The long-term management of these sites needs to be identified through robust evidence, as on older sites where vegetation recovery is well advanced, because the level of standing biomass represents a potentially high fuel loading in the advent of a wildfire.



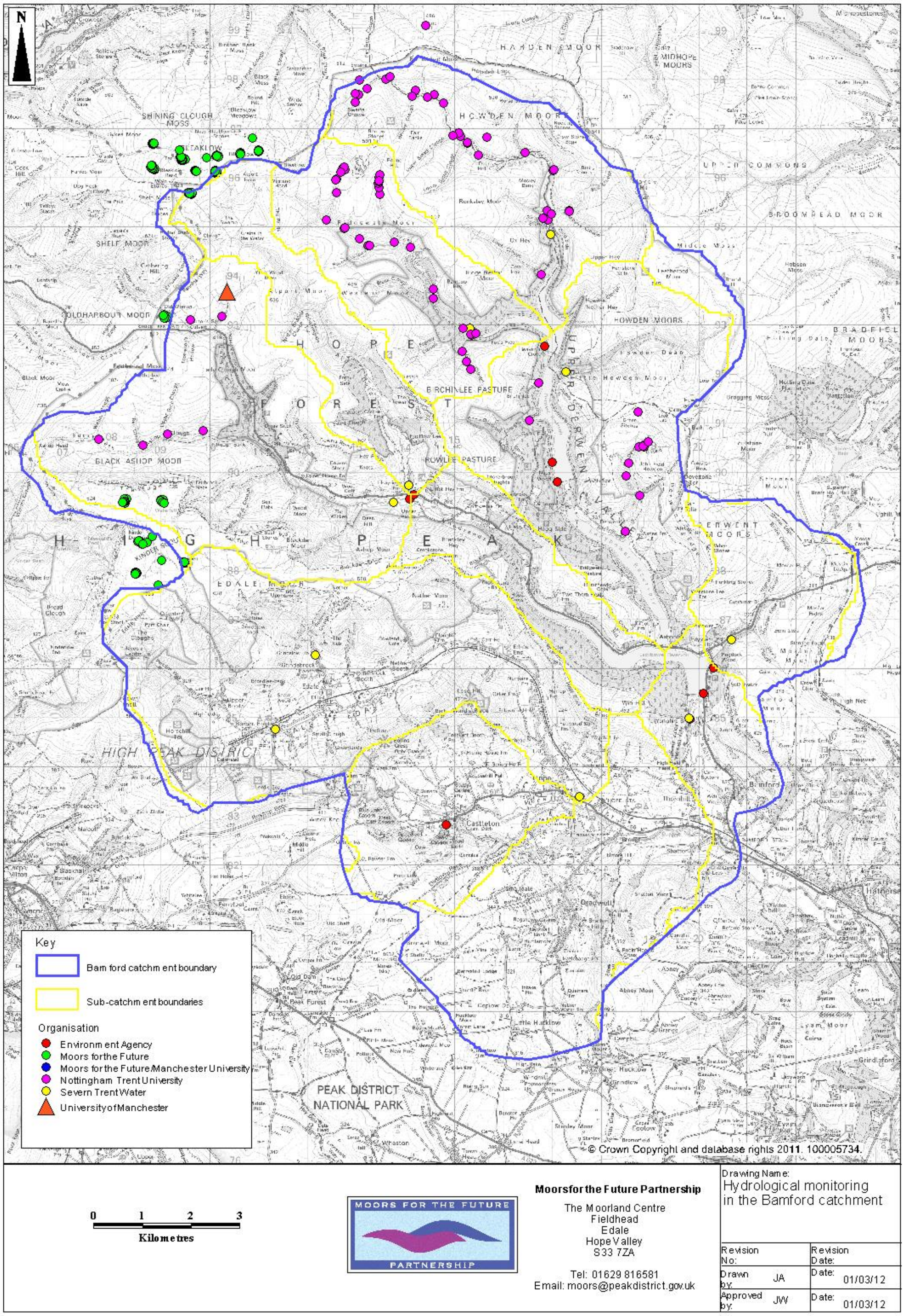
Map 16: ESA agreement tiers within the Bamford Catchment

2.10 Monitoring points for water level and water quality

This dataset has been created by combining spatial information from several different sources to show the locations of hydrological monitoring schemes in the Bamford catchment area (see Map 17). This includes water table, rainfall, run-off and water quality data collected by the monitoring team at Moors for the Future, in collaboration with Manchester University; projects on privately owned land and National Trust / United Utilities sites; Environment Agency water quality monitoring; Severn Trent water quality monitoring; and data from a study by Dr Jillian Labadz of Nottingham Trent University investigating the impact of moorland burning on the discolouration of surface waters. This information records the sites and types of monitoring as well as the temporal extents of the monitoring period. See Table 8 for a list of key live monitoring projects.

Table 8: Key live monitoring projects

Project	Date	Aims	Location	Collaborators	Funders
Making Space for Water	2010 - 2015	To assess the impact of moorland restoration on runoff generation from eroded peatlands	The Edge, Kinder Plateau, Ashop catchment	Moors for the Future, University of Manchester, University of Durham	DEFRA / EA
Greenhouse gas emissions associated with non gaseous losses of carbon – fate of particulate and dissolved carbon	2010 – 2015	See appendix 3	Upper North Grain and Ashop catchments	Centre for Ecology and Hydrology, University of Manchester, University of Durham, University of Bangor, University of Leeds	DEFRA
Ongoing monitoring / research in the Upper North Grain catchment	2001 onwards	To support teaching and PhD research projects - See appendix 4 for list of publication arising from this programme of research	Upper North Grain catchment	University of Manchester	



Map 17: Hydrological monitoring within and immediately surrounding the Bamford WTW catchment boundary. The large orange triangle represents a ‘cluster’ of projects.

3 POTENTIAL CUMULATIVE IMPACTS OF LAND COVER WITHIN THE BAMFORD WTW CATCHMENT

3.1 Introduction and methods

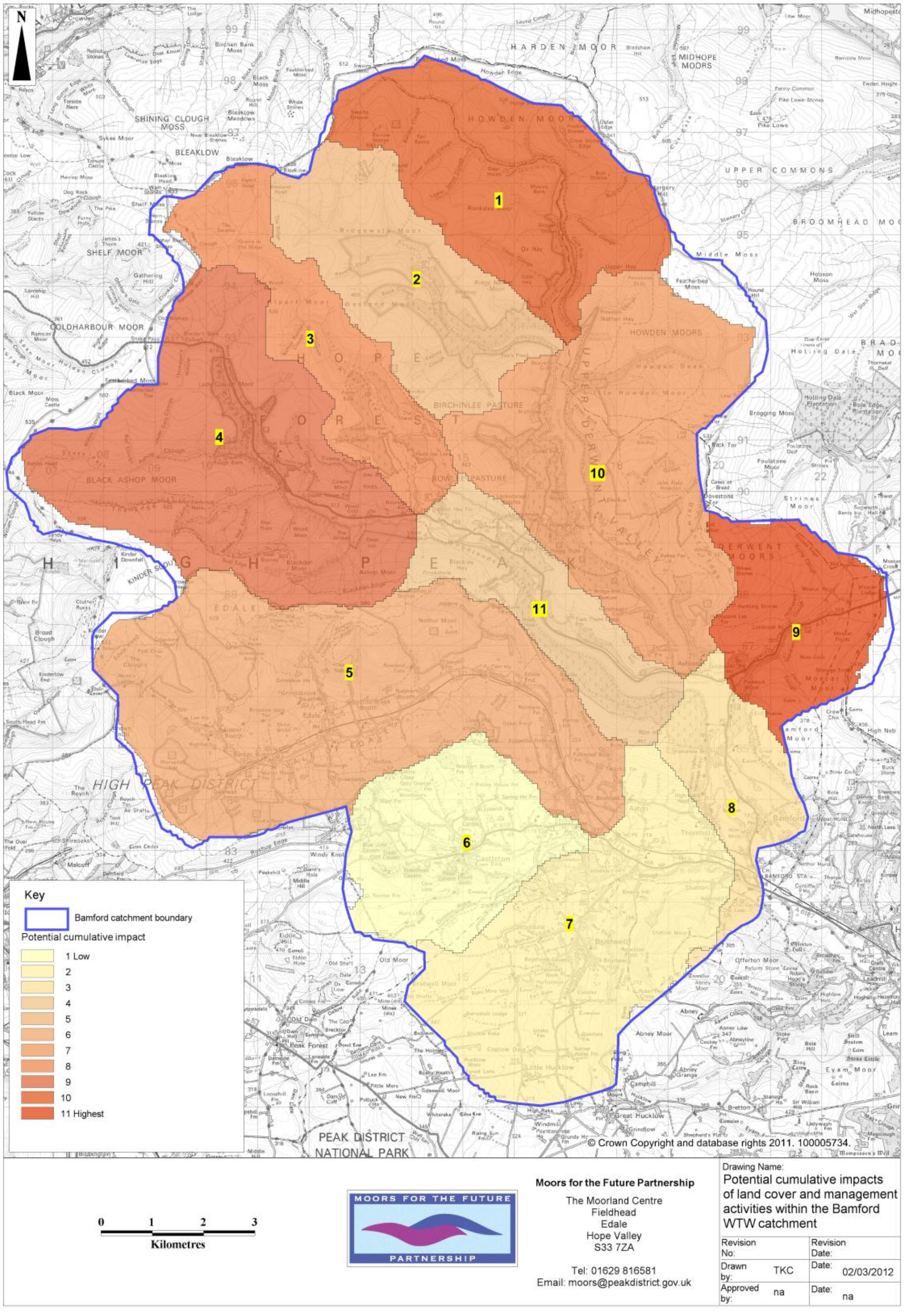
In this section we present a simple analysis of the potential cumulative impact of the land cover / management factors covered within this report to identify areas with greatest 'effect' across the catchment. The approach we take is to look at the relative potential 'impact' across the catchment. We have selected to use sub-catchments. The rationale for this is that the sub-catchment is an appropriate scale to comprehensively address landscape scale issues that impact water quality and regulation.

Summary statistics for different land covers / management were calculated for each sub-catchment (see Map 1 and Table 2 for names and locations). These are presented in Table 9 as proportions of the area of moorland within the Bamford WTW catchment. See Table 15 in appendix 5 for actual values.

This is a simple model; therefore equal weighting was given to bare peat, blanket / deep peat, managed burning, gullies and wildfire. Based on known impact on DOC, vegetation types were weighted with regards to their contribution to water quality, heather and non-heather dwarf shrubs were weighted 1; cotton grass and rushes (sedges) were weighted 0.5. Bracken and grasses were not included in the analysis as the effect of bracken on DOC is unknown and grasses are associated with low concentrations of DOC. Similarly, for grazing Tier 1B was weighted 1, Tier 1C assigned half weighting and Tier 2A assigned a quarter weighting. Tier 2B and N/A were not included as these are exclosure and ineligible land respectively. Map 18 shows the ranked cumulative impact of land cover and management activities for each sub-catchment. Shading on this map only represents the rank order of cumulative impacts relative to the other sub-catchments; further insight is gained from consulting the summary statistics in Tables 9 and 15 (appendix 5).

Spatial impacts of land cover and management

Within the scope of this project we were only able to undertake a 'quick and simple' method of spatially identifying potential impact from key land cover and management issues that affect water quality and run-off. From the data compiled and spatial analysis carried out we are able to suggest that the seven sub catchments with the highest cumulative potential impacts (sub-catchments #1, #2, #3, #4, #5, #9 and #10) can be broadly split into two groups and two geographic areas: the northwest of the Bamford Catchment (#3, #4, #5) and the northeast of the catchment (#1, #2, #9, #10). Based on contemporaneous land cover and management of the moorlands in northwest sub-catchments the current main issue is bare and degraded peat soils and habitats (much of which is either the focus of current or proposed restoration actions). The northeast sub-catchments also have bare peat areas but a far smaller spatial extent than in the northwest sub-catchments; however these northeast catchments are subject to management activities that across space (area) and time (frequency) may potentially affect water quality and run-off.



Map 18: Relative potential impacts of land cover and management within the 11 sub-catchments of the Bamford WTW Catchment. The redder the catchment the greater the relative impact of factors potentially affecting water quality in the catchment – see Table 10.

Table 9: Relative area (%) of various land cover and management activities across the moorlands within the Bamford WTW and sub-catchment boundaries which may increase water colour and run-off

					Vegetation										Grazing (ESA Tier)				
Catchment ID	Catchment	Moorland	Bare peat	Blanket peat / deep peat	Peat / Shallow peat	Heather)	Non-heather dwarf shrubs	Bracken	Grasses	Rushes	Cotton grass	Grips & gullies*	Managed burn	Wildfire	Tier 2A	Tier 1C	Tier 1B	Tier 2B	Tier N/A
Bamford catchment	n/a	61.0	2.4	33.2	29.7	17.2	8.9	10.0	9.3	6.2	7.0	3.0	13.7	0.2	36.6	11.6	3.5	4.0	0.1
1	10.1	95.6	1.3	65.5	33.1	48.4	9.0	10.4	8.7	7.4	7.0	4.8	58.3	0.0	55.4	32.5	5.0	0.0	0.0
2	7.3	85.7	0.9	62.7	36.2	29.3	12.3	11.4	10.7	11.8	8.8	4.9	23.9	0.0	54.7	0.0	0.0	19.1	0.0
3	5.6	83.5	6.5	55.0	37.8	2.4	15.3	9.2	12.8	17.5	17.1	5.2	0.0	0.2	58.9	0.0	7.0	14.8	0.0
4	13.9	89.4	5.7	63.5	32.5	21.7	11.2	8.3	10.9	11.4	15.8	6.9	22.4	0.5	83.9	0.0	1.4	2.8	0.0
5	17.5	57.8	2.0	17.1	39.3	6.1	9.1	11.9	15.3	3.8	6.8	1.8	6.6	0.6	38.7	0.6	8.6	0.1	0.1
6	6.4	10.9	0.0	0.0	11.4	0.6	0.5	3.6	1.9	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	12.2	6.2	0.0	0.0	0.0	0.6	2.8	4.4	2.8	0.8	0.4	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0
8	3.7	24.7	0.1	0.0	9.0	8.7	2.0	20.1	1.2	0.4	0.3	0.0	0.0	0.1	0.0	19.2	2.0	0.6	0.0
9	5.3	92.6	1.1	50.5	41.7	35.6	13.0	17.1	6.4	4.4	4.3	3.3	34.9	0.5	0.0	83.1	2.9	0.0	0.2
10	13.2	63.4	0.7	28.8	41.2	22.9	12.4	11.0	8.9	6.4	4.6	1.0	8.6	0.2	22.0	28.8	6.8	3.4	0.0
11	4.9	38.1	0.6	1.5	32.1	8.5	6.9	8.6	11.5	3.4	2.7	0.0	11.9	0.1	19.8	2.2	6.7	5.3	0.8

* the relative proportion of gullies is presented as km of gullies per ha of land.

Table 10: Potential relative impact of various land cover and management activities across the moorlands within the Bamford WTW catchment (rank 1 = lowest impact; 11 = highest potential impact)

Sub-catchment ID	Bare peat	Blanket / deep peat	Managed burning	Tier 2A (0.25)	Tier 1C (0.5)	Tier 1B	Gullies	Wildfire	Heather	Non-heather dwarf shrubs	Sedges (0.5)	Total	Rank
1	8	11	11	2.8	5.0	7	8	2.5	11	5	2.5	73.8	10
2	6	9	9	2.3	1.3	1.5	9	2.5	9	8	4	61.6	5
3	11	8	2.5	0.6	1.3	10	10	7.5	3	11	5.5	70.4	8
4	10	10	8	2.0	1.3	4	11	9.5	7	7	3.5	73.3	9
5	9	5	5	1.3	3.0	11	6	11	4	6	3	64.3	6
6	1.5	2	2.5	0.6	1.3	1.5	2.5	2.5	1.5	1	0.5	17.4	1
7	1.5	2	2.5	0.6	2.5	3	2.5	2.5	1.5	3	1.5	23.1	2
8	3	2	2.5	0.6	4.0	5	2.5	5.5	6	2	1	34.1	3
9	7	7	10	2.5	5.5	6	7	9.5	10	10	5	79.5	11
10	5	6	6	1.5	4.5	9	5	7.5	8	9	4.5	66.0	7
11	4	4	7	1.8	3.5	8	2.5	5.5	5	4	2	47.3	4
∑	66	66	66	16.5	33	66	66	66	66	66	33	610.7	66

4 RECOMMENDATIONS

In this section we provide recommendations about actions STW could make to address water quality.

Many of the recommendations address issues across the different land cover and management impacts.

Table 11: Data / Maps presented within this report and recommendations to Severn Trent Water

Land cover/ management activity	Key recommendations
Landownership	Engagement with the NT to discuss water quality 'issues' and land management across their land holdings. Engage with private landowners to address potential issues • Support 'knowledge exchange' event(s) across the catchment to communicate current scientific knowledge on water quality 'issues' and promote mutual understanding of aims and objectives of water company and private land owner / manager business interests. This would act as a platform on which future engagement could be developed.
Peat cover	As a result of this project (peat depth survey) we have much greater understanding of the distribution and stocks of peat across the catchment. To improve on this baseline survey STW could support: • A more focused survey to evidence how representative measurements taken at 400 m intervals are of peat depths across the catchment; • A smaller scale survey of the 'bulk density' of the deep peat areas to be able to reliably interpret the peat depths in terms of actual carbon stocks; • Support longer term monitoring of peat depths to better understand and evidence spatially and temporal changes in peat depth.
Peat depth	See 'peat cover' and 'monitoring' sections of this table.
Vegetation cover	Support research to evidence the impact of the reintroduction of Sphagnum on moorland hydrology and water quality across different vegetation types (at present efforts and science focuses on bare peat restoration sites) See 'restoration' section of this table.

Land cover/ management activity	Key recommendations
Grips and gullies	We have very little information on the distribution of peat pipes within the catchment; there is little evidence of the impact of gully blocking on peat pipes – formation, flow paths and water quality. See ‘restoration’ section of this table.
Managed burning	Support research to determine whether managed burning, both in the short and long term, is a direct driver of enhanced colour and DOC in upland water bodies as evidence collected to date is equivocal. Support research into alternative management methods (and their carbon impact) as a potential alternative to burning.
Wildfire	Support / liaise with the Peak District Fire Operations Group in the work they do to mitigate wildfire risk and improve effectiveness and efficiency of response to, and suppression of, wildfires
Restoration	Support restoration efforts to stabilise bare peat and improve hydrological integrity of these areas. Support restoration efforts to establish / increase the distribution and abundance of Sphagnum across the Bamford WTW Catchment. Engage with the restoration community operating with the Bamford Catchment (Moors for the Future Partnership, the National Trust, Natural England, the newly designated “Dark Peak Nature Improvement Area partnership – see Defra: http://www.defra.gov.uk/environment/natural/whitepaper/nia/ Natural England: http://www.naturalengland.org.uk/ourwork/conservation/biodiversity/funding/nia/default.aspx
Grazing	Support research and monitoring into the impact of grazing on restoration site recovery and wildfire risk mitigation. This is a significant knowledge gap.
Monitoring	Support ongoing monitoring programmes / sites to continue to evidence the impact of management / land cover changes and environmental change within the catchment in terms of water quality and run-off.

REFERENCES

Albertson, K., Aylen, J., Cavan, G. & McMorrow, J. (2009) Forecasting the Outbreak of Moorland Wild Fires in the English Peak District, Journal of Environmental Management, 90, 2642-2651.

Anderson, P. and S. Ross (2011) United Utilities sustainable catchment management programme. Volume 1: executive summary. PAA Ltd, Buxton.

Armstrong, A., Holden, J., Luxton, K. & Quinton, J. (in review) Peatland vegetation type – a key driver of DOC? Science of the Total Environment.

Allott, T.E.H., Evans, M.G., Lindsay, J.B., Agnew, C.T., Freer, J.E., Jones, A., & Parnell, M. (2009) Water tables in Peak District blanket peatlands. Moors for the Future Report No. 17.' funded by the Environment Agency and National Trust. Hydrological benefits of moorland restoration.

Bonn, A., Holden, J., Parnell, M., Worrall, F., Chapman, P.J., Evans. C.D., Termansen, M., Beharry-Borg, N., Acreman, M.C., Rowe, E., Emmett, B., Tsuchiya, A. (2010) Ecosystem services of peat – Phase 1. Report to Defra (project code: SP0572). http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=15990

Carroll, J., Anderson, P., Caporn, S., Eades, P., O'Reilly, C., and Bonn, A. (2009) Sphagnum in the Peak District Current Status and Potential for Restoration Moors for the Future Report No 16, Edale.

CCVE (2005) Climate Change and the Visitor Economy – Risk workshop: Moorland Wildfires in the Peak District. University of Manchester.

Chapman, D.S., Bonn, A., Kunin, W.E. and Cornell, S.J. (2010) Random Forest characterization of upland vegetation and management burning from aerial imagery. *Journal of Biogeography* 37: 37–46.

Clay, G. D., Worrall, F., Clark, E., and Fraser, E. D. G. (2009a) Hydrological responses to managed burning and grazing in an upland blanket bog. Journal of Hydrology, 376, 486-495.

Clay, G. D., Worrall, F., and Fraser, E. D. G. (2009b) Effects of managed burning upon dissolved organic carbon (DOC) in soil water and runoff water following a managed burn of a UK blanket bog. Journal of Hydrology, 367, 41-51.

Clay, G.D., Evans, M.G., Bonn, A., Hewson, W., Parnell, M., Wilkinson, R. and Worrall, F. (2009) Grindsbrook Wildfire 2008 – a case study. Moors for the Future, Edale UK

Clay, G. D., Worrall, F., and Aebischer, N. J. (2012a) 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.

Clay, G. D., Dixon, S., Evans, M. G., Rowson, J. G., and Worrall, F. (2012b) Carbon dioxide fluxes and DOC concentrations of eroding blanket peat gullies. *Earth Surface Processes and Landforms*, 37, 562-571.

Daniels, S.M., Agnew, C.T., Allott, T.E.H., and Evans, M.G. 2008 Water table variability and runoff generation in an eroded peatland, South Pennines, UK, Journal of Hydrology 361, 214-226.

DWI (2000). *The Water Supply (Water Quality) Regulations* (on-line). http://dwi.defra.gov.uk/stakeholders/legislation/wqregs2007cons.pdf. Accessed 16 February 2012.

Evans, M., T Allott, J Holden, C Flitcroft & A Bonn (2005) Understanding Gully Blocking in Deep Peat. Moors for the Future Report No 4.

Grayson, R., Holden, J., & Rose, R. (2010) Long-term change in storm hydrographs in response to peatland vegetation change. Journal of Hydrology 389, 336-343.

Hinde, S., Rosenburgh, A., Wright, N., Buckler, M., and Caporn, S. (2010) *Sphagnum re-introduction project: A report on research into the re-introduction of Sphagnum mosses to degraded moorland.* Moors for the Future Research Report 18, Edale.

Holden, J. (2005a), Controls of soil pipe frequency in upland blanket peat, Journal Of Geophysical Research 110, F01002.
http://www.geog.leeds.ac.uk/fileadmin/downloads/school/people/academic/j.holden/JGR2005piping.pdf

Holden, J. (2005b) Piping and woody plants in peatlands: Cause or effect? Water Resource Research 41, W06009.
http://www.geog.leeds.ac.uk/fileadmin/downloads/school/people/academic/j.holden/catena2002.pdf

Holden, J. & Burt, T.P. (2002) Infiltration, runoff and sediment production in blanket peat catchments: implications of field rainfall simulation experiments. Hydrological Processes, 16, 2537-2557.

Holden, J., R.P. Smart, K.J. Dinsmore, A.J. Baird, M.F. Billett, P.J. Chapman (2012) Morphological change of natural pipe outlets in blanket peat. Earth Surface Processes and Landforms, 37(1): 109–118. http://onlinelibrary.wiley.com/doi/10.1002/esp.2239/pdf

Holden, J., Chapman, P. J., Palmer, S. M., Kay, P. and Grayson, R. (2012) The impacts of prescribed moorland burning on water colour and dissolved organic carbon: A critical synthesis. *Journal of Environmental Management* 101: 93-103.

Holden, J., M. J. Kirkby, S. N. Lane, D. G. Milledge, C. J. Brookes, V. Holden, and A. T. McDonald (2008) Overland flow velocity and roughness properties in peatlands. Water Resources Research, 44, W06415.

Holden, J., P. J. Chapman, M. G. Evans, K. Hubacek, P. Kay, and J. Warburton (2007) Vulnerability of organic soils in England and Wales. Final Tech. Rep. Defra Projoct SP0532, Defra, London.

Jones, J.A.A. (2004) Implications of natural soil piping for basin management in upland Britain. Land Degradation & Development 15, 325-349.

The National Trust (2008) From source to sea: working with water. Swindon, UK
http://www.nationaltrust.org.uk/servlet/file/store5/item336806/version1/w-sourcetosea.pdf

O'Brien, H., Labadz, J. and Butcher, D. (2006) An Investigation of the Impact of Prescribed Moorland Burning in the Derwent Catchment upon Discoloration of Surface Waters. Nottingham Trent University.

O'Brien, H. E., Labadz, J. C., Butcher, D. P., Billett, M. and Midgley, N. G. (2008) Impact of catchment management upon dissolved organic carbon and stream flows in the Peak District, Derbyshire, UK. BHS 10th National Hydrology Symposium, Exeter.

Pawson, R. R. Lord, D. R. Evans, M. G. and Allott, T. E. H. (2008) Fluvial organic carbon flux from an eroding peatland catchment, southern Pennines, UK. Hydrology and Earth System Sciences, 12, 625–634.

Rothwell, J.J., Evans, M.G., Daniels, S.A., & Allott, T.E.H. (2008) Peat soils as a source of lead contamination to upland fluvial systems. Environmental Pollution, 153, 582-589.

Stace, C.A. (1991) New flora of the British Isles. Cambridge University Press, Cambridge.

Watts, C. D., Naden, P. S., Machell, J. and Banks, J. (2001) Long term variation in water colour from Yorkshire catchments. *The Science of the Total Environment*, 278, 51-72.

Webster, K. L., and McLaughlin, J. W. (2010) Importance of the water table in controlling dissolved carbon along a fen nutrient gradient. *Soil Sci. Soc Am. J.* 74, 2254-2266.

WHO (2006) *Guidelines for Drinking-water Quality* (on-line). http://www.who.int/water_sanitation_health/dwq/gdwq0506.pdf. Accessed 17 February 2012.

Worrall, F., Clay, G. D., Marrs, R., and Reed, M. S. (2010) Impacts of Burning Management on Peatlands. IUCN Technical Review 5, IUCN UK Peatland Programme, Edinburgh.

Worrall, F., Chapman, P., Holden, J., Evans, C., Artz, R., Smith, P. and Grayson, R. (2011a) A review of current evidence on the carbon fluxes and greenhouse gas emissions from UK peatlands. JNCC Report, No. 442.
http://jncc.defra.gov.uk/page-5891#download

Worrall, F., Rowson, J. G., Evans, M. G., Pawson, R., Daniels, S. and Bonn, A. (2011b) Carbon fluxes from eroding peatlands – the carbon benefit of revegetation following wildfire. *Earth Surf. Process. Landforms* 36(11): 1096-9837.

Yallop, A. R. and Clutterbrook, B. (2009) Land management as a factor controlling dissolved organic carbon release from upland peat soils 1: Spatial variation in DOC productivity. *Science of the Total Environment*, 407, 3803-3813.

APPENDIX 1

Current status of three relevant ecosystem services delivered across the District National Park peatlands and potential changes under different land management scenarios. These summaries are taken from the Defra funded “Ecosystem services of peat” report led by Moors for the Future. We focus on carbon sequestration (budgets), water quality and flood risk mitigation.

A2.1 Carbon Budgets

Overall the peatlands of the Peak District National Park represent a carbon sink. The impact of different types of land management was modelled from the following scenarios:

Business as usual – the land-use is as described from the aerial photographs with no intervention;
Restoration (no drains) – the scenario assumes no drains or gullies of any type in the study regions and that all drains or gullies have been in-filled with no transitionary sink;
Restoration (revegetation) – the percentage bare soil is decreased to 2%;
Conservation led rewilding – all present management is removed, this includes grazing and managed burning. However, active restoration through drain blocking and revegetation is pursued, and – as in all other scenarios – recreation management is not necessarily excluded.
Economy –the imposition of managed grouse shooting and grazing wherever possible including managed burning (except areas of forestry).
Optimal management for carbon – the removal of a management strategy such as grazing, or all of the possible interventions, may not be the best possible ‘carbon’ action for each and every grid square. Therefore, the results of all possible scenarios were examined and the scenario with the maximum carbon sink was noted. This could be no intervention, all possible interventions or only one intervention. For each 1 x 1 km2 grid square the scenario providing the maximum sink was recorded. Only when an intervention provided an improvement that was greater than the acceptable error value for the present CO2 sink with no intervention was that particular intervention selected.

All scenarios except the economy scenario increased the size of the carbon sink. An economy scenario would see Peak District peatlands change from being an overall carbon store to a source of (active) carbon. The results of the six land use scenarios are given in table 12.

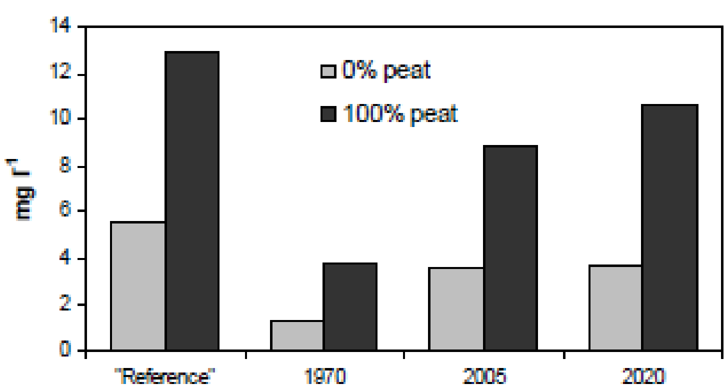
Table 12: The total equivalent CO_2 budget and average equivalent CO_2 export (ktonnes eq.CO_2/km^2/yr) across the peatlands of the Peak District National Park for six land use scenarios

Land use scenario	**Total budget** (ktonnes eq.CO_2/yr)	**Average export** (ktonnes eq.CO_2/km^2/yr)
Business as usual	-62	-86
Restoration - (no drains)	-63	-87
Restoration - (re-vegetate)	-71	-98
Conservation led rewilding	-117	-161
Economy	+32	+44
Optimal carbon management	-160	-221

A2.2 Water quality

Peat occurrence and condition affect the quality of raw water supply via dissolved organic carbon (DOC) generation, and on reservoir storage capacity via particulate organic carbon (POC) generation. These impacts may be either mitigated or exacerbated by peatland condition. Peats naturally produce large amounts of dissolved organic carbon (DOC), due to incomplete organic matter decomposition under waterlogged conditions. Figure 3 illustrates the differences in DOC in runoffs from peat and non-peat catchments in response to varying degrees of atmospheric sulphur and nitrogen deposition.

Figure 3: Modelled average DOC in runoff from peat and non-peat catchments in the Peak District, for pre-industrial (reference) conditions, 1970, 2005 and 2020, as a function of atmospheric Sulphur and Nitrogen deposition



Land-management scenarios were evaluated based on available literature and data on the impacts of each management option on water quality:

Business as usual - maintenance of current management in each region, but taking into account reductions in atmospheric pollution by 2020.

Re-wetting - restoration of a water table close to the surface by blocking drainage ditches and erosion gullies. This is anticipated to lead to a 50% reduction in SO_4 leaching.

Re-vegetation - restoration of a functioning *Sphagnum* cover, leading to the restoration of the N-retention function of the peatland. There was the assumption that the establishment of *Sphagnum* cover would require cessation of current moorland burning for grouse management. Yallop et al. (2009) found a strong positive relationship between DOC and area of recent burn in a range of Pennine catchments. Using their data it was estimated that cessation of this burning could lead to an average 40% reduction in surface water DOC concentrations. It must be emphasised that this estimate is uncertain; few data on burning impacts on water quality are available, and other (experimental rather than correlational) studies have not shown the same DOC response to managed burning.

Conservation-led re-wilding - a combination of re-vegetation, re-wetting, and cessation of burning and grazing. Water quality impacts were calculated by taking a ‘best case’ combination of predicted responses to all individual scenarios.

Food security - an increase in (sheep) grazing density. Although it is possible that changes in grazing density might be expected to impact on water quality (for example via changes in vegetation and nutrient cycling), there is insufficient published evidence available to make clear predictions.

Grouse economy - In the Peak District, much of which is already managed for grouse, this scenario was considered to represent business as usual, which is why there is no difference to the present situation.

Restoration of a fully functioning *Sphagnum* cover (and associated cessation of burning) in the Peak District would have considerable positive impacts in terms of DOC, NO_3 and acidity levels in surface waters. Re-wetting would have benefits in terms of DOC, SO_4 leaching and acidity; ‘re-wilding’ would combine the benefits of both scenarios. Figures 4 and 5 illustrate historic and projected changes in DOC in runoff under these different management scenarios.

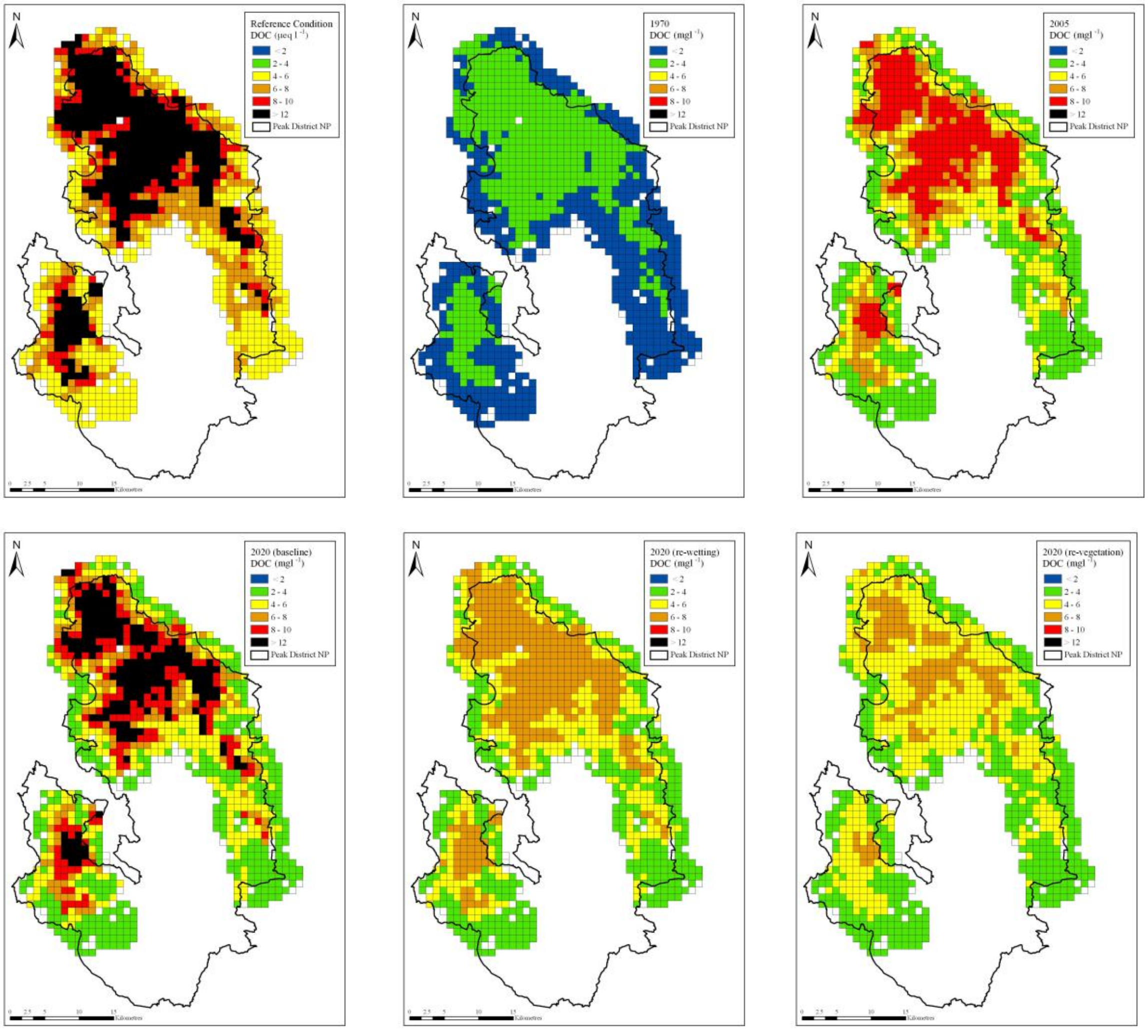
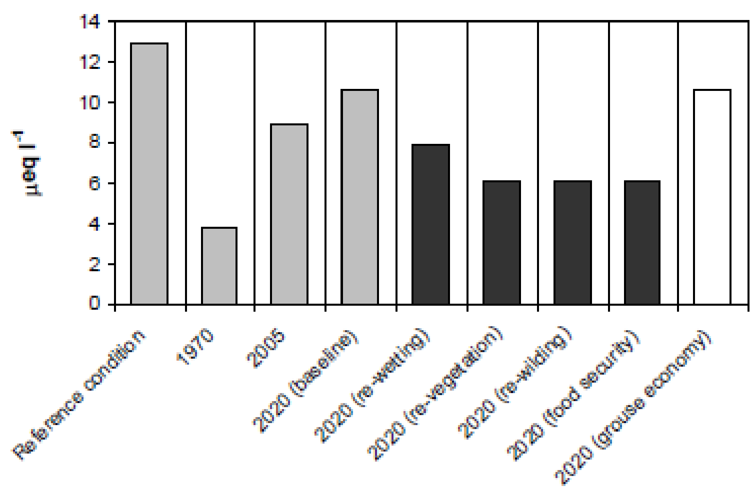


Figure 4: Modelled average Dissolved Organic Carbon concentration in the Peak District, for pre-industrial (reference) conditions, 1970, 2005 and 2020 under different management scenarios

Figure 5: Modelled average DOC in runoff from peat catchments in the Peak District, showing historic and baseline 2020 scenario (grey), and future land-use



Particulate organic carbon production
The sediment within a reservoir originates from a variety of sources including peat erosion from gullies, stream/river bank erosion and reservoir bank erosion and the paucity of data that quantify the impact of different peatland management regimes on organic sediment production and transport. The degree of vegetation or re-vegetation of a peatland is important in controlling the suspended sediment flux either through its role in limiting sediment production on intact surfaces or in reducing slope-channel linkage in eroding but re-vegetating systems. Once organic suspended sediment enters a reservoir it may be deposited and end up in long-term sedimentary storage where it may reside for decades or centuries or it may be oxidised in the fluvial system and then lost to the atmosphere as CO_2.

Peat condition and management can influence runoff water quality in a number of respects, including POC loss, N and S retention, and DOC production. Severe acidification has been exacerbated by the loss of S and N retention functions. DOC loss may have been increased by burning, but also appears to have been suppressed by past acidification, with a part of the recent increases therefore linked to subsequent ecosystem recovery rather than degradation. There is also some evidence that peat gullying could have suppressed DOC loss. This assessment is necessarily preliminary since the quantitative understanding and process models required to fully evaluate the water quality implications of all management scenarios and combinations remain incomplete. The overall impact of gullying and ditch blocking on DOC, N, S and acidity remains uncertain, as does the impact of water table on N retention.

A2.3 Flood risk mitigation

Debate remains as to whether the UK's peatlands act to attenuate or exacerbate flooding. Peat is capable of storing large quantities of water; saturated peat is commonly 90-98% water by mass. This has led to the mistaken supposition that peatlands act as a sponge to soak up rainfall and prevent flooding, before gradually releasing water to maintain baseflow. In reality, peat catchments exhibit a rapid response, with flashy hydrographs. This poses two main problems; the rapid response to rainfall and snowmelt places downstream areas at risk from flooding, while utility companies are tasked with providing a consistent water supply despite poorly maintained baseflows.

Saturation-excess overland flow (OLF) is critical in facilitating peatlands' rapid response to rainfall yet it is only recently that work has been undertaken to determine the controls on overland flow velocity in temperate systems. In neglecting the spatial complexity of peatland vegetation cover and its influence on the degree of connectivity of saturated areas to channels, a crucial mechanism by which vegetation management practices can be used to attenuate the flood hydrograph has been overlooked. The degradation of peatlands is commonly associated with a reduction in the cover of *Sphagnum* moss and an increase in the spatial extent of bare peat areas. This is of critical importance to upland management activities since recent evidence demonstrates that *Sphagnum* offers greater hydraulic resistance to overland flow than other surface covers common in these fragile environments such as *Eriophorum* (cotton grasses), *Sphagnum-Eriophorum* mixes and degraded bare peat surfaces (Holden *et al*, 2008). Due to the dominance of saturation-excess overland flow, there is the potential for the rehabilitation of degraded peatlands to reduce downstream flood risk and mitigate low flows.

Seven scenarios (see Table 13) were explored to compare with business as usual (i.e. present land cover). These scenarios relate to vegetation cover. More *Sphagnum* cover relates to vegetation and water table restoration scenarios and enhanced heather cover relates to increased burning under an economy scenario. Bare peat scenarios relate to the increase in grazing density under the food security scenario, although this is an extreme case to indicate the level of change to be expected if damage was severe.

Table 13: The vegetation scenarios applied for hydrological modelling

Scenario	Description
1	100% '*Sphagnum*' coverage
2	100% 'Bare' coverage
3	All current 'bare peat' areas revegetated to '*Sphagnum*'
4	Scenario 3 plus 50% of the current '*Eriophorum-Sphagnum* mix converted ' to '*Sphagnum*'
5	Scenario 4 plus 50% of the current '*Eriophorum*' converted to '*Eriophorum-Sphagnum* mix'
6	Scenario 5 plus 50% of the current 'Heather' converted to '*Eriophorum*'
7	Scenario 5 plus 30% of the current 'Heather' converted to '*Eriophorum*'

The modelled effects of the re-establishment and management scenarios on the peak discharge are presented in Figure 6. The biggest changes in peak discharge occur at Scenario 5 where 50 % of the *Eriophorum* is converted to Eriophorum-*Sphagnum* mix coverage. The greatest difference in average overland flow velocities between adjacent surface covers in the spectrum occurs here and this is where the majority of the gains are seen. However, in more degraded catchments, where the present bare peat coverage is more extensive, the re-vegetation of bare surfaces (Scenario 3) would also see a more marked reduction in simulated peak discharge.

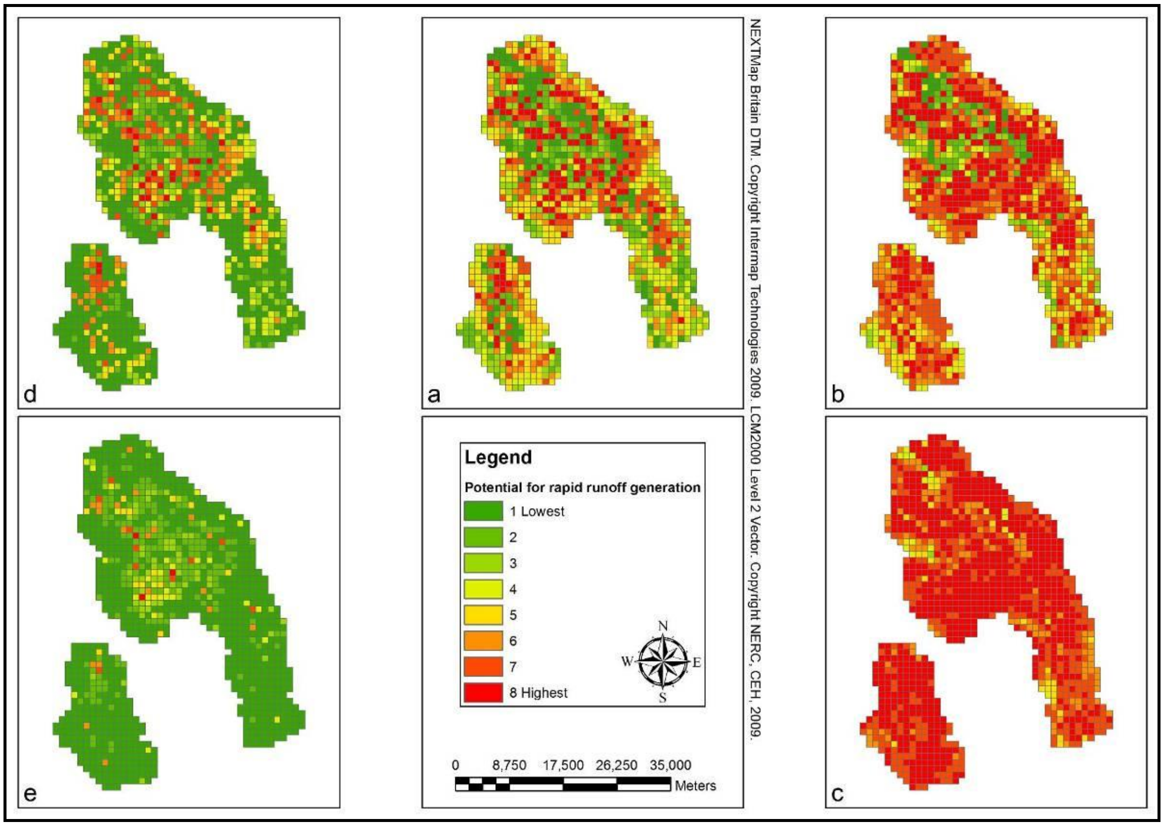


Figure 6: The impact of vegetation change on the potential of areas of the Peak District to rapidly produce runoff. The current situation is shown in the centre (a). Shifts in vegetation coverage of 1 and 2 steps towards the degraded end of the Bare-Heather-*Eriophorum*-*Eriophorum*/*Sphagnum* mix-*Sphagnum* spectrum are shown on the right ((b) and (c) respectively). Shifts of 1 and 2 steps towards the pristine end of the spectrum are shown on the left ((d) and (e) respectively).

A modest simulated reduction in peak discharge is associated with those vegetation re-establishment and management scenarios that involve a significant return toward pristine blanket bog vegetation. However, modest changes in the hydrographs can mean large changes in flood peaks further downstream depending on flood wave synchronicity and connectivity of the river channel network. Eliminating bare areas (i.e. by encouraging vegetation restoration) should be a priority and any return to a more pristine *Sphagnum* cover elsewhere would be beneficial in terms of delaying flow. In practice, this conclusion is emphasised by the partial association of bare areas with erosional features, so that re-vegetation and/or flow diversion/blocking around eroded channel ways should have high priority.

APPENDIX 2

Potential impacts of climate change

The ‘carbon flux’ review by Worrall et al (2011) reports an observed increase in DOC release from peat soils under elevated CO2, attributed to elevated net primary productivity (NPP) and increased root exudation of DOC. This is thought to be a result of labile carbon released by roots simulating microbial activity and leading to enhanced degradation of soil organic matter. Moreover the effect of the interaction of CO2 and warming may lead to greater vascular plant dominance, decomposition and DOC release.

Changes in rainfall could result in changes in runoff. Increases in discharge could lead to increases in DOC concentration; however decreases in precipitation could also lead to increases in DOC because of the decrease in dilution. Changes in rainfall can alter the balance of flowpaths in a peat-covered catchment and cause greater flow through areas rich in DOC. The pattern of DOC flux from the UK, which is dominated by the flux from peatlands, can be explained by an underlying increase in air temperature and by changes in river flow.

Rainfall is a key driver of POC flux, runoff is the primary agent of peatland erosion and increases in runoff have the potential to trigger fresh erosion through increasing the erosive force on stressed vegetation surfaces and also exacerbate the rate of POC flux from eroding systems. The former poses much the greater risk as the shift from vegetated to eroded status entail at least an order magnitude increase in POC flux. Changes in the rate of erosion at bare peat sites will be a lower order and significantly affected by changes in the frequency of high intensity storms, which carry a large proportion of total sediment load.

There is also some evidence to support drought as a driver of change, and drought frequency is increasing in the peatlands of the UK. The catastrophic lowering of the water table in peat during droughts leads to the oxidation of sulphide minerals to sulphate. The increase in sulphate concentration suppresses the mobility of DOC, as the drought ends this suppression is released, as sulphate is reduced or washed out, and DOC concentrations rise.

Increasing drought frequency is potentially significant for POC flux. Desiccation during drought periods is an important process driving sediment production from bare gully walls; increases in summer drought coupled with enhanced autumn rainfalls are therefore likely to enhance POC flux. Drought conditions have also been implicated in the initiation of peat erosion in the southern Pennines. Moisture stress on the surface vegetation and cracking due to desiccation have the potential to destabilise peat masses and produce a step change in POC flux from the system. A second POC related risk of drought periods relates to the risk of wildfire.

APPENDIX 3

Key live monitoring projects:

Making Space for Water (Defra / EA funded *2010-2015*)
The Edge, Kinder Plateau, Ashop Catchment
Moors for the Future, University of Manchester, University of Durham,

This project aims to assess the impact of moorland restoration on runoff generation from eroded peatlands. Five sites have been instrumented with weirs, meteorological instrumentation, dipwells and runoff plots to measure changes in runoff and water balance. Two reference sites are located on Bleaklow, one intact reference and one 'late stage restoration' reference that was restored seven years ago.

Greenhouse gas emissions associated with non gaseous losses of carbon - fate of particulate and dissolved carbon (Defra funded (SP1205), 2010-2015)
Upper North Grain catchment, Ashop catchment forms part of this Dark Peak study
Centre for Ecology and Hydrology, University of Manchester, University of Durham, University of Bangor, University of Leeds.

This project has the following overarching goals:

1) To identify the mechanisms by which peat-derived fluvial C is cycled between different forms within the river network, focusing on DOC and POC but also considering inorganic C
2) To evaluate the influence of biological, chemical and physical conditions at different locations within the river network on fluvial C transformations
3) To quantify rates of C transfer between pools and the ultimate fate of C exported from peatlands, as a function of these chemical, physical and biological controls
4) To determine downstream changes in peat-derived fluvial C as it mixes with water of contrasting character or passes through water treatment works
5) To consider the role that climate change may have on fluvial C dynamics.

These overarching goals will be met through an integrated set of in-situ measurements, laboratory and field experiments. Work will be structured around the following specific technical objectives:

1) To identify 'hotspots' of peat-derived DOC, POC and IC processing in river systems
2) To identify and quantify controls on DOC processing under controlled laboratory conditions
3) To verify laboratory-derived controls on DOC processing by field experiments 4) To identify and quantify controls on POC processing under laboratory and field conditions
5) To investigate whether freshwater and estuarine POC deposition leads to CH_4 emission
6) To evaluate the impact of water treatment processes on fluvial C processing
7) To integrate results and to derive GHG emission factors for peat-derived DOC, POC and IC.

Ongoing monitoring / research in the Upper North Grain Catchment (Ashop sub-catchment) by the University of Manchester

The University of Manchester have been monitoring UNG since 2001. The ongoing monitoring supports teaching and a number of research projects. Since 2001 there have been seven PhD theses entirely or partly based in the catchment and several MSc or undergraduate dissertations – see Table 14.

Table 14: PhD studies at the University of Manchester using Upper North Grain catchment as a study site

Name	Title of PhD	Completed
Emma Shuttleworth	Applying flux natural tracers to the study of peatland sediment	In year 2
Claire Goulsbra	Monitoring drainage network connectivity	2010
Richard Pawson	The role of particulate carbon in upland carbon budgets	2010
Sarah Crowe	Natural revegetation of eroded blanket peat: implications for blanket bog restoration	2007
Steve Daniels	Controls on Streamwater Acidity in a South Pennine Headwater catchment	2006
James Rothwell	Fluvial export of heavy metals from contaminated and eroding peatlands, Southern Pennines, UK	2006
Juan Yang	Monitoring and Modelling sediment flux from an eroding peatland	2005

APPENDIX 4

Publications arising from research at the University of Manchester in the Upper North Grain catchment within the Ashop catchment.

Emma Shuttleworth
Applying flux natural tracers to the study of peatland sediment
Year 2

PhD Aims and objectives:
The primary aim of this study is to investigate sediment dynamics at various scales across the Bleaklow area of the Peak District. This will be realised through a series of sub-projects. The main objectives are as follows:

- Trace the provenance of sediment entering the fluvial system by applying fingerprinting methods, which are widely used in minerogenic catchments, to an organic system. This will allow me to establish the relationship between potential sediment sources and the nature of sediment entering the system.
- Study small scale sediment storage and movement across interfluves and gully walls and floors.
- Investigate sediment transported at different flow depths to look for evidence of changing provenance during and between storm events.
- Determine the effect of different land surface conditions on sediment quality and flux.

Shuttleworth (2011) Impacts of wildfire, erosion and restoration on sediment flux and pollutant mobilisation in the peatlands of the Peak District National Park. Report to Moors for the Future.

Claire Goulsbra
Monitoring drainage network connectivity
2010
Variations in drainage density have been observed in a range of environments as the perennial stream network expands into headwater reaches. This network expansion and contraction results in large changes in drainage density and as such, has implications for the connectivity of the catchment and the associated flux of water, sediments and solutes. One environment where these changes have been observed is peatlands. The accurate characterisation of catchment connectivity in peatlands is desirable for a number of reasons, not least to understand the controls on carbon flux. In addition, the accurate characterisation of these systems will help us to predict the impacts of a changing climate. It is hitherto been difficult to quantify changes in connectivity due to the logistical difficulties of monitoring this phenomenon. The use of Electrical Resistance (ER) technology has shown potential to detect the presence and absence of water. This method is built on here and a range of sensors are developed to monitor connectivity at high temporal and spatial resolutions, specifically flow in ephemeral portions of the channel network, pipeflow and overland flow.

The study takes places in the Upper North Grain research catchment, a small peatland headwater catchment in the south Pennines, UK. The data collected on ephemeral streamflows highlight the importance of water table as a control on changes in network extent in the study catchment, as the presence or absence of flow at each site is strongly controlled by local water table. This allows the minimum and maximum drainage density within the catchment to be determined, as well how frequently these states occur. Pipe stormflow generation appears to be strongly linked to the production of saturation excess overland flow. The pipe network is very sensitive to small inputs of rainfall. In contrast, pipe baseflows seem to be controlled by water table level as pipes are fed by seepage from the peat mass. Pipe behaviour could not be related to any of the morphological characteristics presented here and is though to be dependent on the subsurface morphology of the pipe network. Overland flow production was monitored at a gully head and gully side location. At the gully head the incidence of overland flow increased with distance from the gully edge due to higher local water tables encouraging the production of saturation excess overland flow. At the gully side, extreme water table drawdown has caused the peat to become hydrophobic and the incidence of overland flow is high here, due to infiltration excess. This signifies a major advancement in our knowledge of runoff pathways in peatlands as the importance of infiltration excess overland flow has not been acknowledged until now. In general, ephemeral streamflows occur before the production of either overland flow or pipeflow as incident rainfall causes saturation of the gully floors. The temporal pattern of overland flow and pipeflow is similar, although pipeflow continues after overland flow ceases and is thought to be fed by shallow subsurface flow on the recession limb. Both overland flow and pipeflow precede discharge at the catchment outlet by several minutes. The interaction of these processes is examined under both ‘wet’ and ‘dry’ antecedent conditions. The data collected here provide an accurate characterisation of the dynamics of, and controls on, peatland connectivity under current climatic conditions, providing a reference point to which future observations can be compared.

Full text:
https://www.escholar.manchester.ac.uk/api/datastream?publicationPid=uk-ac-man-scw:128188&datastreamId=FULL-TEXT.PDF

Goulsbra, C.S., Lindsay, J.B., Evans, M.G. "A new approach to the application of electrical resistance sensors to measuring the onset of ephemeral streamflow in wetland environments." *Water Resources Research* 45(2009): 1-7.

Ephemeral streamflow events in headwater catchments are significant in terms of the flux of sediments, solutes, and discharge out of a catchment. Existing attempts to monitor these events, however, have traditionally been restricted to a limited series of manual observations or the use of temperature sensors which demand a great deal of data interpretation and often introduce significant timing errors. The use of electrical resistance sensors has been found to be one potential alternative, but this method has not yet been fully explored. This paper builds upon this method, presenting a new low-cost ephemeral streamflow (ES) sensor which is able to detect the onset and cessation of ephemeral streamflow events at high spatial and temporal resolutions. Furthermore, the data collected by the ES sensor needs only minimal interpretation. Laboratory testing reveals that the sensors are able to clearly distinguish between the presence and absence of water. Field testing in a small peatland headwater catchment in the South Pennines, United Kingdom, confirmed that the sensors were robust enough to withstand field conditions. Careful site selection enabled the production of a high-quality data set, showing the timings of multiple ephemeral streamflow events at numerous locations within the catchment. The low cost, good performance, and minimal data interpretation requirements of the ES sensors permit unprecedented high-resolution monitoring of ephemeral streamflows.

Richard Pawson
The role of particulate carbon in upland carbon budgets
2010

Pawson, R.R, Evans, M.G., Allott, T.E., (2008), Fluvial organic carbon flux from an eroding peatland catchment, southern Pennines, UK, *Hydrology and Earth Systems Sciences* 12, 625–634.

This study investigates for the first time the relative importance of dissolved organic carbon (DOC) and particulate organic carbon (POC) in the fluvial carbon flux from an actively eroding peatland catchment in the southern Pennines, UK. Event scale variability in DOC and POC was examined and the annual flux of fluvial organic carbon was estimated for the catchment. At the event scale, both DOC and POC were found to increase with discharge, with event based POC export accounting for 95% of flux in only 8% of the time. On an annual cycle, exports of 35.14 t organic carbon (OC) are estimated from the catchment, which represents an areal value of 92.47 g C m^{-2} a^{-1}. POC was the most significant form of organic carbon export, accounting for 80% of the estimated flux. This suggests that more research is required on both the fate of POC and the rates of POC export in eroding peatland catchments.

Full Text: http://www.hydrol-earth-syst-sci-discuss.net/4/719/2007/hessd-4-719-2007-print.pdf

Pawson, R.R, Evans, M.G., Allott, T.E., Experimental Evaluation of the Role of Particulate Organic Carbon as an In-Channel Source of Dissolved Organic Carbon.

Pawson, R.R, Evans, M.G., Allott, T.E., The role of Particulate Organic Carbon (POC) in the carbon cycle of degrading upland peat systems, Geophysical Research Abstracts, Vol. 8, European Geosciences Union, 2006.

Pawson, R.R, Evans, M.G., Allott, T.E., Particulate Organic Carbon (POC) dynamics in the hydrological system, Final Project Report, Moors for the Future Research, 2006.

Pawson, R.R, Evans, M.G., Allott, T.E., (2011) Impacts of wildfire, erosion and restoration on sediment flux and pollutant mobilisation in the peatlands of the Peak District National Park. Report to Moors for the Future Partnership.

Sarah Crowe
Natural revegetation of eroded blanket peat: implications for blanket bog restoration
2007

Crowe, S. K., M.G. Evans and T.E.H. Allott (2008) Geomorphological controls on the re-vegetation of erosion gullies in blanket peat: implications for bog restoration. Mires and Peat, Volume 3, Article 01

This paper describes the natural re-vegetation of eroded blanket peat gullies in the Dark Peak National Park, Southern Pennines (UK). Sequences derived from the plant macrofossil records of nine peat cores indicate a two-phase process of re-vegetation consisting of (a) a primary (pioneer) phase of colonisation by *Eriophorum angustifolium* (common cottongrass), and (b) a secondary phase involving colonisation by up to six species, establishing to either wet bog or dry heath vegetation. The stratigraphy not only reveals temporal changes in the development of the plant communities, but also shows patterns in the upstream-downstream direction that give insights into how species spread from the initial re-vegetation zone. The locations where re-vegetation begins are hypothesised to be determined by local geomorphological controls that create zones of re-deposited peat offering favourable conditions for colonisation. Management intervention aiming to restore areas of blanket peatland affected by gully erosion should focus on mimicking these geomorphic controls to reinforce natural trajectories of recovery of the physical system. This would promote colonization by naturally occurring species that are adapted to the specific local environment, and would thus maximize the probability of establishing self-sustaining restored peatland.

http://www.mires-and-peat.net/map03/map_03_01.pdf

Steve Daniels
Controls on Streamwater Acidity in a South Pennine Headwater catchment
2006

Daniels, S.M., Agnew, C.T., Allott, T.E.H., and Evans, M.G. (2008) Water table variability and runoff generation in an eroded peatland, South Pennines, UK, Journal of Hydrology 361(1-2) 214-226.

Hydrological monitoring in an eroded South Pennine peatland shows that persistent and frequent water table drawdowns occur at gully edge locations, defining a deeper and thicker acrotelm than is observed in intact peatlands (an erosional acrotelm). Antecedent water table elevation is a key control on the hydrological response to precipitation events, in particular runoff percent, the timing of peak discharges and maximum water table elevations. Significant discharge is generated whilst water table elevations are relatively low at gully edge locations, and this has a strong influence on flow pathways. Four characteristics of runoff response are recognised: (i) the rapid development of macropore/pipe flow at the start of the storm; (ii) peat rewetting, water table elevation increase and continued macropore/pipe flow; (iii) maximum water table elevations and peak stream discharge with throughflow occurring within the erosional acrotelm and rapid flow through the subsurface macropore/pipe network; (iv) rapidly declining water table elevations and stream flow following the cessation of rainfall. Gully edge peats provide a key linkage between the hillslope hydrological system and channel flow so that their influence on the hydrological functioning of the peatlands is disproportionate to their aerial extent within the catchment. Future climate change may lead to further degradation of the bogs and a reinforcement of the importance of erosion gullies to runoff generation and water quality.

Daniels. S.M., Evans, M.G., Agnew, C.T., and Allott, T.E.H. (2008) Sulphur leaching from headwater catchments in an eroded peatland, South Pennines, U.K Science of the Total Environment 407 481-496.

A detailed investigation into sulphur leaching in peatland headwater catchments in the South Pennines, UK shows that, despite significant reductions in sulphur emissions, sulphur remains a key acidifier. This sulphur can be considered as legacy atmospheric pollution, stored within the peat by processes of dissimilatory sulphate reduction and now being leached into the region's surface waters. Persistently lower water tables at gully edge locations define a thick erosional acrotelm that is vulnerable to aeration, oxidation and flushing throughout the year, and not solely confined to periods of drought. Stream discharge behaves as a two-end member system, whereby pre-event water, rich in DOC and sulphate, is diluted by event water as a result of event water flowing through fast flow pathways such as macropores and overland flow. A rapid increase in water table elevation during the storm and a decrease in elevation after the storm indicate that event water has infiltrated the peat and has then been released into the stream. Streamwaters in peat dominated upland catchments with high densities of gullying have high concentrations of sulphate and low concentrations of DOC, whereas the reverse is true for those catchments with low densities of gullying. This is consistent with the concept that high concentrations of sulphate can suppress the solubility of DOC. A significant store of sulphate exists within South Pennine peats, and continued gully erosion will enhance sulphur leaching meaning that the timescale involved for any depletion is uncertain. It is therefore important that models predicting recovery from acidification in these upland systems include an understanding of how this stored sulphur is being leached, especially with respect to gully erosion, climate change and reduced precipitation.

James Rothwell
Fluvial export of heavy metals from contaminated and eroding peatlands, Southern Pennines, UK
2006

Rothwell, J.J., Taylor, K.G., Evans, M.G., Allott, T.E.H. "Contrasting controls on arsenic and lead budgets for a degraded peatland catchment in Northern England." *Environmental Pollution* 159, no. 10(2011): 3129-313.

Atmospheric deposition of trace metals and metalloids from anthropogenic sources has led to the contamination of many European peatlands. To assess the fate and behaviour of previously deposited arsenic and lead, we constructed catchment-scale mass budgets for a degraded peatland in Northern England. Our results show a large net export of both lead and arsenic via runoff (282 ± 21.3 gPb ha^{-1} y^{-1} and 60.4 ± 10.5 gAs ha^{-1} y^{-1}), but contrasting controls on this release. Suspended particulates account for the majority of lead export, whereas the aqueous phase dominates arsenic export. Lead release is driven by geomorphological processes and is a primary effect of erosion. Arsenic release is driven by the formation of a redox-dynamic zone in the peat associated with water table drawdown, a secondary effect of gully erosion. Degradation of peatland environments by natural and anthropogenic processes has the potential to release the accumulated pool of legacy contaminants to surface waters.

Rothwell, J.J., Lindsay, J.B., Evans, M.G., Daniels, S.M., Allott, T.E.H. (2010) Modelling suspended sediment lead concentrations in contaminated peatland catchments using digital terrain analysis. Ecological Engineering. 36(5) 623-630

Upland peat soils in close proximity to urban and industrial areas can be contaminated with high concentrations of atmospherically deposited lead. The peat soils of the Peak District (UK) are characterised by extensive eroding gullies. Fine-resolution digital topographic data were used to map the extent and depth of these gullies. Peat samples from eroding gully walls and suspended sediments were collected and analysed for lead content. Variability in lead concentrations of gully wall material and suspended sediments can be explained by differences in mean upslope gully depth. The lead content of suspended sediment exported from catchments characterised by shallow peat gullies is higher than that exported from catchments with deep peat gullies. The empirical relationship between sediment-associated lead concentration and mean upslope gully depth was combined with the gully depth mapping to produce a predictive spatial model of suspended sediment lead concentrations across the Peak District. This model may be particularly useful for catchment managers who are currently involved in the restoration of eroding peat soils in the Peak District uplands.

Rothwell, J.J., Evans, M.G., Daniels, S.M., Allott, T.E.H. "Peat soils as a source of lead contamination to upland fluvial systems." *Environmental Pollution* 153(2008): 582-589.

Upland peat soils are generally regarded as effective sinks of atmospherically deposited lead. However, the physical process of erosion has the potential to transform peat soils from sinks to sources of lead contamination. Lead input and fluvial lead outputs (dissolved + particulate) were estimated for a contaminated and severely eroding peatland catchment in the southern Pennines, UK. Lead input to the catchment is 30.0 ± 6.0 g ha^{-1} a^{-1} and the output from the catchment is 317 ± 22.4 g ha^{-1} a^{-1}. Suspended particulate matter accounts for 85% of lead export. Contaminated peat soils of the catchment are a significant source of lead to the fluvial system. This study has demonstrated strong coupling between the physical process of erosion and the mobilization of lead into the fluvial system. The process of peat erosion should therefore be considered when estimating lead outputs from peatland catchments, especially in the context of climate change.

Rothwell, J.J., Evans, M.G., Allott, T.E.H. (2008) In-stream processing of sediment-associated metals in peatland fluvial systems. Water, Air and Soil Pollution 187 53-64.

The interaction between fluvially transported, metal contaminated peat particulates and acidic waters draining peatland catchments has received limited attention. Potential in-stream processing of sediment-associated metals in acidic stream water was investigated in laboratory based mixing experiments, designed to represent conditions of fluvial sediment transport in a highly contaminated and severely eroding peatland catchment in the Peak District (UK). Over the initial 20 min of the first experiment, stream water Cr and Zn concentrations increased by at least an order-of-magnitude and remained elevated for the full duration (24 h) of the experiment. Stream water As, Mo, Pb, Ti and V concentrations increased between 43% (As) and 440% (V) over the first hour of the experiment. After 24 h most of the metals appeared to have reached equilibrium in the water column. Results of the second experiment revealed that when the concentration of metal contaminated peat particulates is increased, there is an associated increase in the stream water As, Cr, Mo, Pb, Ti, V and Zn concentrations. The experimental data suggest that As, Cr, Mo, Pb, Ti, V and Zn are liable to desorption from metal contaminated peat into acidic stream water. The solubilisation of contaminated peat particulates may also contribute to elevated stream water metal concentrations. The laboratory based approach used in this study may indicate that when there is erosion of metal contaminated peat into acidic fluvial systems there is a concomitant increase in dissolved metal levels, especially when suspended sediment concentrations are high. Further laboratory and field based experiments are required to evaluate the relative importance of physical and chemical processes in the interaction between contaminated peat particulates and stream water in peatland fluvial systems.

Rothwell, J.J., Lindsay, J.B. "Mapping contemporary magnetic mineral concentrations in peat soils using fine-resolution digital terrain data." *Catena* 70(2007): 465-474. *ALPORT CATCHMENT.*

Small-scale spatial variability in the concentration of magnetic minerals in peat soils has been explained by differences in the deposition and interception of magnetic minerals at the soil surface and the retention of magnetic minerals within the soil. Each of these processes is controlled by topographic conditions. Recent advances in the field of digital terrain analysis and the availability of fine-resolution digital elevation models means that the relationship between the concentration of magnetic minerals in peat soils and topography can be explored using quantitative methods. Alport Moor is an ombrotrophic peat moorland in the Peak District National Park, UK. 24 peat cores were collected from Alport Moor covering an area of 0.1 km2. Each core was analysed for mass specific magnetic susceptibility. Three topographic attributes (topographic wetness index, difference from mean elevation and elevation as a percentage of elevation range) were extracted from a high resolution LiDAR digital elevation model of Alport Moor. Stepwise multiple regression analyses show that topographic wetness index and difference from mean elevation are excellent predictors of variation in peak magnetic susceptibility and total magnetic susceptibility inventories for peat soils of this upland area. The results demonstrate that the contemporary concentration of magnetic minerals in the peat soils of Alport Moor is controlled by micro- and local-scale variations in water table position. The results also suggest that the contemporary level of magnetic minerals in the peat soils of Alport Moor is controlled by the retention of such particles in the soil environment. Differences in the deposition and interception of magnetic minerals play a secondary role in controlling magnetic mineral concentrations. Spatial maps of magnetic susceptibility reveal that peat soils adjacent to gully edges at Alport Moor have the highest concentration of magnetic minerals. The mapping approach used in this study could be applied to other peatland environments.

Rothwell, J.J., Evans, M.G., Daniels, S.M., Allott, T.E.H. "Baseflow and stormflow metal concentrations in streams draining contaminated peat moorlands in the Peak District National Park." *Journal of Hydrology* 341(2007): 90-104.

Leaching of previously deposited metals from atmospherically contaminated peat moorlands to receiving surface waters is an area of concern. Headwater streams in the Peak District National Park were sampled during baseflow and stormflow conditions to investigate the spatial and temporal variability in dissolved metal concentrations, the source of dissolved metals and the role of dissolved organic carbon (DOC) in the mobilisation and transport of dissolved metals. Under baseflow and stormflow conditions, Cu, Ni, Pb, Ti, V and Zn concentrations are highly variable. The results of this study reveal that Cu, Ni, Pb, V and Zn are leached from the contaminated peat soils into headwater streams. Ni and Zn are mobile within the peatland fluvial system due to poor sorption of these metals to organic matter. Elevated Zn concentrations in the headwater streams can be explained by the severely acidic nature of surface waters in this region. Stepwise multiple linear regression analysis reveals that the most important variable in explaining stormflow Pb, Ti and V concentrations is DOC. Due to the strong complexation of these metals by DOC, the export of dissolved Pb, Ti and V in peatland systems is likely to be controlled by DOC availability. Elevated stormflow dissolved Pb concentrations are due to the large store of Pb within the peat soils and high stream water DOC concentrations in surface waters of this upland area. Contemporary dissolved metal export from peat moorlands in the Peak District National Park may provide an analogue for future dissolved metal export in other contaminated peatland systems.

Rothwell, J.J., Evans, M.G., Liddaman, L.C., Allott, T.E.H. "The role of wildfire and gully erosion in particulate lead export from contaminated peatland catchments in the southern Pennines." *Geomorphology* 88(2007): 276-284.

The near-surface layer of peatlands of the Peak District, southern Pennines, UK, is severely contaminated with atmospherically deposited Pb. Contemporary catchment soil Pb inventories at Upper North Grain and Torside Clough reveal that ~ 23% and ~ 54%, respectively, of the potential store of Pb in each catchment has been lost through erosion of the contaminated near-surface peat layer. Soil Pb inventories and the Pb content of suspended sediments reveal that, in both catchments, the main mechanism for contemporary particulate Pb export is gully erosion. Historical sheet erosion on bare peat flats at Torside Clough has released significant quantities of Pb into the fluvial system, triggered by the exposure of the near-surface peat during an accidental wildfire in 1970. Up to 32% of the total Pb export from the catchment may have been released during a discrete erosion event soon after the wildfire. Accidental wildfires and the subsequent release of highly contaminated peat into the southern Pennine fluvial system may increase under predicted climate change scenarios

Rothwell, J.J. Evans, M.G., Lindsay, J.B. Allott, T.E.H. (2007) Scale-dependant spatial variability in peatland lead pollution in the southern Pennines, UK. Environmental Pollution. 145 111-120.

Increasingly, within-site and regional comparisons of peatland lead pollution have been undertaken using the inventory approach. The peatlands of the Peak District, southern Pennines, UK, have received significant atmospheric inputs of lead over the last few hundred years. A multi-core study at three peatland sites in the Peak District demonstrates significant within-site spatial variability in industrial lead pollution. Stochastic simulations reveal that 15 peat cores are required to calculate reliable lead inventories at the within-site and within-region scale for this highly polluted area of the southern Pennines. Within-site variability in lead pollution is dominant at the within-region scale. The study demonstrates that significant errors may be associated with peatland lead inventories at sites where only a single peat core has been used to calculate an inventory. Meaningful comparisons of lead inventories at the regional or global scale can only be made if the within-site variability of lead pollution has been quantified reliably.

Rothwell, J.J., Evans, M.G., Allott, T.E.H. (2007) Lead contamination of fluvial sediments in an eroding blanket peat catchment. Applied Geochemistry.22(2) 446-459.

Over the last few years there has been growing concern over the mobilisation of anthropogenically derived, atmospherically deposited Pb from upland blanket peat soils to receiving surface waters. The near-surface layer of blanket peat soils of the Peak District, southern Pennines, UK, is severely contaminated with high concentrations of Pb. Erosion of peat soils in this upland area may be releasing large quantities of previously deposited Pb into the fluvial system. Samples of fluvial sediments (suspended, floodplain, streamside fan, trash-line and channel bed) were collected from a severely eroding blanket peat catchment in the Peak District in order to investigate Pb contamination of fluvial sediments, to determine the mechanism for fluvial Pb transport and to determine if erosion of contaminated peat soils in the catchment is releasing Pb into the fluvial system. Concentrations of Pb associated with fluvial sediments are considerably higher than those in the catchment geology, but not as high as those in peat soils in the catchment. Intra- and inter-storm ariability in the Pb content of suspended sediments can be explained by differences in organic matter content of these sediments and differences in erosion processes operating within the catchment. High Pb concentrations are associated with suspended sediments that have a high organic matter content. The results of this study suggest that organic matter is the principle vector for sediment-associated Pb in the fluvial system. Erosion of contaminated peat soils in the Peak District is releasing Pb into the fluvial system. The extent to which this is a problem in other peatland environments is an area requiring further research.

Rothwell, J.J., Evans, M.G., Allott, T.E.H. "Sediment-water interactions in an eroded and heavy metal contaminated peatland catchment, southern Pennines, UK." *Water, Air and Soil Pollution: Focus* 6, no. 5-6(2006) : 669-676. eScholarID:1b6284 | DOI:10.1007/s11267-006-9052-3

Atmospherically deposited lead in the upper layer of the heavily eroded peatlands of the Peak District, southern Pennines, UK, reaches concentrations in excess of 1,000 mg kg^{-1}. Erosion of the upper peat layer in this region is releasing lead, associated with eroded peat particles, into the fluvial system. Understanding the process mechanisms that control dissolved lead concentrations in contaminated peatland streams is vital for understanding lead cycling and transport in peatland streams. Many headwater streams of the southern Pennines recharge drinking water reservoirs. Measurements in the Upper North Grain (UNG) study catchment show that mean sediment-associated and dissolved lead concentrations are 102 ± 39.4 mg kg−1 and 5.73 ± 2.16 μg l−1, respectively. Experimental evidence demonstrates that lead can desorb from suspended sediments, composed of contaminated peat, into stream waters. In-stream processing could therefore account for the elevated dissolved lead concentrations in the fluvial system of UNG.

Rothwell, J.J., Robinson, S.G., Evans, M.G., Yang, J., Allott, T.E.H. "Heavy metal release by peat erosion in the Peak District, southern Pennines, UK." *Hydrological Processes* 19, no. 15(2005): 2973-2989.

Upper North Grain (UNG) is a heavily eroding blanket peat catchment in the Peak District, southern Pennines, UK. Concentrations of lead in the near-surface peat layer at UNG are in excess of 1000 mg kg^{-1}. For peatland environments, these lead concentrations are some of the highest globally. High concentrations of industrially derived, atmospherically transported magnetic spherules are also stored in the near-surface peat layer. Samples of suspended sediment taken during a storm event that occurred on 1 November 2002 at UNG, and of the potential catchment sources for suspended sediments, were analysed for lead content and the environmental magnetic properties of anhysteretic remanent magnetization (ARM) and saturation isothermal remanent magnetization (SIRM). At the beginning of the storm event, there is a peak in both suspended sediment and associated lead concentration. SIRM/ARM values for suspended sediment samples throughout the storm reveal that the initial 'lead flush' is associated with a specific sediment source, namely that of organic sediment eroded from the upper peat layer. Using the magnetic 'fingerprinting' approach to discrimination of sediment sources, this study reveals that erosion of the upper peat layer at UNG is releasing high concentrations of industrially derived lead (and, by inference, other toxic heavy metals associated with industrial particulates) into the fluvial systems of the southern Pennines. Climate-change scenarios for the UK, involving higher summer temperatures and stormier winters, may result in an increased flux both of sediment-associated and dissolved heavy metals from eroding peatland catchments in the southern Pennines, adversely affecting the quality of sediment and water entering reservoirs of the region.

Full text: http://www.sste.mmu.ac.uk/users/jrothwell/4.PDF

Juan Yang
Monitoring and modelling sediment flux from an eroding peatland: a study of moorland erosion in the Peak District National Park (UK).
2005

Evans, M. Warburton, J. and Yang, J. (2006) Sediment budgets for eroding blanket peat catchments: Global and local implications of upland organic sediment budgets Geomorphology 79 (1-2) 45-57.

Globally, peatlands account for circa 50% of terrestrial carbon storage containing as much carbon as is present in the atmosphere. The uplands of the UK have an extensive cover of blanket peat but much of it is actively eroding. This paper presents a detailed organic sediment budget for a blanket peat catchment in the north Pennines and comparative data from a catchment in the southern Pennines. The catchments have total sediment yields (organic and mineral) of 44 and 267t km^{-2} a^{-1} and organic sediment yields 31 and 195t km^{-2} a^{-1}, respectively. They represent two extremes of a spectrum of eroded peat catchments. It is demonstrated that the lower sediment yields in the north Pennines are associated with extensive natural revegetation of the catchment and consequent reductions in slope-channel linkage. Construction of a carbon budget for the north Pennine catchment demonstrates that particulate carbon losses associated with the fluvial suspended sediment load are the largest single carbon loss from the system. The system is currently close to carbon neutral but much higher carbon losses associated with actively eroding systems such as the south Pennine site would make these systems a major carbon source. The possibility that enhanced summer temperatures and winter storminess will accelerate erosion of upland mires means there is a risk that physical degradation of peatlands could become a significant positive feedback on global warming. Mitigation of these potential global effects will depend on local management informed by a clear understanding of peatland sediment dynamics. The sediment budget data here suggest that in gullied peatlands revegetation of gully floors is an effective control on sediment flux so that techniques such as gully blocking are likely to be effective approaches to erosion control.

Full text: ftp://scrimshaw.usace.army.mil/outgoing/FRFstaff/Wadman/coastal%20carbon/papers/carbon%20Bl%20budget/Evans%20et%20al%202006.pdf

APPENDIX 5

Table 15: Area (ha) of various land cover and management activities across the moorlands within the Bamford WTW and sub-catchment boundaries which may increase water colour and run-off

					Vegetation (ha)										Grazing (ESA Tier) (ha)				
Catchment ID	Catchment (ha)	Moorland (ha)	Bare peat (ha)	Blanket peat / Deep peat (ha)	Peat / Shallow peat	Heather	Non-heather dwarf shrubs	Bracken	Grasses	Rushes	Cotton grass	Grips & gullies (km)	Managed burn (ha)	Wildfire (no. of incidents on moorland)	Tier 2A	Tier 1C	Tier 1B	Tier 2B	Tier N/A
Bamford catchment	20100	12316	1010	5977	6700	3470	1801	2008	1880	1251	1412	602	4017	72	7372	2330	702	798	14
1	2050	1761	22	1159	601	890	175	211	176	127	114	98	1150	1	1121	513	0	70	0
2	1481	1254	13	902	352	431	170	154	136	170	126	73	354	0	811	0	0	266	0
3	1131	940	35	617	303	27	172	103	144	197	193	59	0	2	666	0	79	164	0
4	2817	2406	131	1677	724	588	291	208	290	308	422	194	607	14	2268	0	40	63	0
5	3564	2013	59	595	1226	218	305	405	531	127	237	63	237	20	1367	21	282	3	3
6	1293	127	0	0	79	8	6	45	23	4	2	0	0	0	0		0	0	0
7	2477	137	1	0	0	14	22	35	27	12	6	0	0	1	0	2	4	1	0
8	758	187	1	0	67	65	14	151	9	3	2	0	22	1	0	145	15	5	0
9	1071	908	8	474	402	351	123	178	65	42	32	35	217	5	0	809	31	0	2
10	2688	1663	17	719	875	587	300	271	205	166	115	26	1246	5	590	733	184	90	0
11	999	380	6	15	248	84	61	71	109	33	25	0	118	1	198	22	67	53	8