Woodhead Gully Blocking Monitoring

Final Report

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Executive Summary

The Woodhead Gully Block Monitoring was set up monitor the impacts of gully blocking and re-vegetation works on blanket bog habitat undertaken through MFFP's EU LIFE funded 'MoorLIFE' project. The works were delivered on the Woodhead estate on the northern slopes of the Bleaklow Plateau in the Peak District National Park. This estate is the catchment for United Utilities reservoirs in the Longdendale valley and is designated as a Drinking Water Protection Zones (DrWPZ). The monitoring programme established and monitored four flow and water quality monitoring points at micro-catchment scale, four at a larger gully system scale, and one at the moorland edge between 2012 and 2015. Two gullies were monitored for the effects of gully blocking only within a vegetated system. Two gullies and the moorland edge catchment (Stable Clough) were monitored for the effects of both re-vegetation and gully blocking. Five months of data was collected prior to gully blocking, and two years post-gully blocking. A significant constraint to the monitoring was that the baseline period of monitoring, the period against which it was anticipated evidencing change delivered through the conservation works, was during 2012 – the second wettest year on record (Met Office, 2015). To counter this constraint, longer-term monitoring is required to evidence future changes at the treatment and control sites over.

Effectiveness of gully blocks at holding peat and water

Of 68 stone gully blocks surveyed all (100%) were found to holding water, and 82% were found to be holding peat when compared measurements taken prior to gully blocking. The majority of sediment accumulation occurred within just one month of gully block installation, with no significant change observed between one and 17 months post-installation. Sediment depth behind dams was found to have increased by approximately 14 cm of peat relative to an unblocked control. This catchment is vegetated and so accumulation rates are not as high as have been recorded on gully blocked sites on bare peat sites; sediment supply coming just from the gully walls. Dams have not yet fully 'matured' and have capacity to further accumulate sediment.

Impact of re-vegetation works on bare peat

Data from 60 vegetation quadrats showed that the extent of bare peat on Woodhead has been reduced by 83% to approximately 15% between 2011 and 2014. 77% of this vegetation cover was the grass nurse crop, the remainder was 'blanket bog' vegetation (Dwarf shrub species, mosses and some sedges). A National Vegetation Classification of these data showed that one year after seeding, the site is dominated by wavy-hair grassland (*Deschampsia flexuosa*) and heather-wavy-hair grass heath (*Calluna vulgaris-Deschampsia flexuosa*). Examination of long-term monitoring data from MFFP and SCaMP indicate that bare peat is likely to continue to decrease until 2016 as vegetation continues to establish and grow with succession from a nurse crop dominated sward to a more blanket bog species composition.

Impacts of gully blocking on water table

Water table was monitored at two locations adjacent to gully blocks to evidence the direct impact of gully blocking. Because of the anomalous baseline rainfall, because the water table logging equipment was stolen and had to be replaced, analyses to date have proved inconclusive and further investigation is required. The methodology used here highlighted the difficulty of using single dipwells to monitor water table at unique locations. Data collected from the Biffa-funded 'Peatlands for the Future' project on the Kinder Plateau, using the same methods, indicated a change in behavior of water tables within an area 2 m upstream of gully blocks within a 13 month period after installation.

Impacts of revegetation of bare peat on water table

Analysis of water table data collected from manual dipwells as part of the MoorLIFE showed water table levels to have increased, on average, by 11 mm between 15 to 17 months after seeding, relative to untreated bare peat areas. This relative increase was not significantly different to the change on the control gully, but is comparable to the results from MFFP's Making Space for water project which found significant increase in water table depth in revegetated compared with bare peat reference sites of 35 mm after 3 years (Pilkington et al 2015) and SCaMP results that a general trend in increasing water tables following revegetation and gully locking but significant inter-annual variability reflecting annual differences in rainfall (Hammond and Ross 2014).

Impacts of gully blocking on storm flow

The water flow data collected from Woodhead were considerably noisy, particularly due to the record-breaking rainfall in 2012 (the pre-treatment monitoring period) in addition to limited number of storm events monitored prior to gully blocking. There were indications of a decrease in peak storm flow for small storms following gully blocking, although this effect appeared to be transient and subtle. A decrease in percent runoff was also observed for a short time, but again appeared to be transient. This suggested that a level of additional storm water 'storage' was created in the catchment (i.e. behind dams) but reduced rapidly with time. Increases in lag times were also observed. This effect appeared to be delayed at headwater sites, but more immediate lower in the gully systems, but again a transient effect.

Data from the Making Space for Water (MS4W) project showed that re-vegetation of bare peat at the headwater catchment scale increased lag times by 20 minutes and reduced storm flow by 30% (Allott et al 2015). A revegetated and gully blocked headwater catchment had slightly longer, but not significantly lag times and reduced peak flows than re-vegetation only. Re-vegetation alters storm flow through changes in surface roughness (i.e. from bare peat to vegetated surface). Since no re-vegetation work took place within the monitored systems on Woodhead, there has been little change in surface roughness within the catchments. The initial responses and delayed response found in the study highlight the complex responses of these systems over time.

In Stable Clough, a flow monitoring site at the moorland edge, 54% of the catchment was bare peat and was revegetated. No difference in peak discharge and lag times was found as a result of the revegetation within 17 months after of seeding. The response in the MS4W project was between 10 and 29 months: here the vegetation may not have been sufficient established to increase roughness sufficiently to affect storm hydrographs. Longer term monitoring is required to better evidence the impacts of the establishing vegetation on storm flows in this catchment.

Impact of gully blocking on water quality

Gully blocking in vegetated blanket bog on Woodhead had no observable impact on water colour or DOC concentrations during the 17 month post-works monitoring period, this time frame may be too soon to evidence any changes in water quality. Gully blocking on Woodhead has been linked to a decrease in fluvial POC in the headwaters, in concordance with sediment accumulation results behind gully dams. In the blocked headwater catchment POC was detected in 67% of samples before gully blocking and 35% after; although this decrease was not significant.

Impact of re-vegetation treatments on water quality

Re-vegetation treatments – in particular liming treatments – were associated with a temporary decrease in water colour and DOC concentration of between four and six months. Lime applications resulted in reductions of peak DOC concentrations of up to 43%. Maintenance applications of lime were made annually throughout the monitoring period, and so the results presented here show only the short-term impacts of the treatments themselves, rather than the effect of re-vegetation on water quality.

Results from the Making Space for Water Project found that levels of DOC in fluvial water samples from treated bare peat sites were significantly reduced during the treatment phase as a result of the application of lime (Evans et al 2015). Each treatment of lime reduced DOC but by a lesser magnitude. This effect makes evidence the longer term impact of bare peat revegetation impossible in the short timescale which conservation works are ongoing, and longer term monitoring, post completion of revegetation works is required to evidence the impact of the works on water quality. On Woodhead the effects of the liming were apparent in the data but were not as marked as in the MS4W data; probably because only 54% of the catchment was limed compared to 100% in MS4W.

Improvement in water quality as a result of blanket bog conservation can take years to realise. Evidence from United Utilities' SCaMP project monitoring, the longest monitoring dataset of the impact of blanket bog restoration works on water colour (a proxy for DOC)has found that up to two years post treatment raw water colour increased, with a a slight, but statistically significant decrease in raw water colour only recorded seven years post treatment and while preliminary, these results are extremely encouraging (Hammond & Ross, 2014).

The largest, short-term, impact of re-vegetation treatments is likely to have been on POC. Surveys undertaken by Shuttleworth *et al* (2015) show that re-vegetated sites have a sediment loss several orders of magnitude lower than untreated bare peat sites.

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1. Introduction

The Woodhead Gully Block Monitoring programme began in 2012 as a two-year monitoring project jointly funded by the Environment Agency (EA) and United Utilities (UU). The purpose of the project was to monitor the impacts of extensive programme of gully blocking works, that formed a major part of Moors for the Future Partnership's EU LIFE Nature funded MoorLIFE project and Natural England-funded conservation plans, on storm water flows and water quality. These works were undertaken between 2010 and 2015 on blanket bog habitat of the Woodhead Estate on the northern slopes of the Bleaklow Plateau within the Peak District National Park.

This area of blanket bog is severely eroded. It is divided by long, wide and generally linear gullies, more than two metres deep in places, that channel water flow off the site into cloughs (steep-sided streams). Towards the watershed, extensive loss of vegetation had left large areas of peat bare and eroding. The worst of the erosion resulted in bilberry (*Vaccinium myrtillus*) dominated peat haggs that form islands amongst the extensive areas of thin soils or base rock. The lower slopes of Woodhead have largely retained vegetation cover and are typically heather (*Calluna vulgaris*) dominated and species poor.

The area is situated above the River Etherow and the Longdendale chain of reservoirs, and is part of the Longdendale Drinking Water Safeguard Zone (SGZ). This SGZ was designated because of the high levels of dissolved organic carbon (DOC) and colour of the water entering Arnfield Water Treatment Works (WTW). The source of the colour is largely attributed to the degraded upland blanket peat which makes up a major proportion of the Arnfield WTW catchment. The works on Woodhead formed part of the SGZ Action plan for this catchment. By stabilising the peat through revegetation and raising the water table, the long-term objective was to reduce colour in the raw water leaving the blanket bog watershed catchment and entering the Arnfield WTW.

1.1. The capital works programme

The scale of the capital works programme on Woodhead is reported separately and covers a wide range of conservation and land management techniques (MFFP, 2015). Here we present details of just the gully blocking and stabilisation work within the areas / catchments monitored in this project.

1.1.1. Gully blocking

Gully blocks were installed primarily to reduce sediment loss from peatlands; but also to inhibit further gully erosion through reduction in flow velocities, raise local water tables to increase saturation of peat domes and reduce further degradation of the peat mass and reduction of fluvial carbon loadings. Stone gully blocks were the predominant type of dam installed because of their low continued maintenance requirements and efficient installation.

1.1.2. Stabilisation

Without a layer of vegetation to protect the soil, bare peat is highly vulnerable to erosion as a result of rain, wind, and freeze-thaw action as well as degradation through oxidation. Areas of bare peat are the source of high carbon emissions and contribute significantly to fluvial carbon loadings (Worrall et al 2011).

Revegetation protects the peat from erosion and slows overland water flows (Allott et al 2015; Holden *et al* 2008).

1.2. Aim of the monitoring programme

The Environment Agency funded the initial phase of the monitoring programme on Woodhead with the aim of the monitoring were to assess the impact and effectiveness of gully blocking with respect to:

- Improving water quality (primarily DOC and particulate organic carbon (POC)
- Attenuating storm flow (peak storm flow and lag times).

With United Utilities additional, and continuation, funding the monitoring programme was expanded to include:

- Impact of gully blocking raises water tables
- Contribution of storm events to fluvial DOC / colour
- Sedimentation accumulation behind dams
- A review of the data to assess yield to the reservoirs
- Additional resource to monitor vegetation recover on bare peat areas
- Scoping the creation of hydrological trajectories

The monitoring was developed so as to link with two other projects evidencing the impacts of blanket bog stabilisation and gully blocking on water flows and quality: Making Space for Water Project and the Kinder Catchment Project, both located on National Trust land holdings on Kinder Scout within the Peak District National Park. Both monitoring projects MFFP are delivered by MFFP in collaboration with the University of Manchester.

Woodhead presents a different land management scenario to the projects on Kinder Scout. It is a managed grouse moor, is on a steeper gradient. Woodhead allowed the first monitoring of the impact of blocking erosion gullies associated with ‘intact’ vegetation; not bare peat. It also enabled the study of the combined impacts of re-vegetation and gully blocking at a blanket bog watershed catchment scale on a blanket bog on a steeper slope than monitored by MFFP elsewhere.

1.3. Monitoring set up and methods

A Before-After-Control-Intervention (BACI) monitoring programme was set up on Woodhead. Monitoring took place within four linear gully systems within the Smithy Clough and Stable Clough catchments (Figure 1). Each gully system (named S1, S2, S3 and S4) had one flow monitoring station installed to measure discharge through the gullies at a small headwater (HW) sub-catchment, and approximately 600 metres downstream (DS) from this a second flow monitoring station was installed. A ninth monitoring station was installed at the edge of the Bleaklow Plateau to monitor the flow and water quality across the entire

Stable Clough catchment. Systems S3 and S4 are located within this catchment, allowing intensive monitoring of flow conditions at three spatial scales within the same catchment.

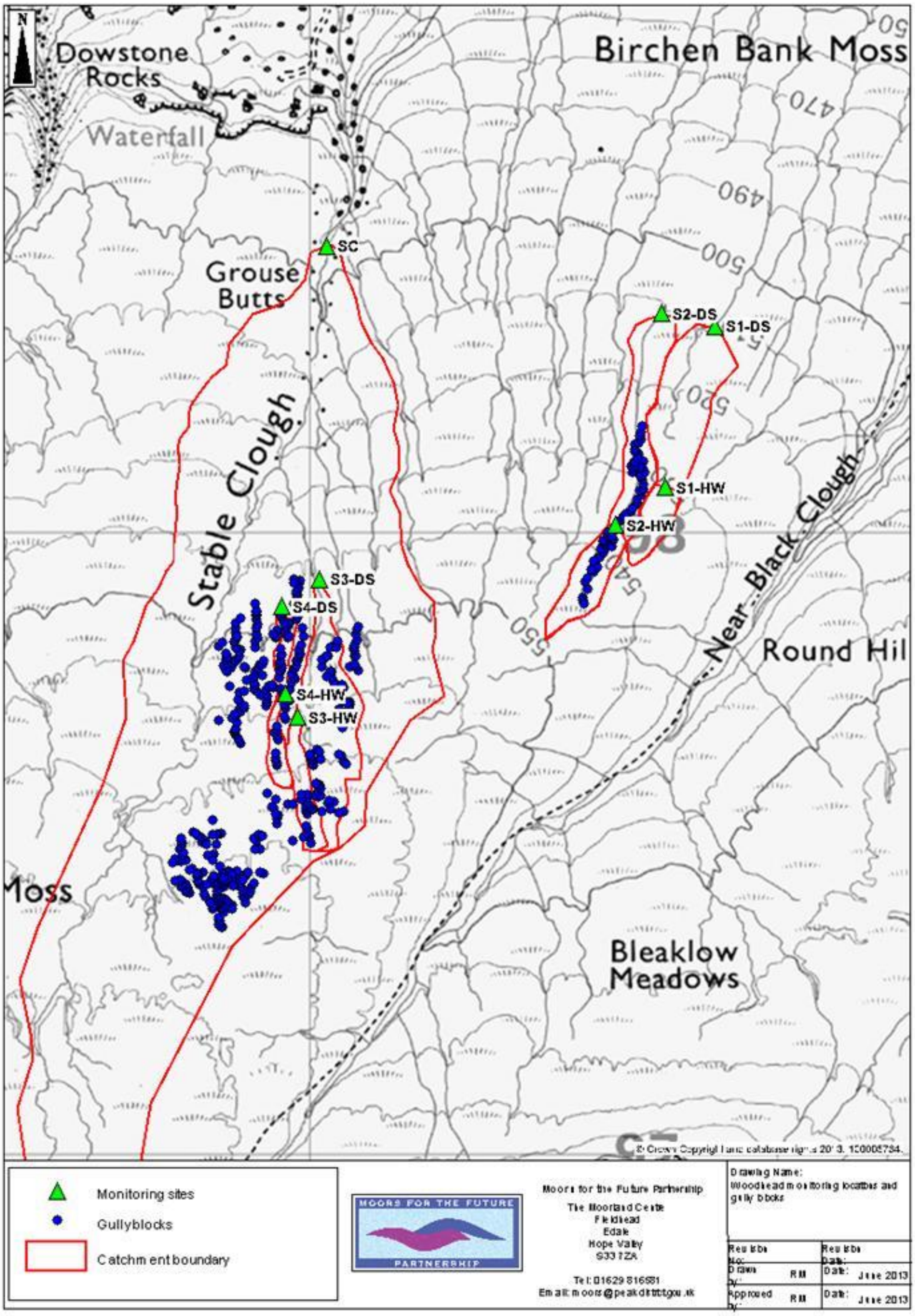


Figure 1 - monitoring locations on Woodhead and associated gully blocks.

Table 1 provides details the nine monitoring sites. S1, S2 and S3 are of comparable size and topography. They are long, linear systems with largely mineral bases. In comparison, S4 is a much smaller system, largely peat based and V-shaped with steep sides.

Table 1 - characteristics of the nine monitoring points on Woodhead

Catchment	System	Reference	Catchment	Location	Area (m^2)	Mean Slope (°)
Smithy Clough	S1	S1-HW	Control, no restoration	headwater	4,572	5.95
		S1-DS	Control, no restoration	downstream	23,776	8.89
	S2	S2-HW	Blocked, no revegetation	headwater	7,580	7.12
		S2-DS	Blocked, no revegetation	downstream	22,268	9.10
Stable Clough	S3	S3-HW	Blocked, revegetation	headwater	6,957	11.90
		S3-DS	Blocked, revegetation	downstream	24,472	12.90
	S4	S4-HW	Blocked, revegetation	headwater	2,653	10.90
		S4-DS	Blocked, revegetation	downstream	5,413	11.90
	SC	SC	Stable Clough	catchment	572,444	10.70

As S1 was the system furthest away from planned peat stabilisation treatments on Woodhead, it was selected to be an unblocked control gully. S2, S3, S4 and Stable Clough catchments were blocked with stone dams between October and November, 2012. The gully blocking treatments received by each system are shown in Table 2.

Table 2 - details of gully blocking treatments within each monitored system

Monitoring point	Date of gully block installation	Number of gully blocks within system
S1-HW	n/a	0
S1-DS		0
S2-HW	27/10/12	30
S2-DS		71
S3-HW	29/10/12 to 10/11/12	20
S3-DS		89
S4-HW	07/11/12	10
S4-DS		34
Stable Clough	29/10/12 to 13/11/12	414

The Stable Clough catchment (including the S3 and S4 sub-catchments) overlapped with areas of bare peat that were not only gully blocked but also treated with aerial applications of lime, seed and fertiliser. The treatments received by each catchment are detailed in Table 3 and maps of the applied treatments can be found in Figure 2 - Figure 9.

Table 3 - details of lime and seed treatments within the Stable Clough catchment. Figures show the percentage of the catchment treated. Systems 1 and 2 were not treated with lime, seed or fertiliser.

	Initial lime April 2012	Seed July 2012	Initial lime Sept 2012	Maintenance lime July 2013	Maintenance lime March 2014
S3-HW	0	100	100	100	100
S3-DS	0	100	100	100	100
S4-HW	0	100	100	100	100
S4-DS	0	100	100	100	100
Stable Clough	19	54	43	83	56

Mapping of lime, seed and fertiliser flight lines show that System 1 received no direct applications of these treatments. System 2 received a small amount of lime and seed close to the S2-DS monitoring point in April and July 2012. These treatments amounted to 3.0% and 4.5% of the catchment of S2-DS and are considered to be minor. No further LSF treatments have been in the vicinity of Systems 1 and 2.

Data presented and analysed for in this report include that collected up until the end of November 2014.Further maintenance lime and fertiliser applications were made in March 2015.

1.4. Pre-works conditions

Efforts were made to install pre-works monitoring on the site, and data collection began in April 2012. However, by this time, the jet stream was positioned unusually far south-east of the UK, causing cyclonic conditions throughout much of the rest of the year. Rainfall recorded at national, regional and local levels between April and December 2012 was extremely high, almost twice the average between April and July 2012. November and December 2012 were the second wettest on record for England and Wales since 1929 (Marsh *et al*, 2013). Examination of the rainfall records from Woodhead indicate that these extreme weather patterns have contributed to higher rainfall intensity and volume in the time period before conservation works began. A possible implication of the unusually wet 'before' period is that if any differences exist only in dry conditions, then potentially the magnitude of any changes could be underestimated.

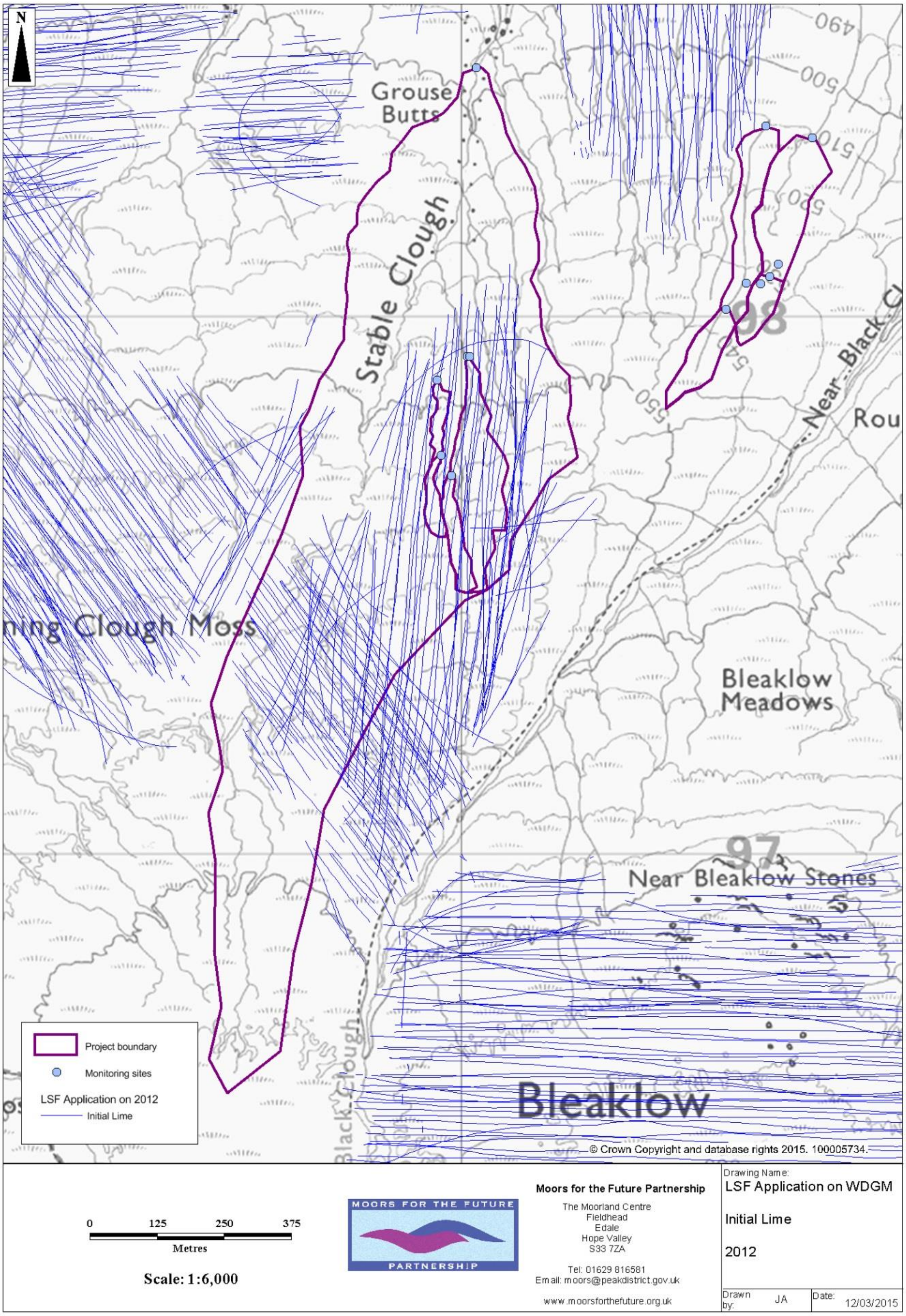


Figure 2 - Initial area treated with lime (2012). Lines are helicopter flight lines during lime spreading.

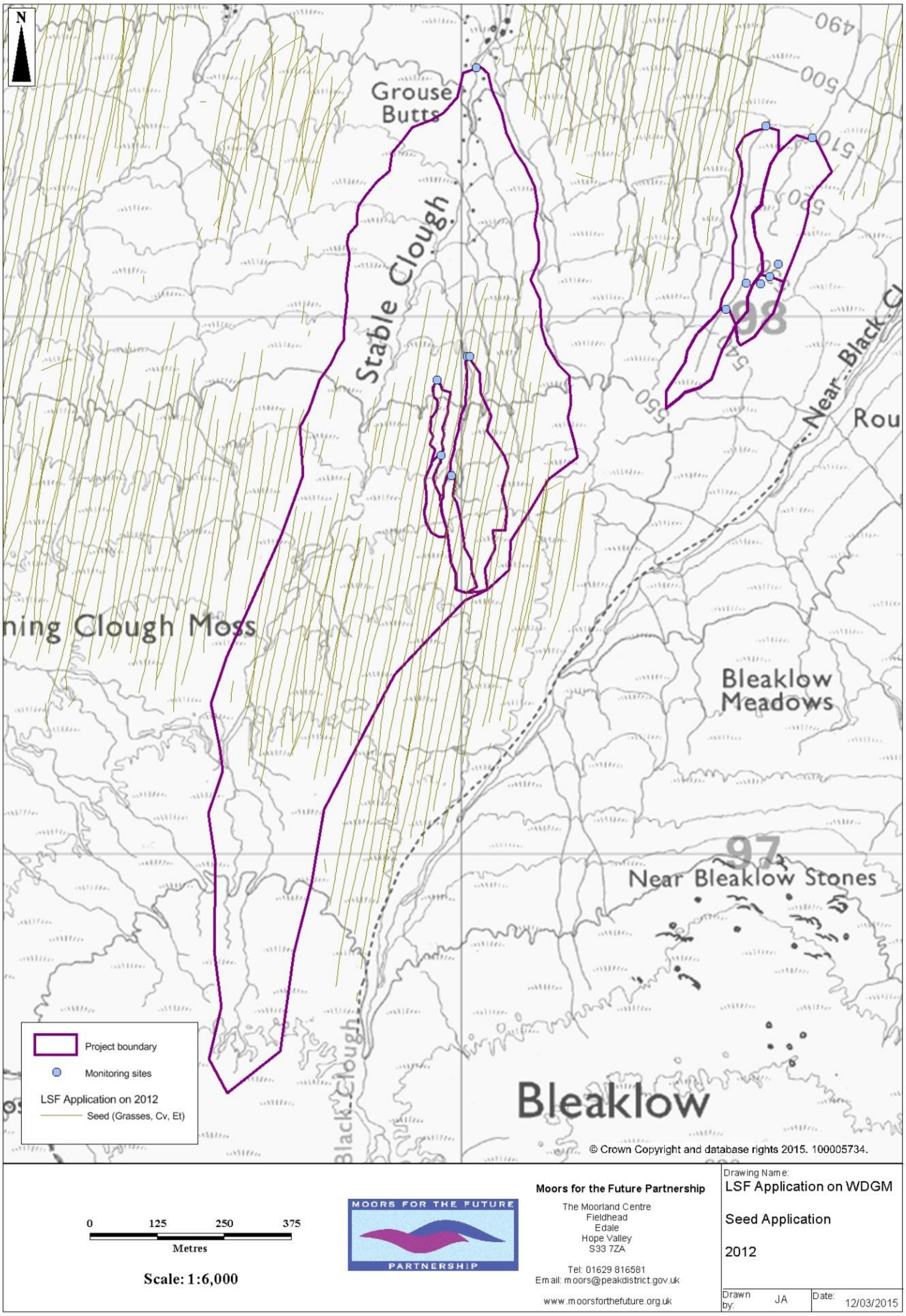


Figure 3 Areas treated with seed (2012). Lines represent helicopter flight lines during application.

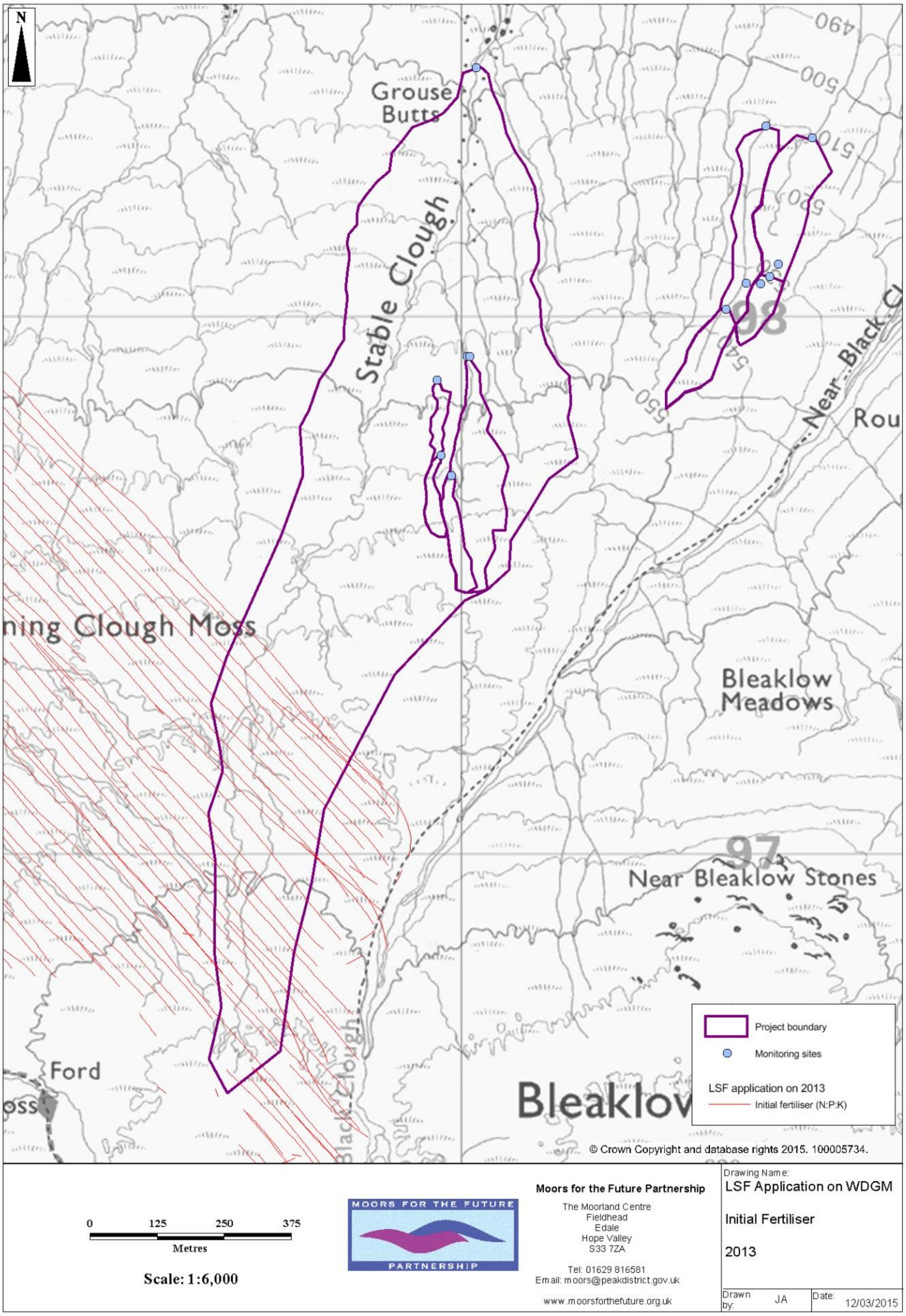


Figure 4 Area treated with fertiliser (2013). Lines represent helicopter flight lines during applications.

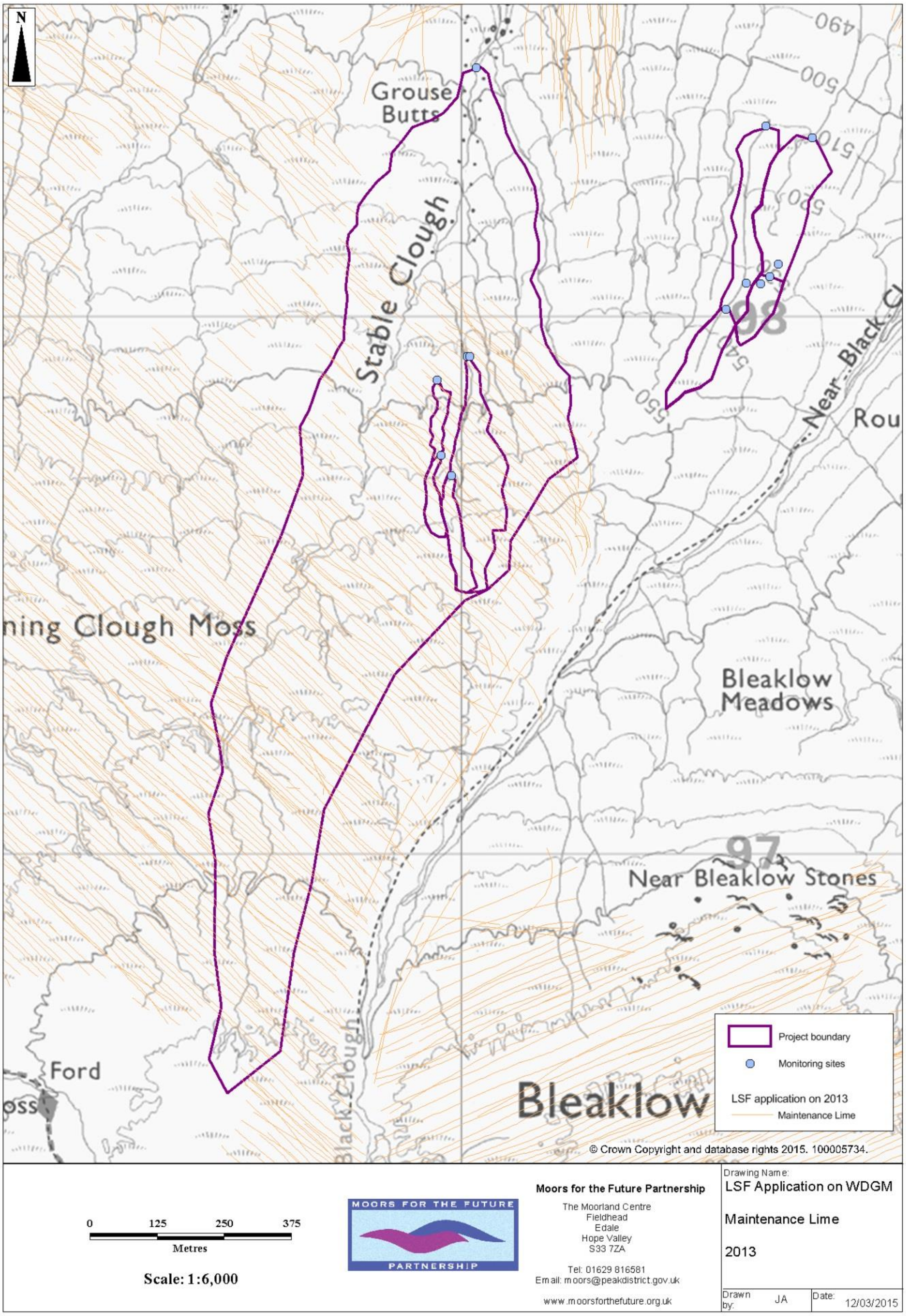


Figure 5 Area treated with maintenance Lime (2013). Lines represent helicopter flight lines during applications.

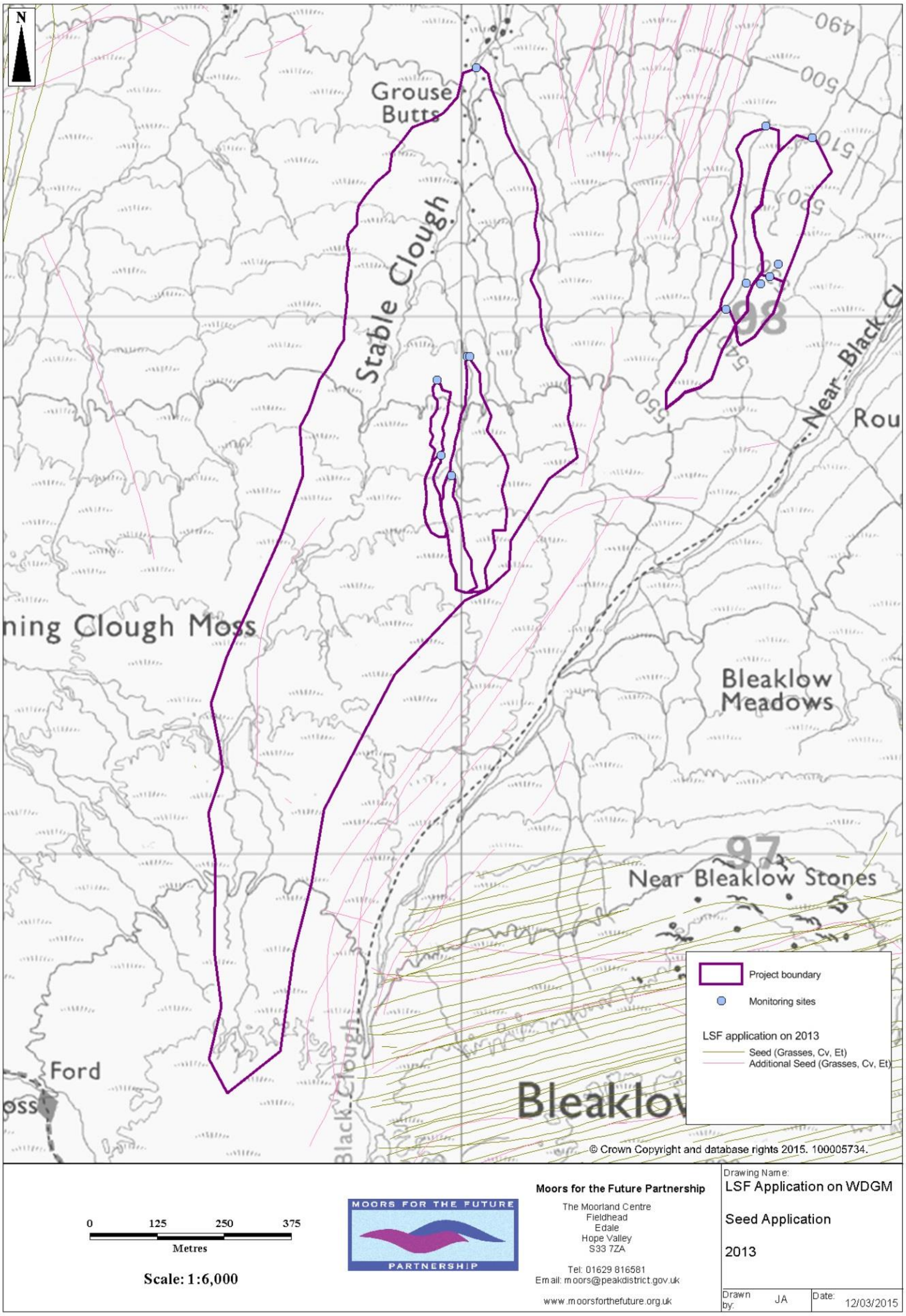


Figure 6 Area treated with seed in 2013. Lines represent helicopter flight lines during applications.

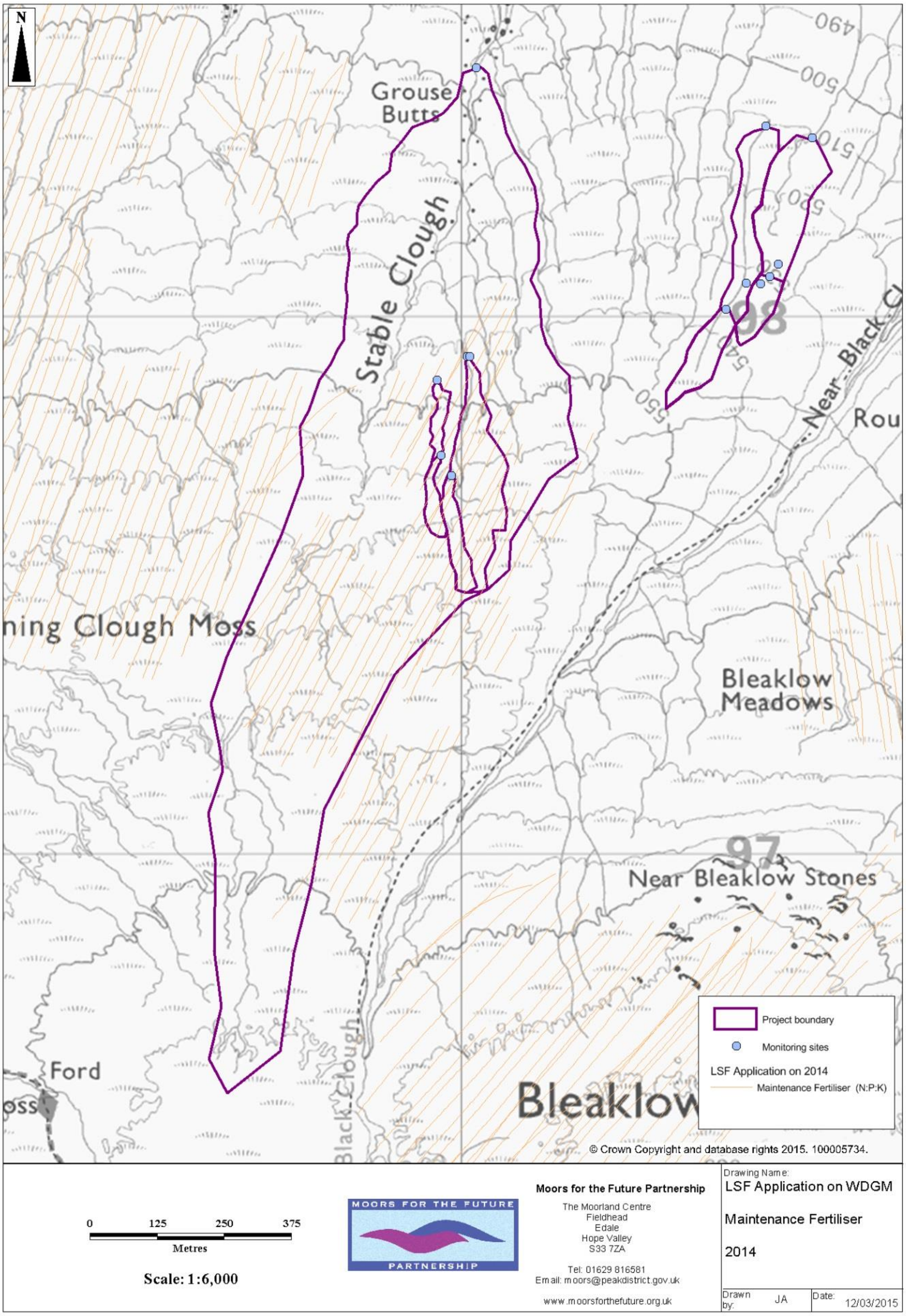


Figure 7 Area treated with maintenance Fertiliser in 2014. Lines represent helicopter flight lines during applications.

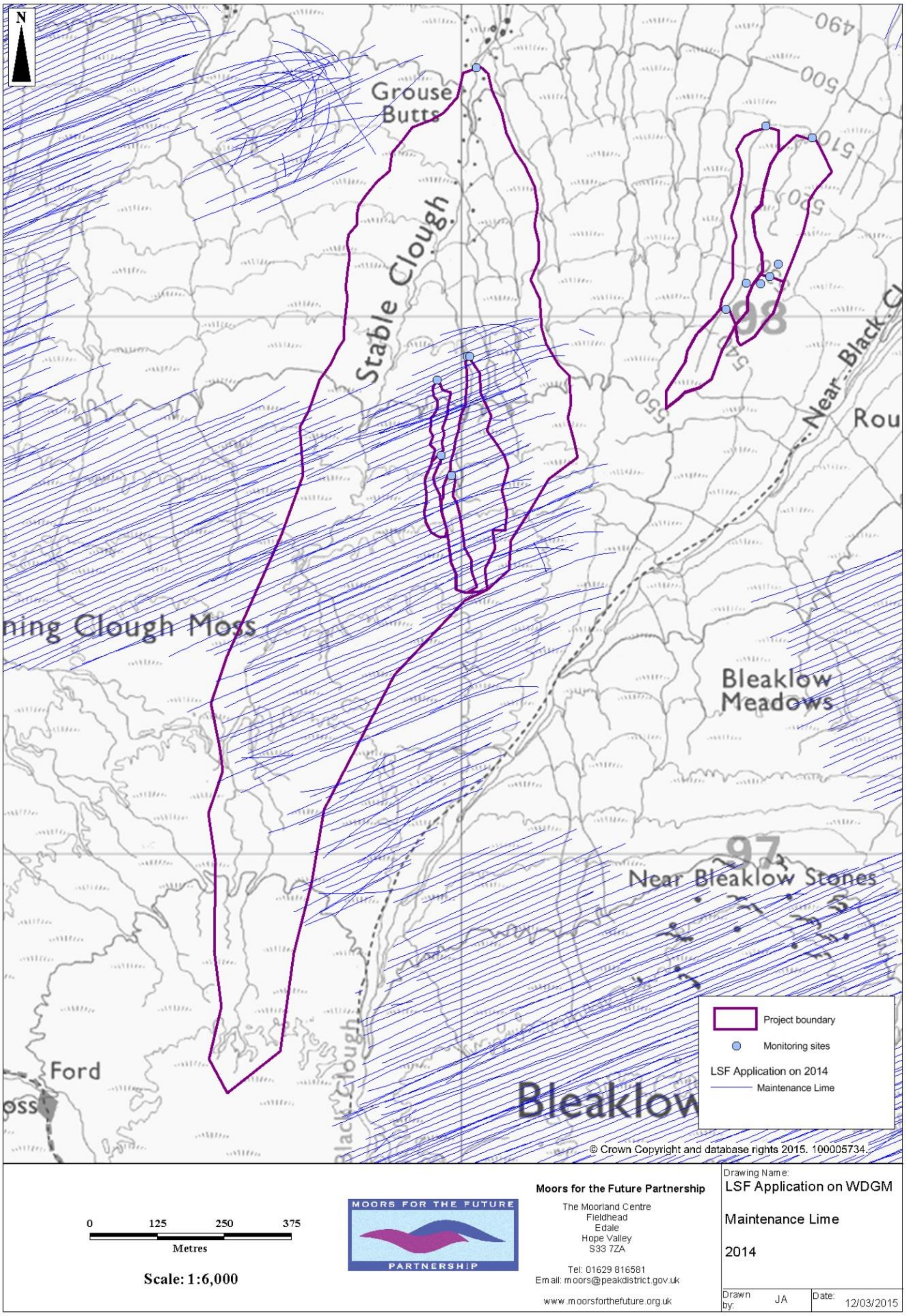


Figure 8 Area treated with maintenance Lime in 2014. Lines represent helicopter flight lines during applications.

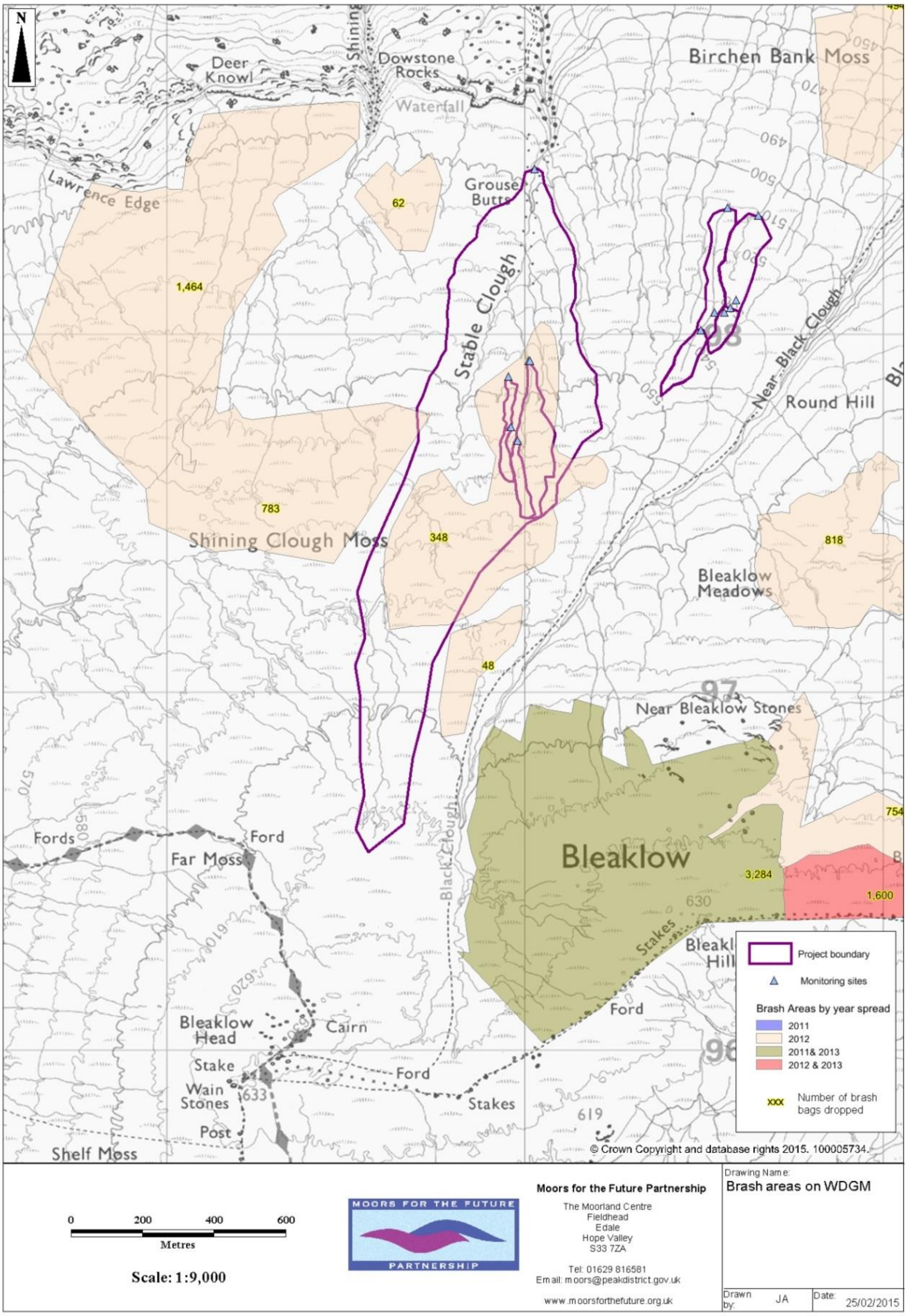


Figure 9 Areas where heather brash was applied, identified by year of treatment.

2. Sediment accumulation behind stone dams

Sediment surveys were undertaken at proposed gully block locations in System 1, and of proposed and actual gully blocks within System 2 to provide information as to the success of gully blocks, the rate and amount of sediment accumulation behind dams and to assess the degree to which vegetation established on deposited peat.

2.1. Methods

Three sediment surveys were undertaken over the course of the project (Table 4). The August 2012 surveys were part of a ground-truthing survey undertaken while scoping the scale of the capital works. During the ground-truthing surveys, sediment depth was only measured up to 100cm, anything deeper than this was recorded as >100cm. These data points had to be excluded from the analysis and so sediment depths are likely to be underestimates.

Table 4 - Sedimentation surveys and the number of measurements taken on Woodhead.

	BEFORE GULLY BLOCKING	INITIAL RESPONSE	LONG-TERM RESPONSE
Date of survey	Aug 2012	Nov 2012	Feb-Mar 2014
Control system	27	-	27
Treated system	66	68	68

The first survey in November 2012 took place within one month of the installation of stone dams and was considered to be a measure of the *initial response* to gully blocking. The second repeated survey in February 2014 took place between 15 and 17 months following installation and is regarded as a short-term response to gully blocking.

Typically, when blocks are installed pools of water form upstream. Depending on the spacing of dams, these pools can form and extend up to the base of the upstream gully block. Therefore, variables and photos were collected both upstream and downstream of each gully block. Variables recorded are described in Table 5.

Table 5 - variables collected during gully block survey

Variable	Definition
Water depth	Measured with the aid of a secchi plate – 1 metre upstream (Figure 1, 3) and downstream from centre of dam.
Gully block height upstream	Distance between top of dam and sediment surface, measured 1 metre upstream and downstream (2, 3, 1: Figure 1) from centre of dam.
Sediment depth (includes original peat and re-deposited sediment)	Distance between sediment surface and mineral gully floor, measured 1 metre upstream and downstream of centre of dam (4, 5: Figure 1).
Gully block width	Gully width measured at both base and top of dam.
Distance between dams	Measured from centre of each dam.
Gully floor substrate	Categorised for each block both upstream and downstream of the block as either sediment, mineral or mixed

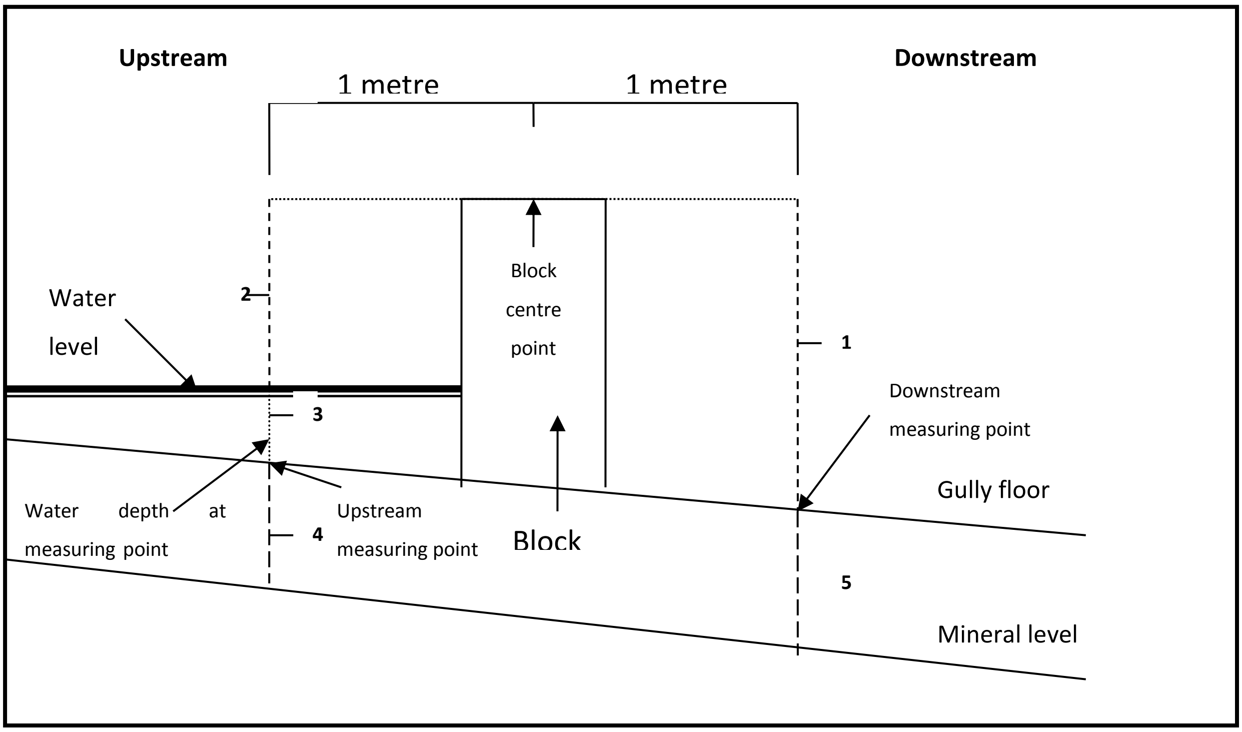


Figure 10- gully block survey measurements

2.2. Results

2.2.1. Success rate of gully blocks

A year and a half after installation 100% of dams were holding water and 82% were holding accumulated sediment to an average 34 cm of the tops of gully dams. None of the dams in System 2 showed signs of vegetation establishment in the vicinity, beyond what intact vegetation were already present (Figure 11).

Figure 11 – Photograph of a gully block at System 2 taken at time of surveys two weeks after gully block installation in November 2012 (a); and fifteen months after gully blocking in February 2014 (b).

2.2.2. Changes in peat depth behind dams

Table 6 - summary data for sediment accumulation behind dams on Woodhead in the control (S1) and treatment gullies (S2).

	Before		Initial response		Long-term	
	Control (S1)	Treatment (S2)	Control (S1)	Treatment (S2)	Control (S1)	Treatment (S2)
Date of Survey	August 2012		November 2012		February/March 2014	
No. measurements	27	66	-	68	27	68
Height of sediment (cm)						
Mean	32	33	-	47	34	50
Range	80	80	-	104	96	120
Standard deviation	24.5	26.5	-	25.6	24.5	25.7

In the treated system there was a significant increase, 14 cm, in peat depth behind dams in the initial response - just three weeks compared with baseline peat depths in this gully (Table 6; paired t-test: $t = -6.866$, $df = 49$, $p < 0.001$). Levels of accumulation and year and a half later were not significantly different, only increasing 3 cm (paired t-test: t = 0.286, df = 66, p > 0.05.)

The control system showed no significant change in sediment depth during the same period (paired t-test: t = -0.946, df = 19, p > 0.05), with sediment heights the same (+2cm) as recorded in the baseline survey.

2.3. Discussion

Results from the Woodhead Gully Block Monitoring project however do show significant changes in sediment depth behind stone dams. Here, sediment depth was found to increase 14cm relative to an unblocked control. In addition, measurements taken before and after gully block installation in 2012 also supported this, with the majority of sediment accumulation occurring within 3 weeks of installation, with no significant change observed following this (as measured 17 months after installation).

17 months following installation, the mean height of the dams above the sediment surface was 34cm, with a range of 10cm to 65cm. This indicates that at the time of the survey dams had not yet reached their full capacity. Dams have not yet fully 'matured' and have capacity to further accumulate sediment. The supply of sediment is likely to be lower than on other sites such as Kinder Scout, therefore it would be expected for dams on Woodhead to take longer to accumulate sediment to the top of dams. Repeat surveys would enable any further change in sediment accumulation to be quantified.

None of the dams within System 2 showed signs of vegetation establishment. This is not an unexpected observation given that this gully has not been treated with lime, seed or fertiliser, which would rapidly stabilise peat and contribute towards consolidation of sediment behind dams. Studying peat accumulation behind the dams within System 2 helps inform the storm flow responses within these systems, and this is discussed further in Section Four.

Most of the dams installed on Woodhead were associated with areas of peat stabilisation, and so the dams monitored here are not typical of the wider MoorLIFE project. Additional surveys of dams installed within the Stable Clough catchment, and specifically within the areas treated with lime, seed and fertiliser would be useful to monitor vegetation establishment in areas receiving full treatments. Additional surveys would also better inform the changes observed in flow within the Stable Clough catchments.

3. Vegetation

3.1. Methods

In late 2010 / early 2011 fixed 2 x 2m vegetation quadrats were established on Woodhead as part of the EU-funded MoorLIFE project. Repeat visits were made to each quadrat in summer 2011, 2013 and 2014. A bare peat reference site on Bleaklow was also monitored.

Data collected from fixed quadrats included:

- Percentage cover of bare peat
- Percentage cover of standing water
- Percentage cover of main vegetation types: grasses, sedges and rushes; nurse crop species; dwarf shrub; herbaceous species; invasive species; tree and shrub species; mosses and lichens. These are broken down further into plant species wherever possible.
- The average heights of dwarf shrub, moorland graminoids and nurse crop.
- Presence of grouse, hare or sheep droppings
- Heather condition
- Signs of grazing

Fixed point photos were taken of each quadrat at each monitoring visit.

The surveys were designed to enable assessment of habitat condition against the Common Standards Monitoring (CSM) targets used by Natural England and the Joint Council Conservation Committee (JNCC, 2009) for Sites of Special Scientific Interest (SSSI).

The data was also entered into a computer programme, MAVIS (freely available from the Centre for Ecology and Hydrology), to enable a number of other classifications to be calculated. These included:

- National Vegetation Classification

- Countryside Vegetation System classification
- Ellenberg scores for light, pH, wetness and fertility

National Vegetation Classification communities were assigned to each monitoring area as a way of monitoring progress towards typical blanket bog communities. The Countryside Vegetation System classification contains 100 vegetation classes. More information about the classes can be found in Bunce *et al* (1999). These methods of classification provide a way of describing the plant communities present and monitoring changes in plant assemblages, rather than simple changes in individual species or species groups.

To help understand how the sites on Woodhead compare to other sites of a similar ‘age’, and how the vegetation on this site might be expected to continue to develop after capital works have been completed, Woodhead data were compared against data from sites that have undergone similar peat stabilisation works. Moors for the Future Partnership has collected such data for 12 years. Data collected from 2007 onwards were included in this analysis, (this being the year that 2 x 2 m quadrats were installed on many of MFFP’s Bleaklow and Black Hill sites). Vegetation data collected from United Utilities’ Sustainable Catchment Monitoring Programme (SCaMP) was also collated.

The data was combined by establishing a common ‘starting’ point. In this case, the year of seeding was taken to be ‘year zero’ for that site, and data following this was given a year post-seeding. In this way, data spanning an eleven year period was plotted alongside data from Woodhead to provide an indication of how this site compared with other monitored sites and to provide some insight into what changes might be expected in the short- to medium-term. The degree of change between ‘before’ and ‘after’ works periods were also calculated to take into account different starting points of the sites.

3.2. Results

By 2014, the majority of the sites monitored on Woodhead had been seeded in the previous year (July 2013), with a very small number of sites seeded 2 years previously. The data from 2014 is reported here to provide an overview of the diversity and condition of the treated bare peat areas on Woodhead at the end of the MoorLIFE project.

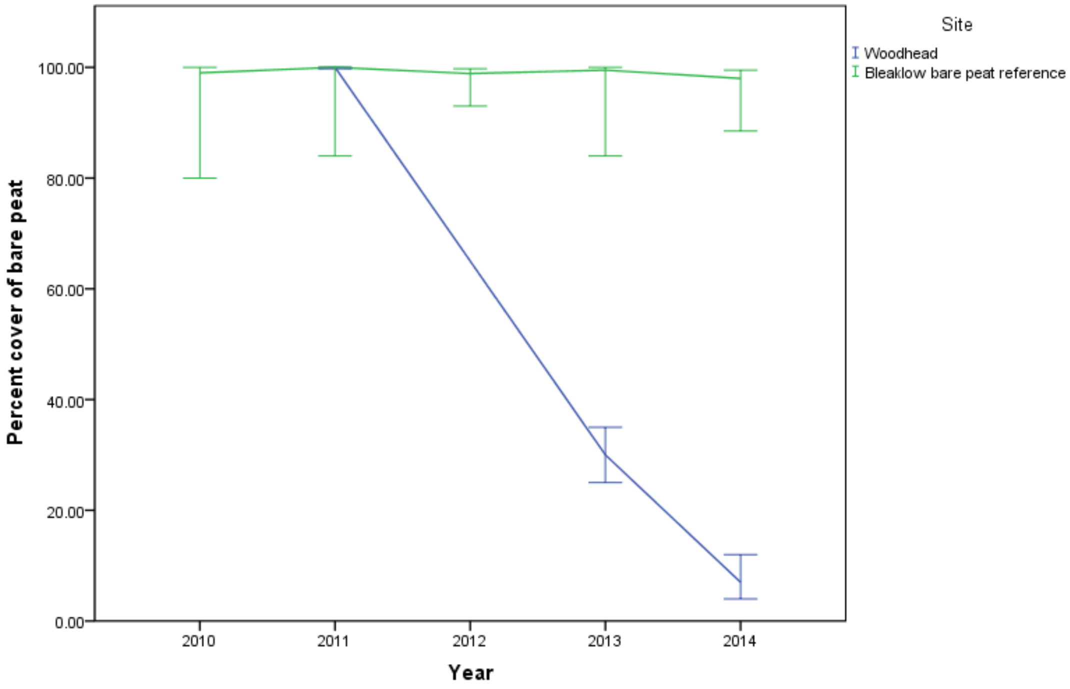
3.2.1. Changes in bare peat and total vegetation cover

Between 2011 and 2014, bare peat cover decreased by 93%, with a corresponding increase in vegetation cover of 104% (Table 7; Figure 3). In contrast, bare peat cover on an untreated, bare peat reference site, remained high and showed no significant change over the course of the project (2011: 100%, 2014: 98%). Significant increases in cover were seen in all plant groups on Woodhead.

Table 7 - percent cover on treated bare peat sites on Woodhead before treatment (2011) and in 2014.

Cover type	**Median percent cover**		**Significance**
	2011 Pre-works	**2014**	
Bare peat	100	7	U = 146.5, $p < 0.001$***
Total vegetation	<1	104	U = 0.0, $p < 0.001$***
Dwarf shrub	0	1	U = 482.5, $p < 0.001$***
Moorland herb species	0	0	U = 1584.0, $p < 0.001$***
Grasses, sedges, rushes	0	3	U = 262.5, $p < 0.001$***
Nurse crop	0	77	U = 0.0, $p < 0.001$***
Mosses, lichens and fungi	0	14	U = 35.0, $p < 0.001$***

a)



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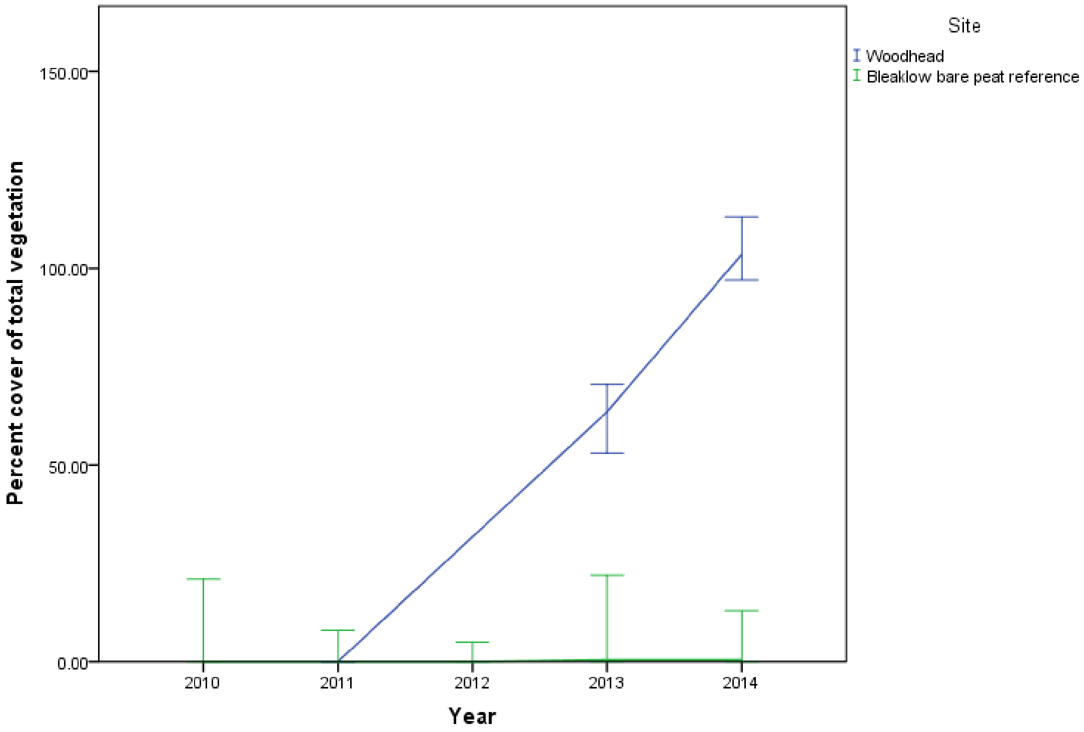

Figure 12 - bare peat cover change on Woodhead

3.2.2. Nurse crop cover

Nurse crop grasses were the dominant vegetation within quadrats on Woodhead, making up 77% of quadrat area. Nurse crop grasses were present in all quadrats on Woodhead.

3.2.3. Dwarf shrub cover

Dwarf shrub cover increased significantly over the monitoring period and comprised mostly of common heather. In 2014, heather was present in 77% of quadrats (Figure 13) and over two thirds of quadrats had multiple heather plants. Other dwarf shrub species that were present within quadrats were bilberry (9% of quadrats) and crowberry (5% of quadrats).

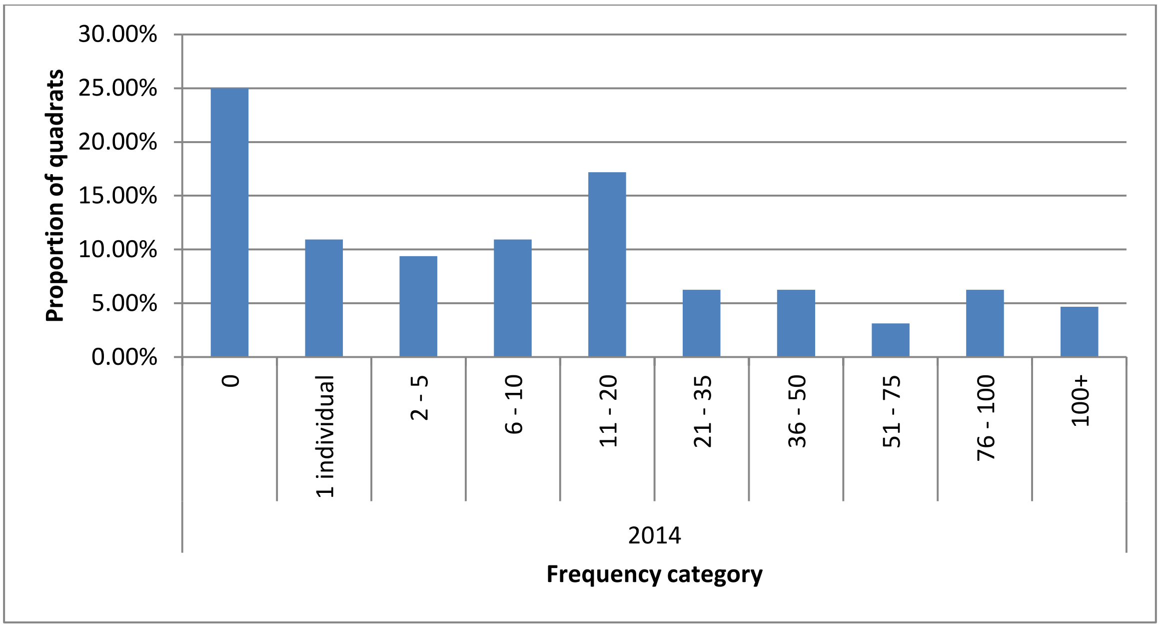

Figure 13 – Frequency of common heather in 2014.

3.2.4. Moorland herb species

Moorland herb species cover in quadrats remained low in 2014. The increase in herb species was predominantly due to heath bedstraw, which was present in 25% of quadrats. Cloudberry was not present within any quadrats on Woodhead in 2014.

3.2.5. Grasses, sedges and rushes

Within this group of plants wavy hair-grass (*Deschampsia flexuosa*), was the most common species with a median cover of 2% and was present in 83% of quadrats. Other species of grass were present but their contribution to quadrat cover was minimal. Common cottongrass and hare's-tail cottongrass were present in 38% and 32% of quadrats on Woodhead, but had a low median percent cover of less than 1%.

3.2.6. Moss, lichens and fungi cover

This group of species was dominated by mosses, with feather mosses accounting for a median of 4% cover and cushion mosses 2%. No *Sphagnum* moss was present within quadrats.

3.3. Analysis of data against Common Standards Monitoring targets

3.3.1. Frequency of indicator species

One of the targets for upland blanket bog habitats is that at least six positive indicator species should be present on a site.

All quadrats on Woodhead gained blanket bog indicator species, with 92% of quadrats containing at least two in 2014 (Figure 14). Nearly a third of quadrats contained at least four indicator species. The most commonly occurring indicator species were feather mosses, common heather, common cottongrass, lichens and hare's-tail cottongrass.

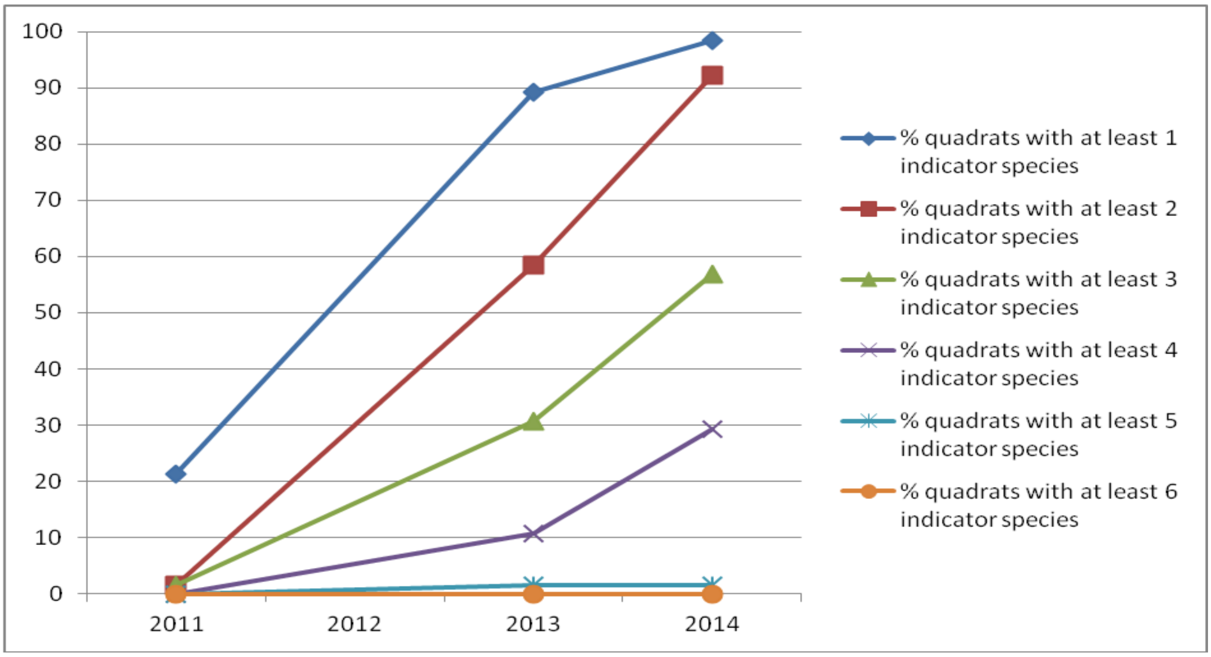

Figure 14 - proportion of quadrats containing indicator species.

3.3.2. Vegetation composition – cover of indicator species

The CSM target relating to vegetation composition states that at least 50% of vegetation should consist of at least three positive indicator species. In 2014, 8% of quadrats on Woodhead had at least three indicator species contributing to 50% or more of total vegetation cover. Indicator species increased following initial works between 2011 and 2013. By 2014 indicator species contributed, on average, 19% of cover in re-vegetated areas of Woodhead (Figure 15 - proportion of cover types and indicator species on Woodhead compared with the intact reference site on Bleaklow.), with non-indicator species covering 67%.

The targets also state that Sphagnum cover should not only consist of *Sphagnum fallax*. No *Sphagnum* mosses were found to be present in any treatment quadrats. In addition, hare's-tail cottongrass and Ericaceous species (i.e. dwarf shrub species) collectively should not exceed 75% of the vegetation cover. The percent cover of these species was low on Woodhead.

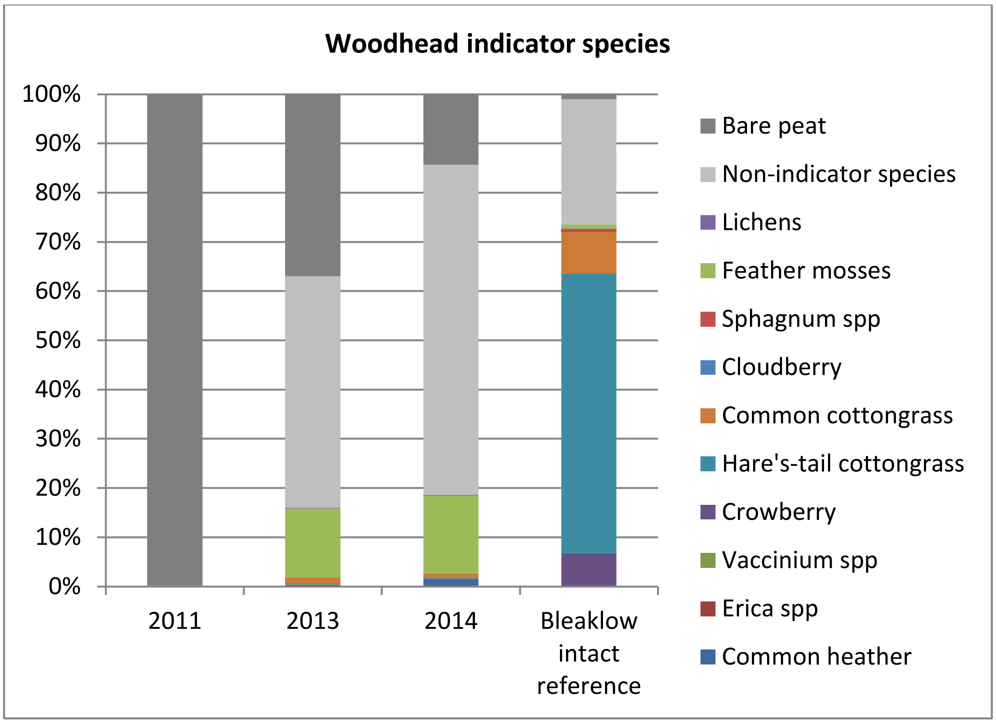

Figure 15 - proportion of cover types and indicator species on Woodhead compared with the intact reference site on Bleaklow.

3.3.3. Vegetation composition – cover of other species

CSM guidelines also state that:

1) Less than 1% of vegetation cover should be made up of non-native species
2) Less than 10% of vegetation cover should be made up of scattered native trees and scrub.

3) Less than 1% of vegetation cover should consist of, collectively, common bent grass (*Agrostis capillaris*), Yorkshire fog (*Holcus lanatus*), common reed (*Phragmites australis*), bracken (*Pteridium aquilinum*), creeping buttercup (*Ranunculus repens*).

The only non-native species that was found on Woodhead was Rhododendron. A single plant was found within one quadrat and accounted for less than 1% of the total surveyed area. Small tree seedlings occupied less than 1% of the area of the quadrats on Woodhead. They occurred frequently, and were present in 25% of quadrats on Woodhead.

Agrostis species were counted as sown nurse crop species, and were not identified down to species level. *Agrostis* species accounted for a high proportion of ground cover 58% at Woodhead.

Yorkshire fog was occasionally present in quadrats, but the average cover was under 1%. Neither common reed, bracken nor creeping buttercup were identified within quadrats in 2014.

3.3.4. Countryside Vegetation System (CVS)

Classification of individual quadrats into CVS categories indicated a range of vegetation classes were present on the treatment sites in 2014. Woodhead had a wide range of habitat classifications, predominantly of grassland types, with occasional heath and blanket bog (Figure 16).

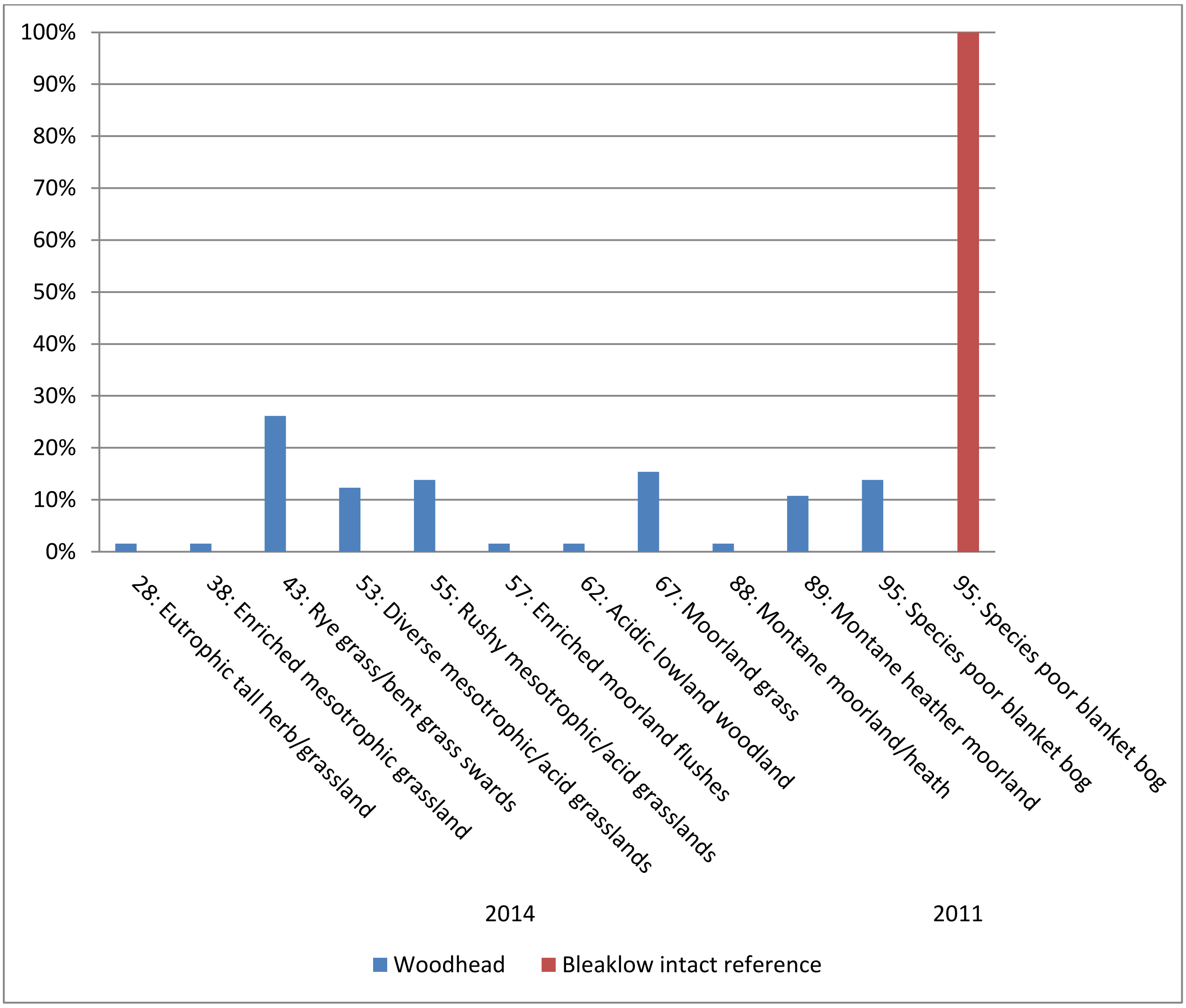

Figure 16 - Countryside Vegetation System categories identified on Woodhead in 2014.

3.3.5. National Vegetation Classifications

Quadrats from each site were sorted into groups and NVC classifications using the Centre for Ecology and Hydrology's software – MAVIS. Woodhead treatment areas were most strongly associated with U2 *Deschampsia flexuosa* grassland and H9 *Calluna vulgaris-Deschampsia flexuosa* heath habitats.

3.4. Comparison with other revegetated sites

Results from Woodhead were plotted alongside data collated from other MFFP and SCaMP sites for the main species groups (Table 8). Those sites from SCaMP that were treated with a similar treatment regime to Kinder Catchment sites were selected and all sites are within the South Pennines SAC. However, SCaMP treatments were focused on bare peat gullies, and care should be taken in interpreting a range of data collected different topographical settings.

Table 8 - description of sites examined for patterns of vegetation change.

SITES	**Description**
MFFP:	
Black Hill	A 46 ha site treated with brash, lime, seed and fertiliser in 2006.
Kinder CRF	Areas of Kinder Scout within the Alport catchment that were treated with brash, lime, seed and fertiliser in 2013 as part of the MFFP/National Trust Catchment Restoration Fund.
Joseph Patch	Bleaklow: Re-vegetated in 2003
Shining Clough	Bleaklow: Re-vegetated in 2003
Shelf Moss	Bleaklow: Re-vegetated in 2004
Sykes Moor	Bleaklow: Re-vegetated in 2004
The Edge	Data collected from two small micro-catchments on the north Edge of Kinder as part of the Making Space for Water project. Brash, and initial lime, seed and fertiliser treatments were undertaken in 2011.
SCAMP:	
Ashway Gap: BB1	Bare peat gullies treated with lime, nurse crop seed/heather seed and fertiliser added (autumn 2007)
Arnfield Moor: BB5	Bare peat gullies with lime, seed and fertiliser added (autumn 2007)
Quiet Shepherd: BB6a	Bare peat gullies with lime, seed and fertiliser with brash added (autumn 2007)
Quiet Shepherd: BB6b	Bare peat gullies with lime, seed and fertiliser plus brash and Geojute applied (autumn 2007)

3.4.1. Bare peat

Following seeding, all sites demonstrate an immediate decrease in bare peat which continues for between four and five years (Figure 17). After five years the proportion of bare peat appears to level off for all sites and remains low and stable, with no signs of a reduction in the 11 year period that has been monitored. The sites vary in the degree to which bare peat is reduced, but common patterns appear to be present.

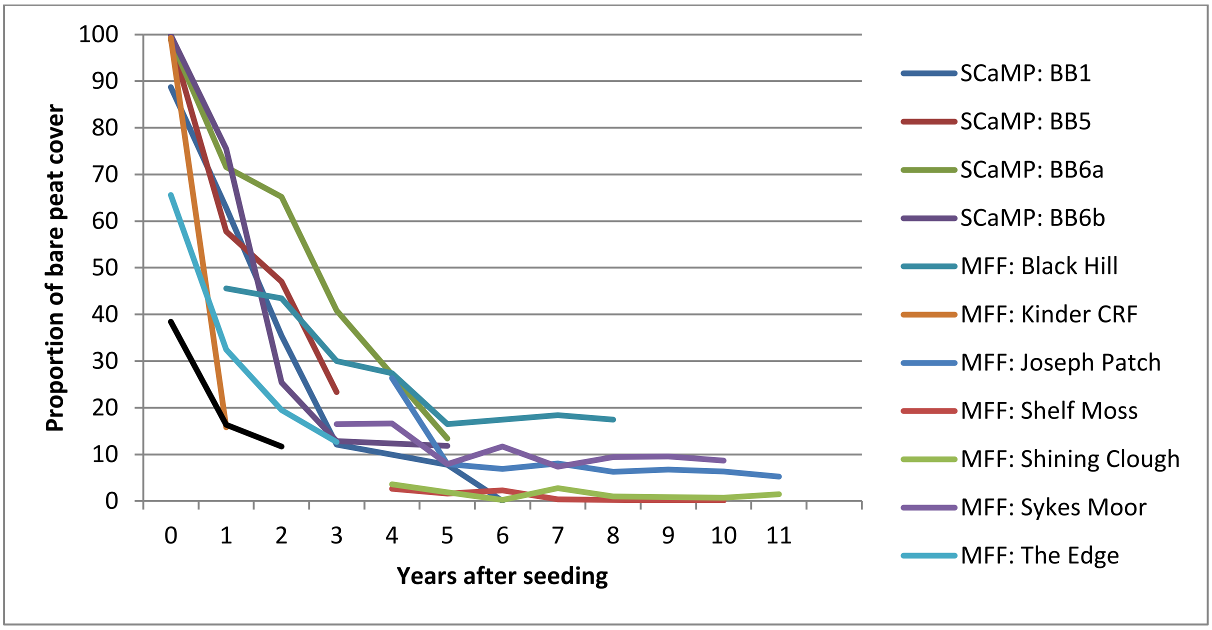

Figure 17 - Changes in bare peat across multiple revegetated bare peat sites over 11 years of monitoring

3.4.2. Total vegetation cover

Following seeding, total vegetation continues to increase at all sites, even after the end of maintenance treatments (Figure 18 - Changes in total vegetation cover across multiple revegetated sites over 11 years of monitoring.). In comparison to other sites, Woodhead has a high level of vegetation cover.

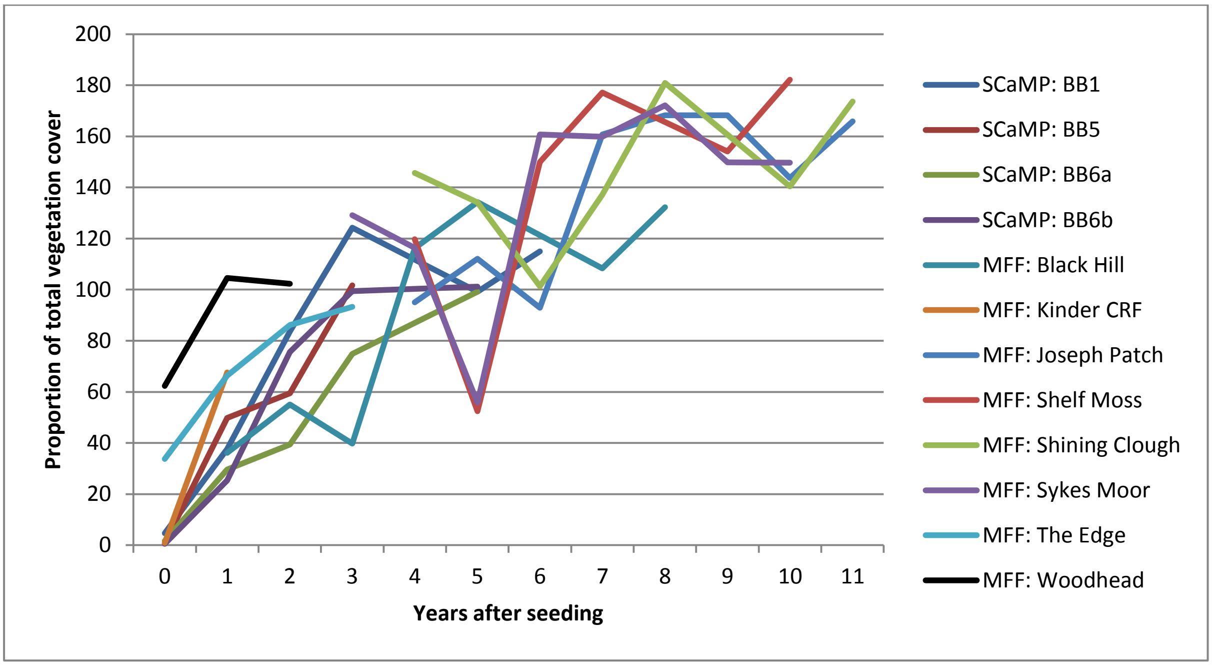

Figure 18 - Changes in total vegetation cover across multiple revegetated sites over 11 years of monitoring.

3.4.3. Nurse crop

Cover of nurse crop grasses usually peaked between years one and two following seeding (Figure 19). Three years after seeding nurse crop cover is in decline. From around year five onwards nurse crop cover appears to vary considerably at each site and fluctuates for a number of years.

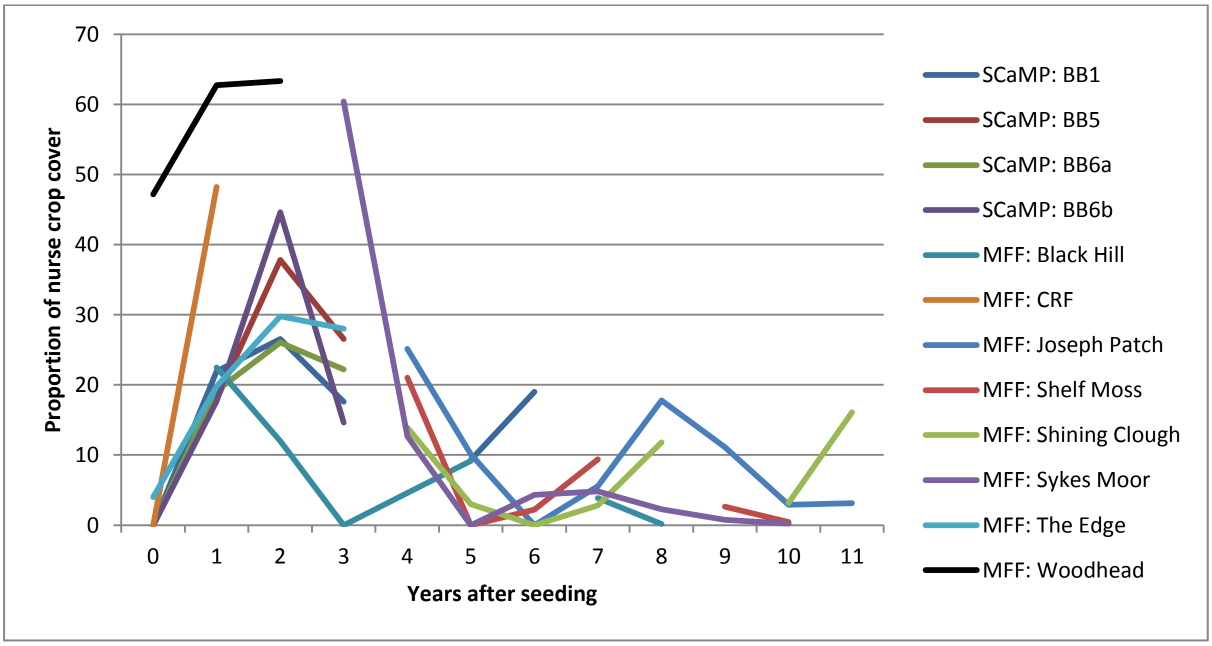

Figure 19 - Changes in nurse crop cover across multiple revegetated sites over 11 years of monitoring.

3.4.4. Total dwarf shrub

Dwarf shrub cover increases steadily over a ten year period (Figure 20). While some sites appear to be sustaining a stable level of dwarf shrub cover (e.g. Shining Clough), most sites seem to have increasing proportion of dwarf shrub species.

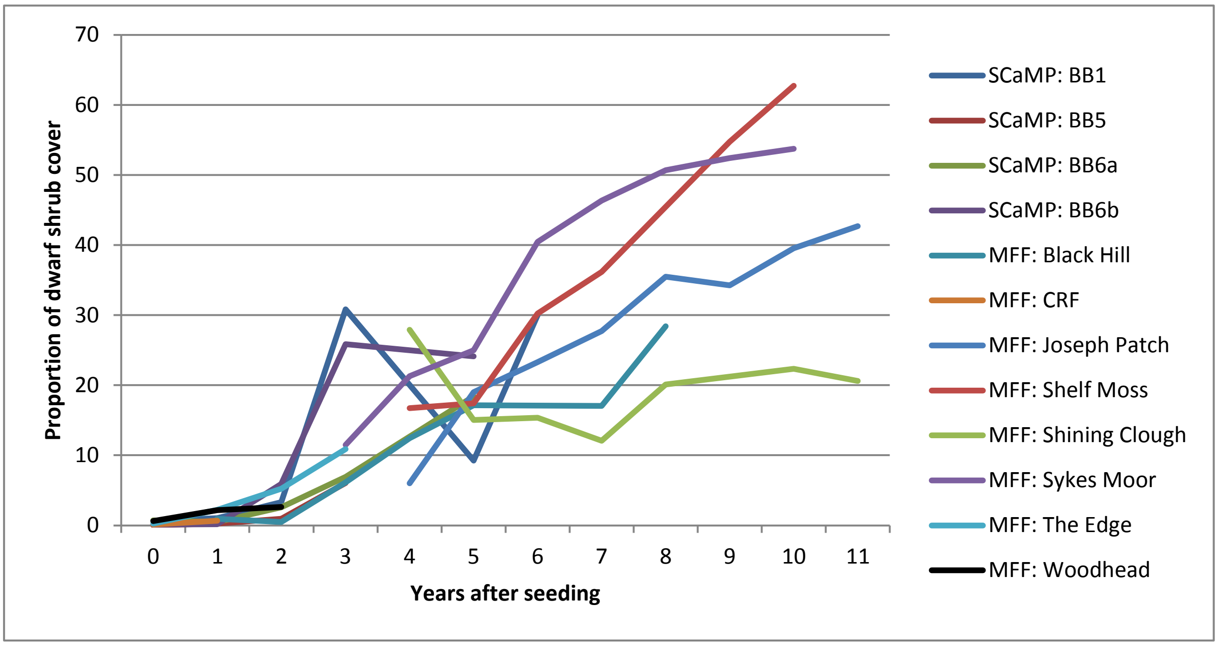

Figure 20- changes in dwarf shrub cover across multiple revegetated sites over 11 years.

3.5. Discussion

3.5.1. Stabilisation of bare peat

The stabilisation work undertaken on Woodhead has been highly successful, resulting in a reduction of bare peat cover of, on average, 93%. Monitoring of a bare peat control site on Bleaklow has clearly demonstrated that had such works not been undertaken, the extensive areas of bare peat would still persist.

Nurse crop species have successfully and rapidly established and currently dominate vegetation cover on Woodhead. This is a desirable result at such an early stage of re-vegetation of such highly degraded peatlands. The purpose of the nurse crop is to protect the fragile surface of the bare peat against erosional processes such as freeze/thaw, rain and wind. In stabilizing the peat surface, more typical moorland species have a higher chance of colonizing these areas.

3.5.2. Moorland plant assemblage

One year following seeding of bare peat areas, it is still very early in the revegetation process to expect treatment sites to be meeting targets set by CSM guidelines. Treatment areas are currently dominated by non-indicator species – mainly nurse crop grasses – which is be entirely expected as part of the peat stabilisation process.

Nevertheless, the targets provide a useful way of tracking and interpreting the changes in habitat condition, the plant communities present and the blanket bog indicator species. The number of CSM indicator species present on treated sites on Woodhead have increased, suggesting that the habitat is beginning to develop more typical blanket bog habitats. The proportion of these indicator species are also of importance, and it will be important for these species to continue to colonise, grow, and develop for other targets to be met. The surveys undertaken at this early stage has established a baseline for the site against which presence and proportion of indicator species can now be monitored in future.

Despite the level of disturbance on the treatment areas through lime and fertiliser applications, the presence of tree seedlings and ruderal species indicative of disturbance are very low and currently of low concern. The presence of cushion mosses is also still low, if a little higher than the cover of feather mosses.

Assessment of SSSI units against Common Standards Monitoring targets should be undertaken as a broad overview, not simply on data from quadrats. Therefore the data here should not be taken as an assessment of condition, simply as a comparison to a useful set of indicators with which to monitor progress of a developing stand of vegetation.

3.5.3. Habitats present on revegetated sites

Assessment of revegetated areas of Woodhead according to NVC techniques suggest that in 2014, one year after seeding, the site is dominated by grassland habitats such as *Deschampsia flexuosa* grassland and *Calluna vulgaris-Deschampsia flexuosa heath* habitats.

Again, this is not surprising given the sown nurse crop. The CVS classification of individual quadrats again suggests that many quadrats are grassland type communities. But a small proportion of quadrats (<10%) were classified as species poor blanket bog. This is an encouraging sign that some quadrats have already develop more typical moorland plant communities.

Mapping of the occurrence of these habitats could give some insight as to whether there are spatial patterns in the distribution. In addition, further work to classify older revegetated areas could help to determine if a particular sequence of transitional plant communities can be observed, and what timescales these plant communities will develop.

3.5.4. Performance of Woodhead against other monitored sites

Woodhead showed greater success in terms of reduction in bare peat cover and increase in total vegetation and nurse crop cover. Patterns of vegetation change observed from other sites suggest that it is reasonable to expect the extent of bare peat to decrease a little more, total vegetation to continue to increase, and nurse crop to begin to fall – most likely following the final lime and fertiliser applications. Dwarf shrub percent cover appears to be in line with other sites. Currently the percent cover of dwarf shrub is low, but composed of many small plants across the majority of quadrats and very likely to continue to increase for several more years.

4. Water tables

4.1. Introduction

Erosion gullies have been shown to lower, or drawdown, of the water table in eroded peatlands. There are two effects of water table drawdown described by Allott *et al.* (2009):

1. Local water table drawdown adjacent to gullies. This occurs within 2m of the gully edge. Within this drawdown zone water tables are approximately 200mm lower than in the adjacent peatland.
2. General water table drawdown in the wider peatland landscape. Median water table depths at heavily eroded sites are up to 300mm lower than intact sites.

Water table monitoring on Woodhead investigated two individual treatments for their effects on water table:

Impact of stone gully dams - This work was part of the original Woodhead gully block monitoring project. Gully blocking has the potential to raise water table adjacent to gullies through the creation of pools and/or sediment. Such effects have been demonstrated in grip blocking studies, but studies of water table following gully blocking are limited. Monitoring of the Biffa-funded Peatlands for the Future project (Maskill *et al*, 2012) found an impact of a log dam on local water tables - the strongest effect being detected within 1 metre upstream of dams.

Re-vegetation of bare peat - This study was part of the MoorLIFE project monitoring programme. Re-vegetation has the potential to lead to a rise in water table, with a likely mechanism being the alteration to evapotranspiration rates. Loss of water through evapotransipiration from re-vegetated areas is likely to be lower on re-vegetated sites than from bare peat. Allott *et al* (2009) demonstrated evidence that re-vegetated sites had mean water tables 80 mm higher than topographically comparable bare peat sites.

4.2. Methods

4.2.1. Impact of gully blocking on water table

Four automated dipwells were installed adjacent to the two Smithy Clough gullies prior to gully blocking work. Two dipwells were associated with the untreated System 1 (S1a and S1b), and two were associated with System 2 (S2a and S2b). The System 2 dipwells were installed at points deemed suitable for gully blocking, with the intention that dams would be installed within one metre downstream of the dipwell. All four were installed within two metres of the gully edge: an area heavily influenced by water table drawdown (Allott *et al* 2009).

Data collection began on 27th September 2012, providing approximately one month of pre-blocking data. The post-works data collection period was fragmented due to theft of three of the dipwells. These were replaced as soon as possible. Comparisons between dipwells have been made using data collected simultaneously.

4.2.2. Impact of re-vegetation on water table

Water tables were monitored using clusters of automated and manual dipwells, using a methodology developed by Allott *et al* (2009). Automated dipwells were installed at five monitoring locations prior to revegetation works: three bare peat areas scheduled to be treated, a hydrologically intact area, and a bare peat control site. Automated dipwells were programmed to measure water level every hour and were used to provide information about the temporal behaviour of water tables.

Within a 30 x 30m area around each automated dipwell, a cluster of 15 manual dipwells were installed. Manual dipwells were measured in annual campaigns of approximately 12 weekly measurements in autumn/winter (Table 9). Data collected from manual dipwells were used to provide information on the spatial variability of water table.

Table 9- Sites and treatment types with manual dipwell campaign dates

Site	Treatment type	Campaign dates	Number of measurement days
SB	Treatment	15/09/2011 – 01/12/2014	12 / 12
DN	Treatment		12 / 11
LO	Treatment		12 / 12
RI	Treatment		12 / 12
TA	Bare peat reference		12 / 12
TC	Bare peat reference		12 / 12
PE	Intact reference	18/09/2014 – 04/12/2014	12 / 12
SH	Intact reference		12 / 12

4.3. Results

4.3.1. Impact of gully blocking on water table

The four dipwells showed variable patterns of behaviour (Figure 21), with two occupying similar parts of the peat profile, and two others behaving very differently. S1a and S2b were most closely matched in their behaviour prior to gully blocking. The responses to rainfall were similar, but S1a showed a lower range than that of S2b.

The water table at S1b was typically within the top 20cm of peat and was relatively stable. At S2a water table was extremely low and lacked any of the event response shown by the other thee dipwells. In addition, a greater amount of data was lost from this location due to the theft of the dipwell. Dipwells S1b and S2a were not considered further in this report.

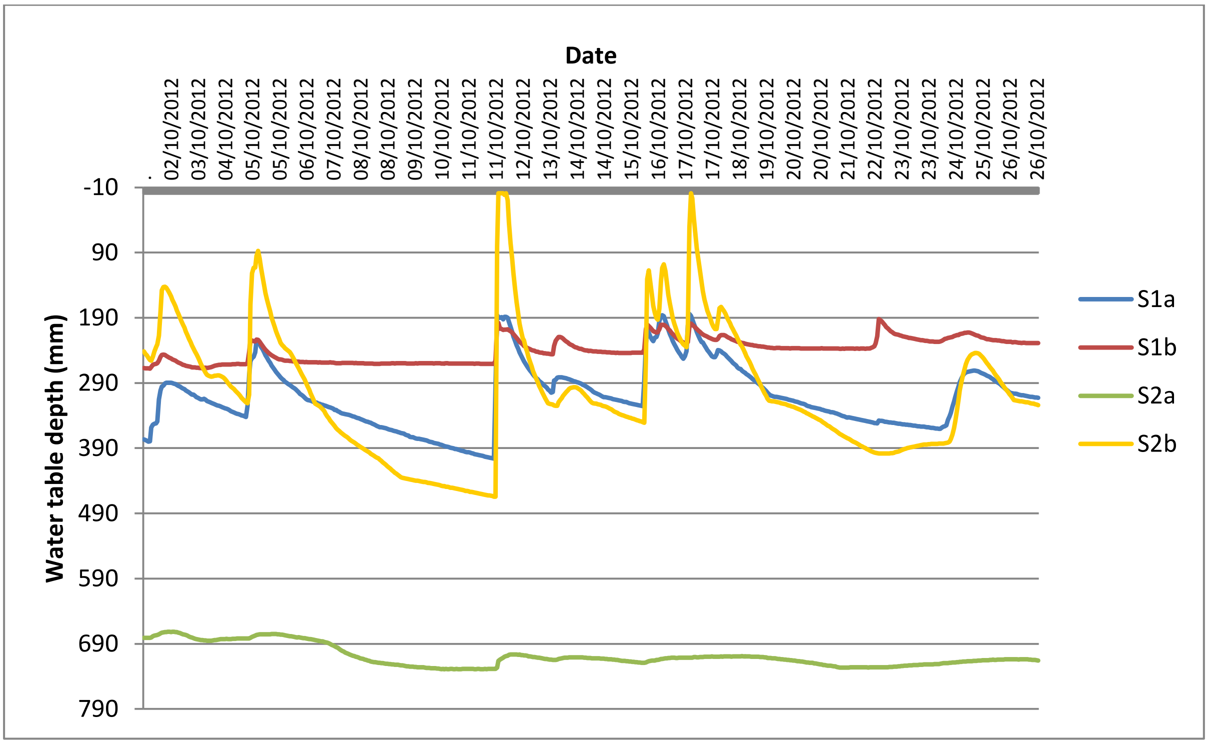

Figure 21 - water table time series before gully blocking

The water tables before and after gully blocking at S1a (control) and S2b (treated) were compared using cumulative frequency curves (Figure 22) with the two locations behaving in very similar ways. The period after gully blocking appears to be characterised by drier conditions, as the control dipwell shows the water table occupying a greater range of depths and occupying deeper depths for a greater proportion of the time.

The treatment dipwell continues to match the behaviour of the control dipwell, indicating that climatic conditions have a greater impact on water table behaviour than the gully blocking treatment.

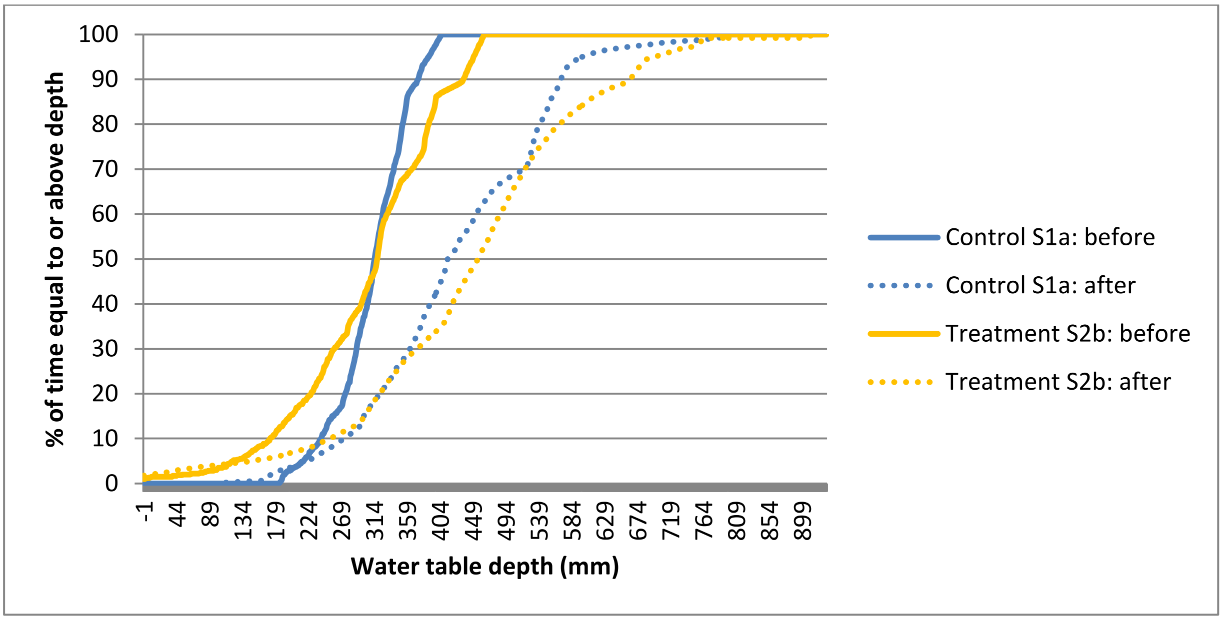

Figure 22 - cumulative frequency graph comparing S1a and S2b before and after gully blocking.

4.3.2. Impact of revegetation on water table

Due to the high degree of variation within dipwell clusters, water table values are based on the mean depth of water measured at each dipwell cluster. Each cluster showed a normal distribution. There was also variation between dipwell clusters within sites.

Individual clusters showed considerable variation on Bleaklow (Figure 23 - distribution of water tables at Bleaklow. LS = late-stage revegetated site.). Water tables at treatment and bare peat control exhibited approximately similar and overlapping ranges.

Variations between sites are likely to be because of several factors, such as topography, hydrological contributing area, slope etc which have an impact on the hydrology of blanket bog. Studying the impacts of these factors on water table depth is beyond the scope of the MoorLIFE project analysis. Therefore, analysis is undertaken on status rather than individual dipwell clusters.

a)

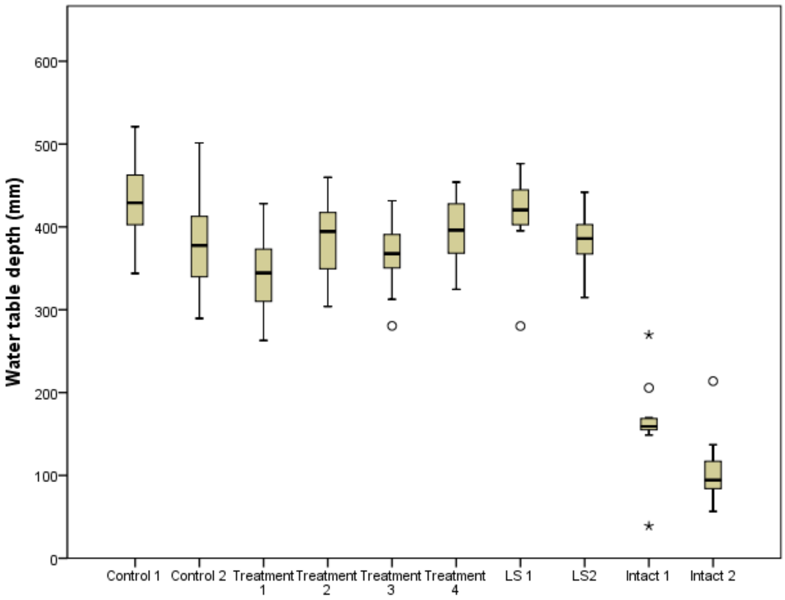

Figure 23 - distribution of water tables at Bleaklow. LS = late-stage revegetated site.

4.3.2.1. Spatial variation in water tables

Significant differences existed between the vegetation scenarios (F = 223.465, df = 2, $p < 0.001$) in 2011.

Bare peat and late-stage re-vegetated sites exhibited the deepest mean water tables (Table 10; Figure 24 - Distribution of water table depths at bare peat, late-stage re-vegetated and intact sites on Bleaklow in 2011), with bare peat sites showing the deepest recorded water tables. Mean water tables on bare peat and late-stage re-vegetated sites were not significantly different ($p > 0.05$).

The shallowest water tables were measured at the intact site where water tables were always within 270mm of the peat surface. Mean water tables on intact blanket bog were significantly higher than both bare peat and late-stage re-vegetated sites ($p < 0.001$).

Table 10 – summary figures of intact, late-stage revegetated and bare peat sites in 2011

		Intact	**Late-stage re-vegetated**	**Bare peat**
2011	**Max**	270	476	521
	Mean	134	401	383
	Median	143	400	385
	Min	39	280	263
	Range	231	196	258

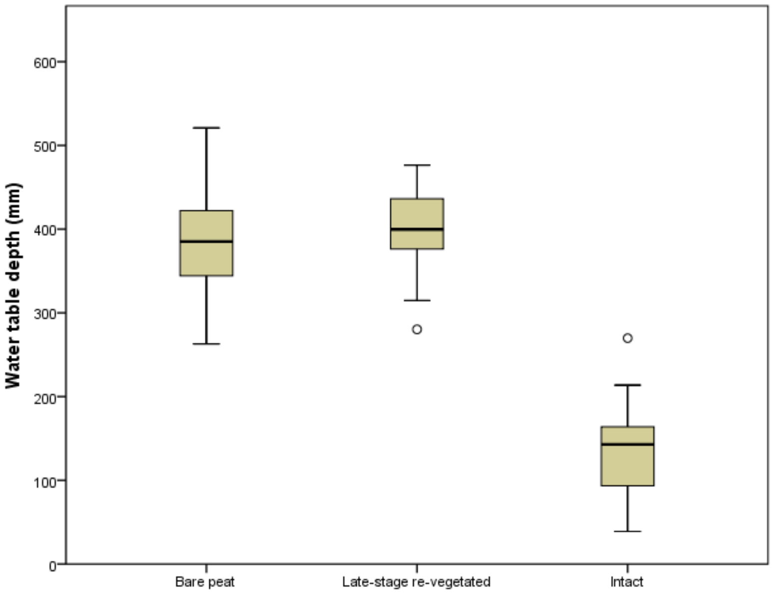

Figure 24 - Distribution of water table depths at bare peat, late-stage re-vegetated and intact sites on Bleaklow in 2011

4.3.2.2. Changes in water tables following re-vegetation

In this section the comparison is only between treatment and control scenarios.

In 2011, both treatment and control sites showed a similar range of water table (Figure 25 – Distribution of water table depths at treated and control sites in 2011 (before treatment) and 2014 (after treatment).); between 263 and 460 mm, and 289 and 521 mm at the treatment and control sites respectively (Table 11). However, sites due to be treated by the MoorLIFE project exhibited significantly higher water tables than the bare peat control sites (t = -2.632, $p < 0.05$) due to the fact that the control site water tables were consistently deeper on all measurement days (Figure 26).

Table 11 – summary figures for dipwell clusters monitored in 2011 and 2014

		Treatment	**Control**
2011	**Max**	460	521
	Mean	372	406
	Median	376	404
	Min	263	289
	Range	197	232
2014	**Max**	475	633
	Mean	345	402
	Median	346	390
	Min	242	261
	Range	234	372

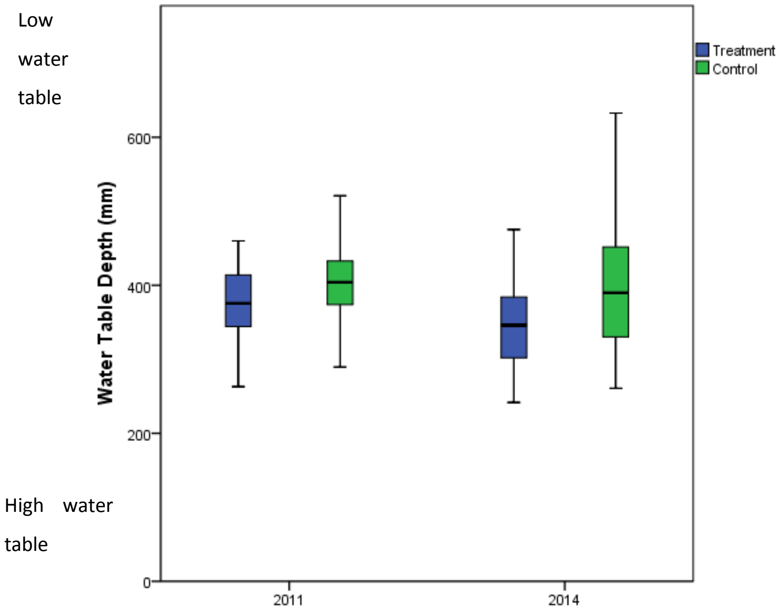

Figure 25 – Distribution of water table depths at treated and control sites in 2011 (before treatment) and 2014 (after treatment).

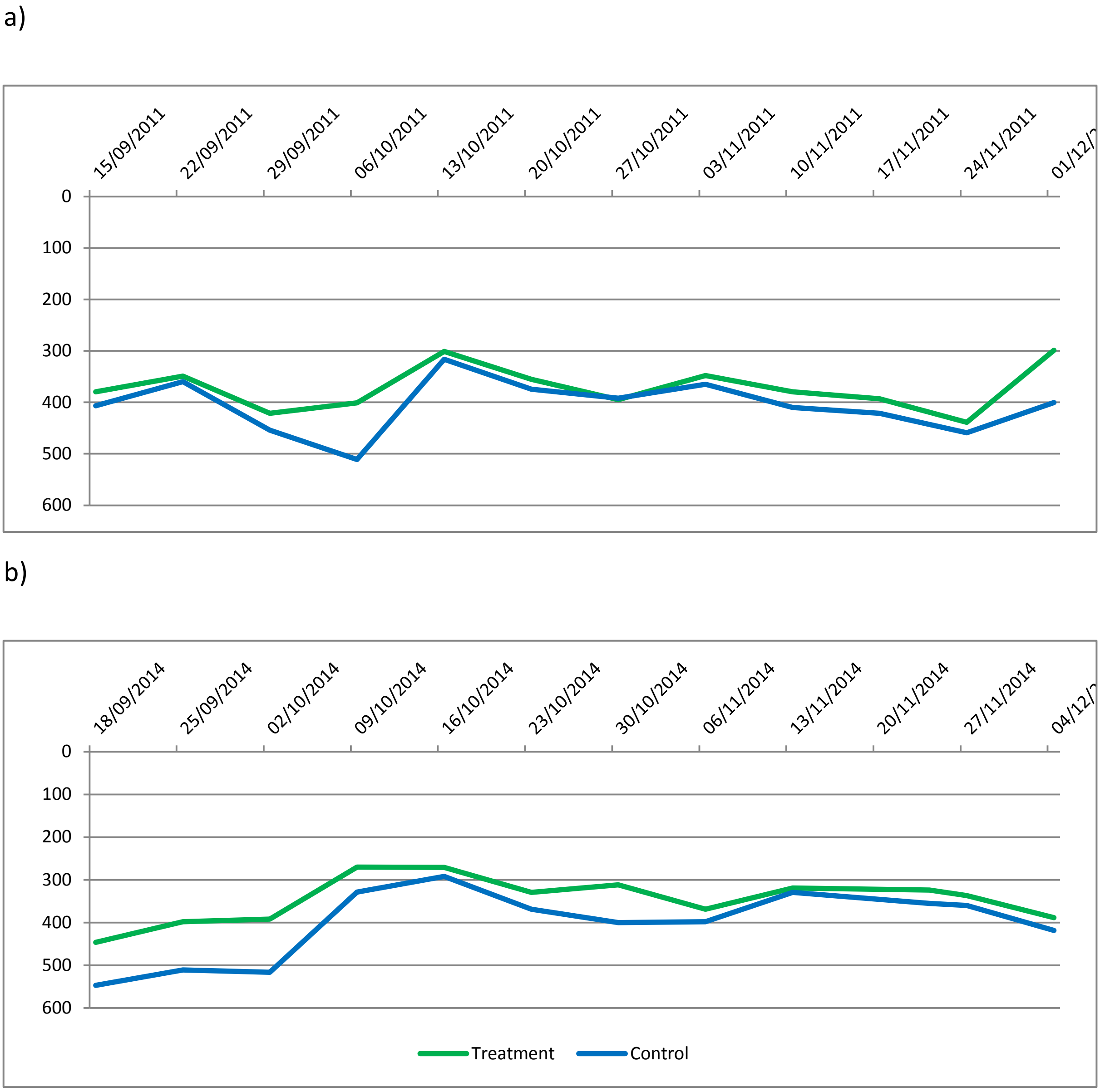

Figure 26 – time series of dipwell cluster measurements over the 2011 and 2014 monitoring campaigns

Initial examination of water tables in 2014 indicates that both sites were wetter than in 2011. The control site increased in variability, whereas treatment sites maintained a similar range. Since peatland water depths are controlled by precipitation and evapotranspiration, these factors are significant influences on variation in water table between years. Therefore, a direct comparison of water tables before and after re-vegetation is not appropriate here.

The relative differences between treatment sites and control sites were calculated and examined before and after re-vegetation. This enabled the relative behaviour of the treated and control sites before and after re-vegeation to be compared.

In 2011, water table depth at the treatment sites was, on average 24mm higher than that of the control sites. In 2014, water table depth at the treatment sites was, on average 35mm higher than that of the control sites – a relative increase of 11mm. While box-and-whisker plots of the relative differences suggests a change in behaviour (Figure 27), there was no significant difference (t = -1.412, df = 22, p > 0.05.

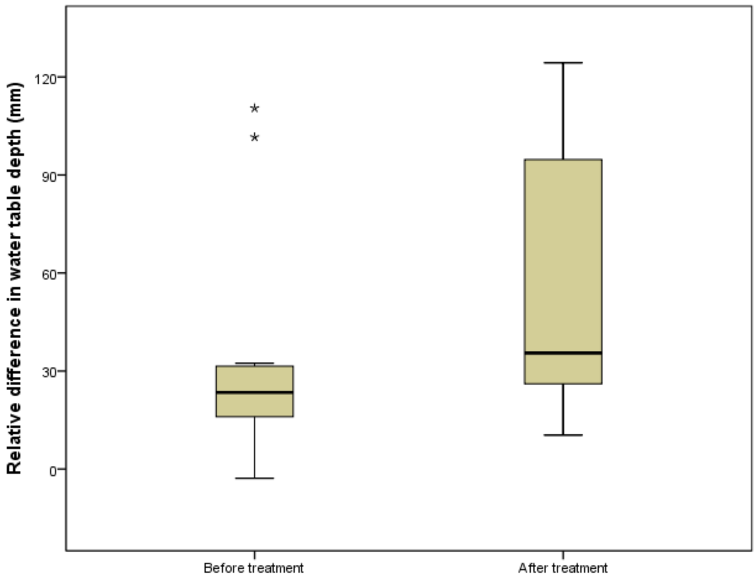

Figure 27 – distribution of the mean differences between treated and control sites on Bleaklow, before and after treatment.

4.4. Discussion

4.4.1. Impact of gully blocking on water table

Analysis of data from Woodhead gave inconclusive results on the impact of gully blocking on water table. The characterisation of water table behaviour in pre-treatment conditions was limited due to the fact that only one month of data was able to be collected prior to gully blocks being installed. Therefore the full range of hydrological conditions has not been captured, unlike during the post-gully blocking period, which covers a longer time period and a full range of dry and wet conditions. Continued monitoring will evidence the ongoing impact of the gully blocking works.

4.4.2. Impact of revegetation on water tables

The establishment of a control site was extremely beneficial in the analysis of water table on the Woodhead, enabling the interpretation of water table behaviour in relation to both climatic factors and differences in treatments.

The data presented here provide encouraging signs of increasing wetness at early-stage revegetated sites on Woodhead. Water table depth at treated sites was 11 mm higher relative to the bare peat reference site, although this was not a statistically significant result.

Allott *et al* (2015) reported a significant rise in water table depth of 35mm three years post-treatment. This study did not examine data in the intervening years. Initial results from the MoorLIFE monitoring programme on Bleaklow perhaps suggest that the changes in water table are not rapid, but provides evidence of a gradual change. It is likely that another one to two years of monitoring would be required before a significant change is detected.

5. Storm Flow

Flow monitoring was undertaken with a view to understanding the impact of damming erosion gullies on water flow during storm events under two scenarios: focused monitoring of erosion gullies in vegetated blanket bog habitat and larger scale monitoring of a watershed catchment that had an extent of bare peat which was subject to revegetation treatment (see Figure 1 -Figure 9 in the Introduction).

5.1. Methods

Flow monitoring stations were installed at each of the nine monitoring points. Where gullies were relatively narrow and peat-floored, v-notch weirs were installed. Where gullies had mineral floors flumes were installed. Upstream of each flow station, data loggers (Hobo pressure transducer, Tempcon Instrumentation Ltd) were suspended in stilling pools where they took measurements of water level every ten minutes.

At Stable Clough, at the edge of the blanket bog watershed catchment we set up a rated-section flow station because it is not possible to install a flume or weir at this site. A data logger was installed in a natural pool and a series of flow gauging measurements allowed the volume of water to be calculated using ratings curves.

Rainfall was monitored using Hobo tipping bucket rain gauges at two locations on the site to enable lag times between peak rainfall and peak flow through gullies to be calculated and studied.

Flow data was collected from the Smithy Clough gullies and the Stable Clough moorland edge site from April 2012. Flow measurements began in the two gullies within Stable Clough catchment in November 2012.

The treated gully in Smithy Clough had 68 stone dams installed on the 27th October 2012 and there was approximately five months of pre-treatment data. Analysis of the monitoring sites in Smithy Clough focuses on the impacts of gully blocking only.

The Stable Clough moorland catchment was seeded in July 2012, and had 413 stone dams installed between 29th October and 13th November 2012. There is approximately five months of data before gully blocking took place and approximately three months before seeding. Analysis focused on the impacts of gully blocking within the Stable Clough catchment, and the five months of data before gully blocking has been taken as the pre-treatment period.

5.1.1. Storm flow analysis

Storm flow analysis involves the extraction from the hydrograph of suitable storm events. Simple hydrographs (i.e. those with single or with minor secondary peaks) are selected from the flow record. In this study the metrics of particular interest are (Figure 28):

- peak storm flow;
- storm lag time (time between peak rainfall and peak storm flow);
- percent runoff

For the Smithy Clough gullies, paired storms have been extracted and compared.

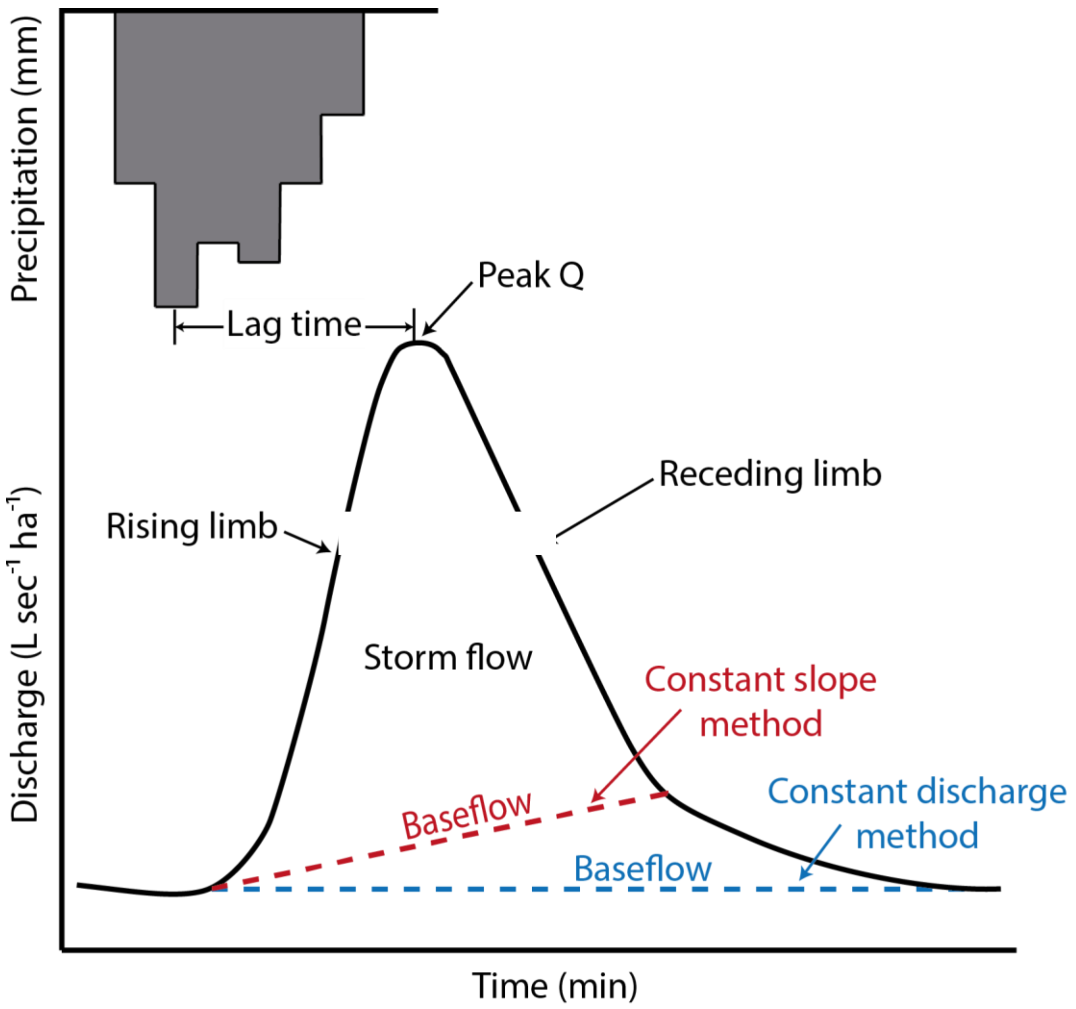

Figure 28 - features of a simple hydrograph showing the different methods of calculating storm flow. Peak Q is peak storm flow. The 'cut-off point' of a storm event (i.e. the point at which storm flow water has passed through the system and flow returns to base flow can be established by either constant-slope or constant-discharge method. The former was used for V-notch weirs, the latter was used for data collected at flumes. Adapted from Allott *et al* (2015).

Statistical analysis has been undertaken on the storm metrics for each site pre-and post-treatment. The differences (residuals) between the control and treatment gully in Smithy Clough has also been each variable and inspected for observable temporal patterns.

5.2. Data

Approximately 3 months of data between 31st January and 23rd April 2013 was excluded due to heavy snow and ice remaining in gullies for most of this period. This data was excluded to prevent interference of snow melt in the record.

Table 12 shows the number of storms extracted for each set of paired storms for the Smithy Clough gullies, and the number of storm events extracted for Stable Clough.

Table 12 Number of storms extracted

Monitoring point	**Monitoring period (in relation to gully blocking)**	**Number of storm hydrographs extracted**	**Time period**
S1HW and S2HW	Before	11	May 2012 - Oct 2012
	After	19	Nov 2012 - Nov 2014
S1DS and S2DS	Before	8	May 2012 – Sept 2012
	After	17	Oct 2012 – April 2014
Stable Clough	Before	11	May 2012 – Sept 2012
	After	21	Nov 2012 – Dec 2013

5.3. Results

5.3.1. Smithy Clough gullies – headwater sites

Figure 29 to Figure 31 show the differences in peak storm flow, lag time, percent runoff between paired storms events from the treated and control gullies. Figure 32 shows the total rainfall and maximum intensity for each event.

5.3.1.1. Peak storm flow

In the pre-treatment data, the treatment gully had a significantly higher peak storm flow (median 10.3 L/sec) than the control (median 3.8 L/sec; U=20, Z=-2.659, p <0.05).

After gully blocking, both systems had lower median peak storm flows than prior to gully blocking. Peak storm flows in the control systems were 55% lower than the pre-treatment period (median 1.7 L/sec; U = 59, Z = -1.958, p = 0.05), and the treated system were 44% lower than the pre-treatment period (5.8 L/sec; U = 20, Z = -2.659, p < 0.05).

Inspection of the residuals of peak storm flow between the two headwater sites indicated a sustained change in relationship between the two sites at the event on 15th October 2012 (Figure 29). It was not clearly related to the gully blocking itself since there were other events with low differences between systems prior to gully blocking.

5.3.1.2. Lag time

In the pre-treatment data, the treated system had a longer lag time (median = 40 minutes) than S1HW (median = 30 minutes; U= 50, Z = -0.697, $p > 0.05$).

After gully blocking, the treated system median storm lag time was 120 minutes - 80 minutes longer than before the treatment took place (U = 42, Z = -2.699, $p < 0.01$). The control system median storm lag time was 95 minutes - 65 minutes longer than in the pre-treatment period (; U = 59.6, Z = -1.943, p = 0.052).

An inspection of the residual lag times between paired storms indicated a potential delayed effect of gully blocking, with an effect only becoming observable from in the storm measured on 23rd October 2013 onwards (Figure 30) nearly one year post works.

The median difference in lag times between the control and treated systems for paired storms before gully blocking was 10 minutes. Post-gully blocking, this difference was 20 minutes. When only storms from 23rd October onwards were considered, this difference was 30 minutes.

5.3.1.3. Runoff

Analysis of the proportion of runoff generated by rainfall events indicates that gully blocking had no impact on the treated system, with a median percent runoff of 63% before gully blocking, 58% (5% less) after (U=95, Z = -0.409, $p > 0.05$), Figure 31.

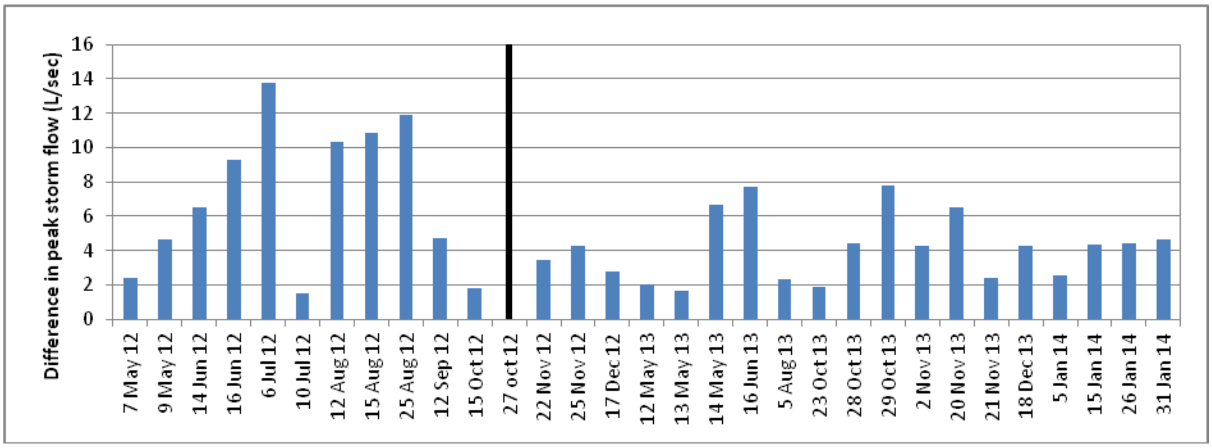

Figure 29 differences in peak storm flow from the treated and control gullies

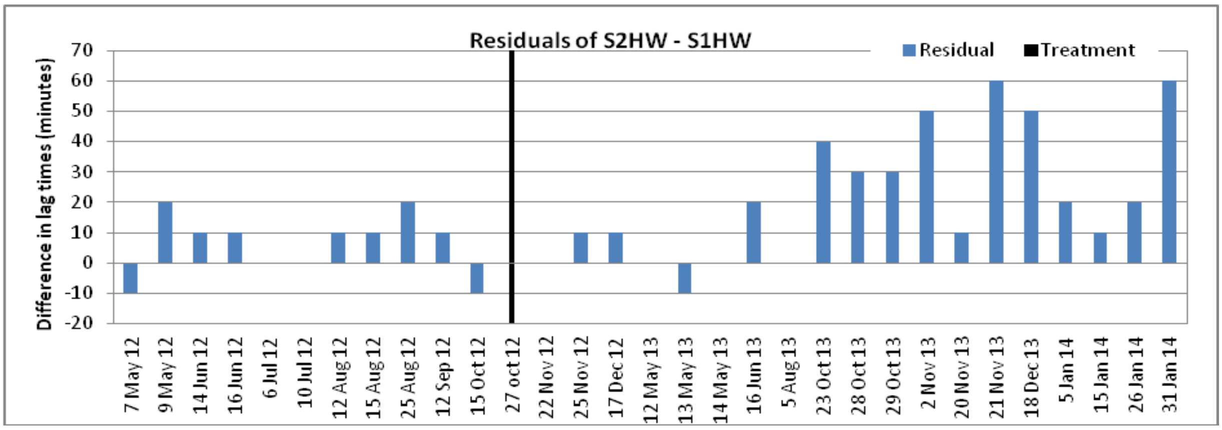

Figure 30 differences in lag time from the treated and control gullies

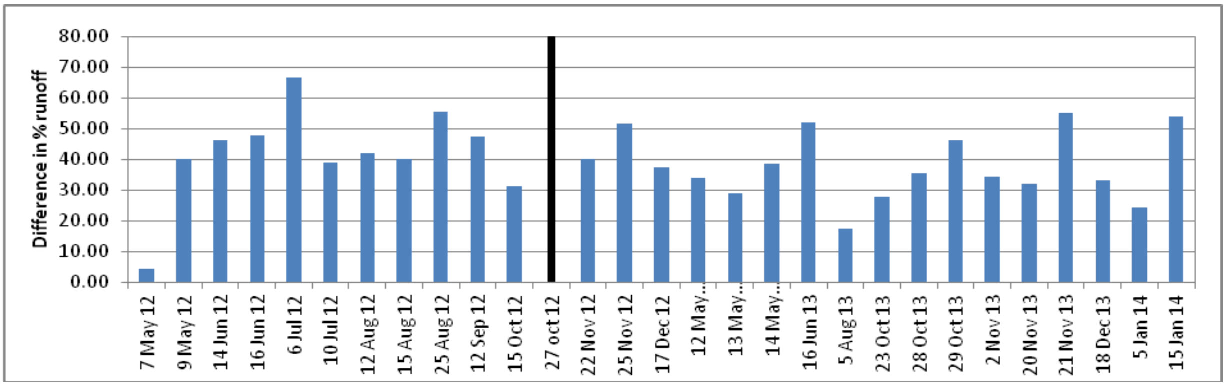

Figure 31 differences in percent runoff between paired storms events from the treated and control gullies

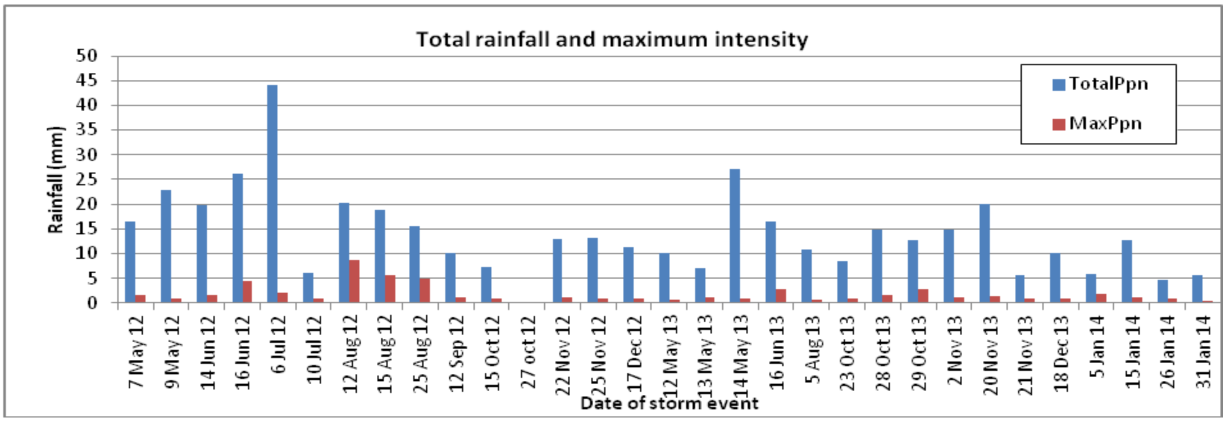

Figure 32 total rainfall and maximum intensity for each event.

5.3.2. Smithy Clough - downstream sites

Figure 33 to Figure 35 show the differences in peak storm flow, lag time, percent runoff between paired storms events from the treated and control gullies. Figure 36 shows the total rainfall and maximum intensity for each event.

5.3.2.1. Peak storm flow

In the pre-treatment data, median peak storm flows in the control and treatment systems were similar, with a median of 14 L/sec in the control system and 18 L/sec in the treated system

After gully blocking, both systems appear to show a lower peak storm flow. The treated system showed a 67% higher peak storm flow ($U = 41$, $Z = -1.869$, $p = 0.066$) compared to the pre-treatment period, while the control system shows 57% lower peak storm flow ($U = 36$, $Z = -2.125$, $p < 0.05$) than the pre-treatment period.

Visual inspection of the residuals of peak storm flow indicated that within the treated system, those storm events that immediately follow gully blocking had consistently lower peak storm flow than that of the control system (Figure 33). This appeared to be particularly strong for 14th May 2013. Beginning with the event on 16th June; however, this relationship changed and peak storm flow for the treated gully appeared to be consistently higher than that for the control.

5.3.2.2. Lag time

In the pre-treatment period, the treated system had lag times of a median of 55 minutes, compared to the control system with a median lag time of 40 minutes.

After gully blocking, the median lag time of the treated system was 160 minutes, 105 minutes longer, three times longer, than before treatment ($U = 31.5$, $Z = -2.368$, $p < 0.05$). The control system had lag times which were 1.75 times longer than the pre-treatment period to a median of 70 minutes ($U = 35$, $Z = -2.186$, $p < 0.05$).

In the pre-treatment data lag times at the treated system had longer lag times than the control by a median of 10 minutes. A Mann-Whitney U test indicated that there was no significant difference between S1DS and S2DS before gully blocking. After gully blocking, the median difference in lag time increased to 20 minutes – suggesting a ten minute increase in lag time overall.

A visual inspection of the differences in lag times between paired storms (Figure 34) suggested that after gully blocking, a number of storm events (26th December 2012 through to 12th May 2013 exhibited changes in lag times in the treated system, with lag times being longer relative to the same storms sampled in the control system.

In storm events extracted from 13th May 2013 onwards, the residuals of the control and treated gully lag times returned to times similar to those in the pre-gully blocking period. The median residual of events extracted between 13th May 2013 and 12th February 2014 was 10 minutes, matching that of the pre-treatment storm events. Visual inspection of the hydrographs from November 2013 onwards indicated that many storm events returned to tracking each other well.

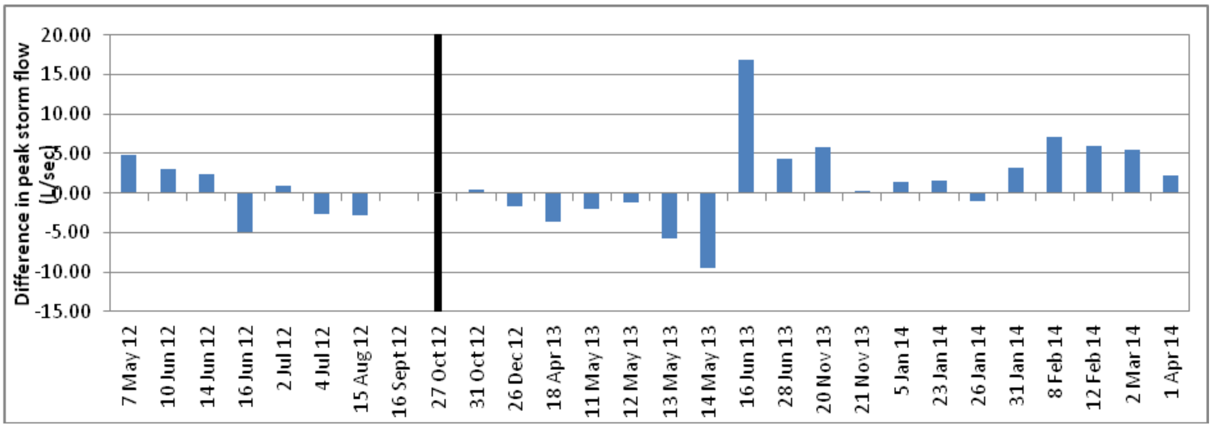

Figure 33 differences in peak storm flow from the treated and control gullies

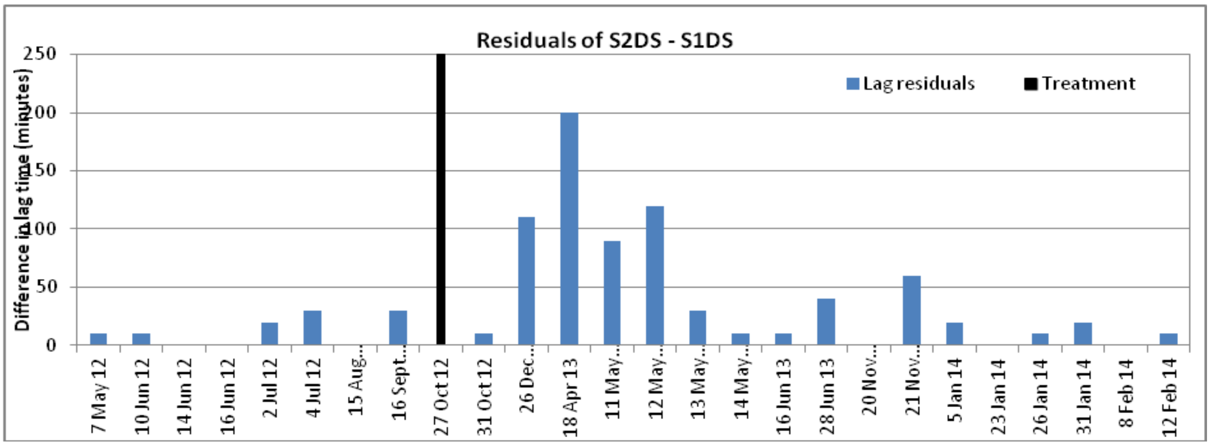

Figure 34 differences in lag time from the treated and control gullies

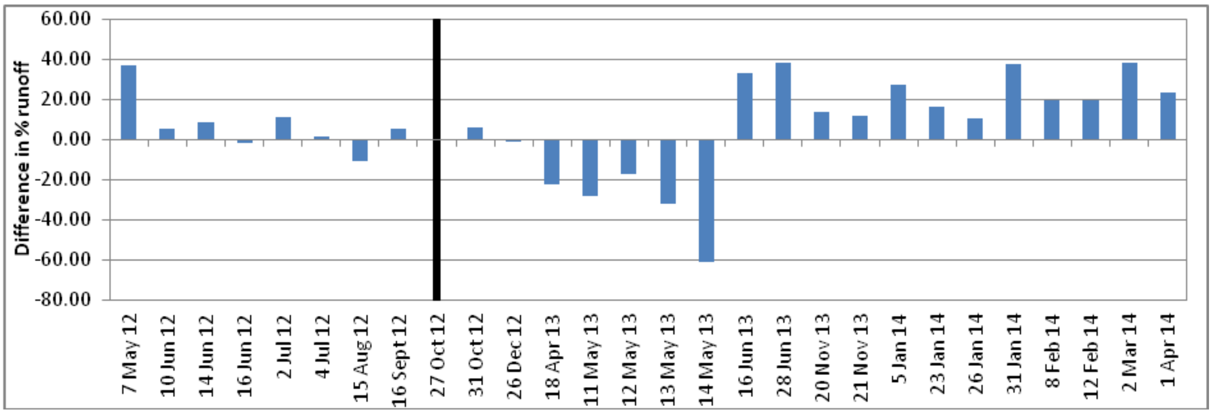

Figure 35 differences in percent runoff between paired storms events from the treated and control gullies

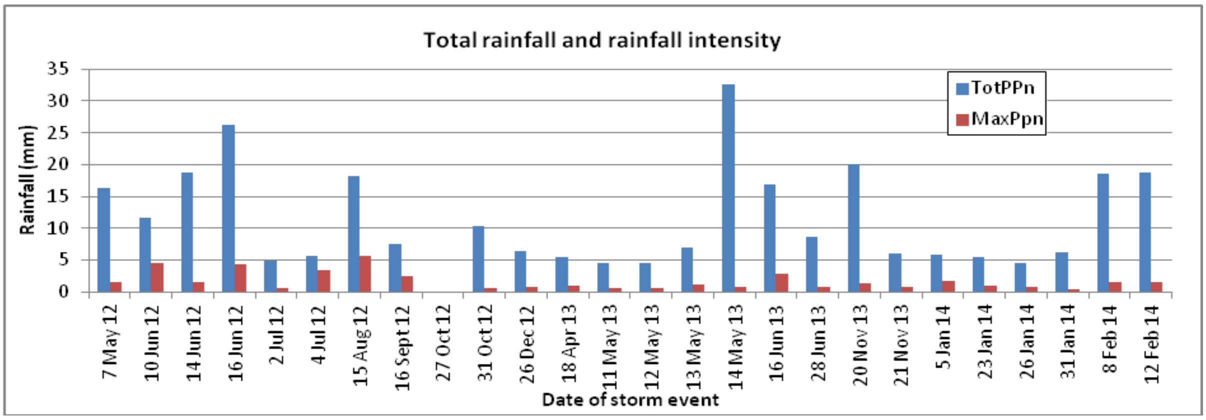

Figure 36 total rainfall and maximum intensity for each event

5.3.2.3. Percent runoff

In the pre-treatment data, the percent runoff for the control and treated systems were similar, with medians of 43% and 52% of flow generated by surface runoff.

After gully blocking, the percent runoff in the control system was 24% (U = 53, Z = -1.221, $p > 0.05$) and in the treated system was 40% (U = 58, Z = -0.956, $p > 0.05$).

The pattern of percent runoff between the two systems during events extracted between 26th December 2012 and 14th May 2013 indicated a change in behaviour after gully blocking. During this period, percent runoff in the treated system was consistently lower than that of the control. This pattern then reversed, and in events from 16th June 2013 onwards the treated system had a percent runoff that was consistently higher than the control.

5.3.3. Stable Clough

There was no suitable control system for the Stable Clough moorland edge monitoring site. Therefore results describe the change in behaviour before and after gully blocking without comparison to an untreated control.

5.3.3.1. Peak storm flow

In the pre-treatment data, median peak storm flow at the Stable Clough moorland edge site was 214 L/sec. Following gully blocking treatments, median peak storm flow was 36% lower, with a median of 136 L/sec (U = 57, Z = -2.321), $p < 0.05$).

5.3.3.2. Lag time

The median lag time for Stable Clough before gully blocking was 80 minutes. This was 190 minutes longer in the post-gully blocking data – 2.4 times longer than before treatment (U = 68.5, Z = -1.868, $p = 0.062$).

5.3.3.3. Percent runoff

The median percent runoff in the pre-treatment period was 32%. After gully blocking it was 25% ($U = 114$, $Z = -0.06$, $p > 0.05$).

5.3.4. Differences in rainfall in the pre- and post-treatment periods

We used two of the metrics to describe the total rainfall in millimetres during a storm event (referred to as Ppn_{TOT}) and the maximum intensity in millimetres in a ten minute period (referred to as Ppn_{MAX}). Storms in the post treatment work period had significantly lower total rainfall and significantly lower rainfall intensity than in the pre- treatment period for storm events used in the analyses in this report, in the before and after treatment periods.

At Smithy Clough headwater site, median Ppn_{TOT} and the Ppn_{MAX} were higher in the pre-treatment period than in the post-treatment period ($U = 53.5$, $Z = -2.197$, $p < 0.05$; $U = 53$, $Z = -2.238$, $p < 0.05$). At the downstream sites, Ppn_{MAX} was significantly lower in the post-treatment period ($U = 30.5$, $Z = -2.537$, $p = 0.01$).

Similar patterns were found in the Stable Clough precipitation characteristics, with a Ppn_{TOT} median of 18mm in the pre-treatment period, compared to 11mm in the post-treatment period ($U = 66.5$, $Z = -1.945$, $p = 0.052$). Ppn_{MAX} median was 1.6mm in the before period, reducing to 1mm in post-gully blocking storm events $U = 52.5$, $Z = -2.523$, $p < 0.05$.

An analysis of co-variance (ANCOVA) on the Smithy Clough gully datasets to test the relationship between treatment (gully blocking) and the three storm metrics while controlling for the effects of storm size Ppn_{TOT} showed no statistically significant changes in hydrograph characteristics at the gully blocked sites that were independent of storm size for either the headwater sites (lag: $F = 1.7034$, $p > 0.05$; PD: $F = 1.191$, $p > 0.05$; PR: $F = 0.001$, $p > 0.05$) or the downstream sites (Lag: $F = 1.4991$, $p > 0.05$; PD: $F = 0.4947$, $p > 0.05$; PR: $F = 0.0322$, $p > 0.05$).

An ANCOVA on the peak stormflow datasets from the Stable Clough moorland edge catchment showed no statistically significant changes in peak storm flow following gully blocking that were independent of storm size ($F = 0.928$, $p > 0.05$).

From this dataset we cannot therefore conclude that gully blocking, during the period of monitoring, had a statistically significant impact on lag time, peak stormflow, or percent runoff in the blocked gully in Smithy Clough, or in the wider Stable Clough moorland catchment.

5.4. Discussion

The dataset collected from three years of monitoring on the Woodhead estate provides the first evidence of the impact of stone gully blocking in gullies associated with intact surrounding vegetation, on storm flows.

There were significant differences in rainfall between storm event ‘sizes’ between the 2012 ‘control/ baseline, year and 2012/13/14 post treatment years which will affect our ability to adequately assess the true impact of the gully blocking works. In April 2012, at the start of data collection, the jet stream was positioned unusually far south-east of the UK, causing cyclonic conditions throughout much of the rest of the year. Rainfall recorded at national, regional and local levels between April and December 2012 was extremely high. Rainfall was almost twice the average between April and July 2012, and November and December 2012 were the second wettest for England and Wales since 1929 (Marsh *et al*, 2013). Examination of the rainfall records from Woodhead indicate that these extreme weather patterns have contributed to higher rainfall intensity and volume in the time period before conservation works began. Care must therefore be taken in interpreting the results as any changes in lag times and peak storm flow that might be a result of conservation works are likely to be masked by the differences in rainfall volume and intensity.

Just looking at storm flow behaviour in vegetated, linear gullies following gully blocking we found some consistent patterns: peak storm flows decreased at all sites, lag times increased significantly and percent runoff remained unchanged at all sites. However, the results of the

ANCOVA statistical analysis showed that it is not possible to statistically prove that these effects are attributable to the effects of stone gully blocking or differences in rainfall patterns before and after treatment.

This broad result masks more complex temporal responses in behaviour following gully block installation. Inspection of the differences in paired hydrographs from the Smithy Clough treatment and control gullies indicate that there were apparent temporal delays in responses and well as immediate effects that were not sustained over the longer period of the post intervention monitoring. For example, at Smithy Clough headwater site increases in lag times were not consistently recorded until a year and gully bocks were installed. At the downstream site, sharp initial reductions in peak storm flow and percent runoff, and increases in lag times, were observed for a period of approximately seven months before returning to apparent pre-treatment levels.

The initial short-term responses on Woodhead could be linked to a relatively small increase in the storage of water behind dams, as indicated by the temporary decreases in percent runoff observed at S2DS. A possible explanation for this is that the stone dams in the gully blocked system fill up and drain out quickly after a storm event. Once re-deposited sediment accumulates behind dams and on the gully floors, the ability of water to filter through the dams, or into the mineral floor of the Woodhead gullies is reduced. If the areas behind the dams are then mostly full of water, this would provide little surface roughness to slow water down. It is surface roughness that is the mechanism that the MFFP Making Space for Water project (MS4W) has demonstrated to be responsible for reductions in peak discharge and increases in lag times following gully blocking and the revegetation of surrounding bare peat areas (Allott *et al* 2015) - most significantly through the establishment of grass cover. In Smithy Clough we have not increased roughness through increased in vegetation cover or type of cover; in Stable Clough we have only increased roughness (revegetated bare peat) on 54% of the catchment, compared to nearly 100% of the catchment in the MS4W project. In addition, the storms analysed from Stable Clough were all within 17 months of seeding. In the MS4W study, storms were analysed between 10 and 29 months of seeding. This could indicate that a certain degree of maturation of treatments is required (gully blocks or vegetation cover establishment) is required before changes in overland flow are observed.

The 'maturation' of stone dams (i.e. the extent to which sediment accumulates behind dams) is an important factor in it. In a well vegetated system, the main source of sediment is the bare gully walls. The volume of 'available' sediment is not as great as in bare peat catchments. The more recent of the sedimentation surveys indicate that none of the gully blocks in the treated system have accumulated sediment to the top of the stone dams – with an average of 33 cm of available space behind dams in February 2014, just over one year after installation of dams. The dams appear to hold water well, but sediment accumulation is relatively slow. Continued maturation of the dams or changes in the gully profile could lead to further changes in storm hydrology.

MS4W found that that big changes in storm flow runoff characteristics occur when bare peat is revegetated; that there are some apparent benefits from gully blocking, but no statistically significant difference in hydrograph changes between the re-vegetated catchment and the re-vegetated and gully blocked catchment. This finding in conjunction with the subtle and complex responses in storm flow s in this study demonstrate that, gully blocking has a much more subtle effect, to date, masked by extremely noisy data.

5.5. Recommendations

- Investigate potential to extract more storms from the 2012 'before' period.
- Extract more data from 2014 to increase the size of the dataset, and identify if any storm events are of a comparable size to 2012 storms that make for a more suitable comparison.
- Continued monitoring in the expectation that storms of a similar intensity will occur in future.
- Analyse the data to determine whether antecedent precipitation conditions have an impact on storm-flow characteristics.

- Examine sedimentation behind other dams to build up a picture of how long it takes for dams to ‘mature’. Repeat dam surveys on Woodhead would inform us of the status of dams in 2015 – 2.5 years or more following gully block installation.

6. Water Quality

6.1. Introduction

Degraded blanket bog in the Dark Peak is associated with a number of water quality issues, including elevated water colour/dissolved organic carbon (DOC), high levels of sediment (particulate organic carbon) and heavy metal pollution.

The capital works on Woodhead have the potential to improve water quality through a number of mechanisms:

- Higher water tables brought about by both gully blocking and re-vegetation could lead to reduced levels of DOC.
- Peat stabilisation through re-vegetation is known to reduce sediment loss (Shuttleworth *et al*, 2015). Such a reduction in erosion would both reduce POC levels and prevent heavy metals locked up in the peat from entering the fluvial system.
- Sediment trapping by gully blocks could also reduce the levels of POC and associated pollutants from reaching reservoirs.

The aim of this project was to monitor the impact of gully blocking in erosion gullies in blanket bog associated with intact surrounding, heather dominated, vegetation.

6.2. Methods

6.2.1. Spot sampling

Water samples were collected in sterilised bottles every fortnight from each of the nine flow monitoring stations during periods of flow. During the sample collection a Hanna HI 98130 was used to measure pH, water temperature, conductivity and total dissolved solids. The time of each sample collection was also recorded to enable it to be related to the discharge as calculated at each flow station using logged sensor depth. Samples were stored in a fridge at and sent for analysis as soon as possible following collection.

6.2.2. Storm sampling

Storm water sampling was undertaken to supplement the spot sampling, and investigate the episodic release of POC.

An ISCO 6712 auto-sampler with 24-bottle configuration was been installed at the Stable Clough system, adjacent to the flow monitoring station, between March and December 2014. The auto-sampler was linked a water level sensor which triggered sampling when the water in the stilling pool rises to the level at which the sensor is fixed. Auto-samplers were emptied as soon as a visit was possible after a major storms and samples stored in a fridge. Analysis of samples was undertaken as soon as possible after collection.

A total of 17 storm events were sampled between March 3014 and November 2014. All storm samples were tested for Absorbance at 254, 400, 465 and 665. However, not all storms triggered the sampler in time to catch the peak storm flow, therefore it was decided to only send storms where sampling had captured the water flow at its highest point to external labs for DOC, POC and colour (Hazen) measurements. Samples from ten storms were sent for these analyses, following checks of the storm hydrographs to ensure that the peak storm flow was sampled.

6.2.3. Water quality analysis

All spot samples and storm samples were analysed for Total Organic Carbon (TOC), Dissolved Organic Carbon (DOC), and Particulate Organic Carbon (POC), colour in Hazen, absorbance at 254, 400, 465 and 665nm. For the first year of monitoring, samples collected from Stable Clough were also tested for heavy metals.

For testing for TOC, DOC, POC and colour in Hazen, samples were sent to a UKAS accredited commercial lab. Absorbance measurements were undertaken in-house, following filtering using 0.45µm syringe filters. A Jenway 7315 scanning spectrophotometer was then used to measure absorbance at 254, 400, 465 and 665 nm.

Absorbance data was used to establish relationships between the different frequencies and DOC to enable use of absorbance as a proxy for DOC for longer term monitoring. In addition, for each sample the composition of DOC was analysed through calculation of the following:

- E4/E6 ratio calculated by dividing Abs^{465} by Abs^{665}). This gives an indication of the relative proportions of fulvic and humic acids making up DOC. A low value indicates dominance of humic acids and indicates a higher level of humification, and therefore can indicate a greater degree of microbial activity.
- Colour to carbon (C/C) ratio, calculated by dividing Abs^{400} by the corresponding DOC value. This value gives an indication of how dominant coloured DOC is compared to uncoloured DOC.

Each of these ratios provides information as to the composition of DOC within a sample, and can indicate origins of DOC.

6.3. Results

6.3.1. Impact of gully blocking on water quality in Smithy Clough

Water quality data collected from systems 1 and 2 (unblocked control and gully blocked respectively) in Smithy Clough were analysed for changes in water quality.

Figure 37 shows DOC concentrations in the headwater monitoring sites between April 2012 and November 2014. The standard seasonal cycle of DOC concentration can be clearly seen. In 2012, the first year of monitoring, the DOC concentration in the two systems peaked around late August/early September 2012 at 60 mg/l in the control gully and 45 mg/l in the treatment gully.

In 2013, the second year of monitoring, the control system peak DOC concentration was 51 mg/l and the treatment system 52 mg/l. The peak values for 2014 were not available since dry conditions during site visits in late summer 2014 meant that the peak DOC concentrations were missed due to absence of flow.

Where water samples were collected from the control and treatment gullies on the same day, the difference between DOC concentrations (residuals) were calculated and graphed (Figure 38). At the headwater site, the blocked gully was consistently lower than at the control. Following gully blocking on 27th October, 2012, there was no noticeable change on DOC at either the headwater or downstream site.

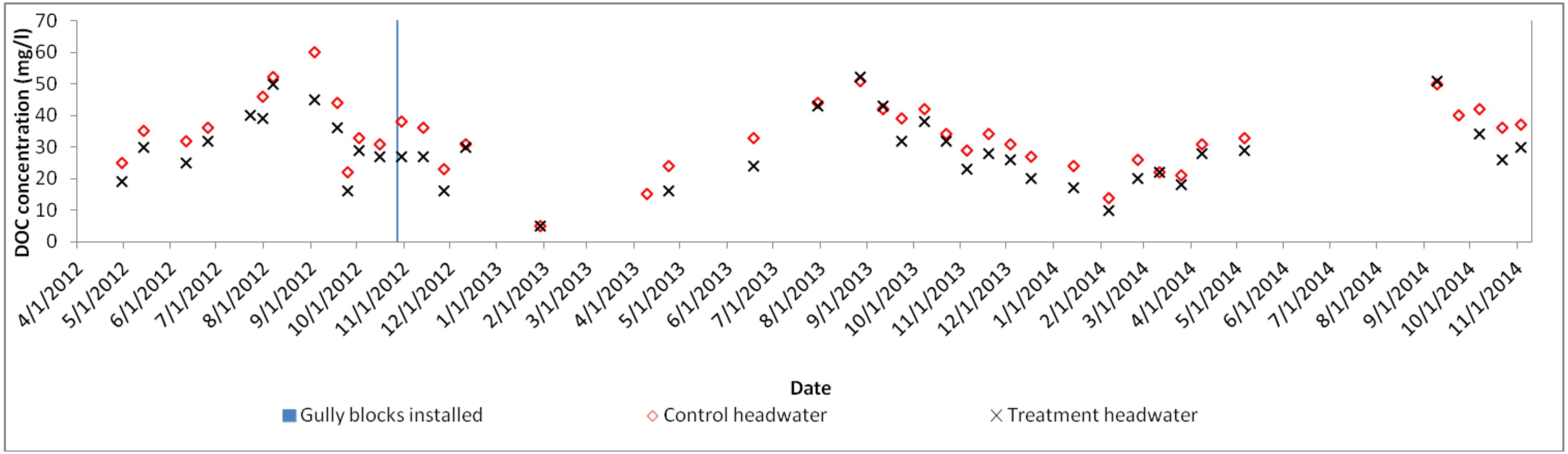

Figure 37 - DOC concentration in Smithy Clough - untreated control and blocked gully.

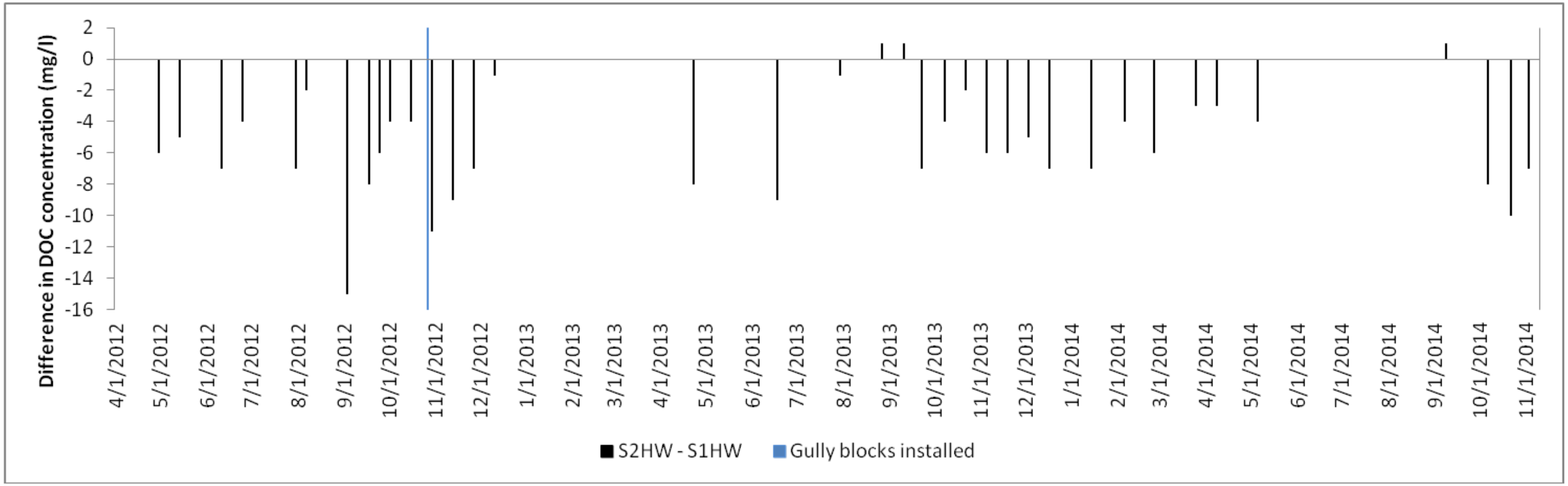

Figure 38 -difference in DOC concentrations between unblocked control and blocked gullies in Smithy Clough

6.3.2. Impact of revegetation and blocking treatments on water quality in Stable Clough

Few samples were collected from system 3 within the Stable Clough catchment because it was dry more often than the other monitored gullies. Therefore data from this system is not considered further in this report.

DOC at Stable Clough a blanket bog watershed catchment scale site

Stable Clough received both gully blocking, and peat stabilisation treatments across 54% of the sampled catchment…date. The data collected from this site is compared with that of the unblocked control (system 1). The typical seasonal variation was apparent in the first year (Figure 39), with peak DOC concentrations reaching 56 mg/l in early September, 2012. In the second and third years DOC concentrations in Stable Clough exhibited reduced seasonal variation when compared with that of the control system.

In summer 2013, there was a sudden decrease in Stable Clough DOC concentration, relative to the control system. Stable Clough peaked at 32 mg/l – a 43% reduction in peak DOC concentration compared to 2012. This then gradually returned to levels recorded in 2012 by winter 2013/2014. The change in DOC concentrations coincided with lime treatments in July 2013 (when 83% of the catchment was limed). This change in the seasonal cycle of DOC was not observed in earlier lime applications in April and September 2012 when 19% and 43% of the catchment was treated).

The residuals of Stable Clough and the control system also indicated a change in the relationship of DOC concentration in Stable Clough (Figure 40) beginning spring 2013.

DOC in gully system 4 (within Stable Clough catchment)

Similar patterns of change in DOC concentration were observed at the two monitored gullies within the Stable Clough catchment, with system 4 exhibiting a 64% reduction in peak DOC concentration (graphs not presented here)

Water colour (Hazen) - Stable Clough blanket bog watershed catchment scale site

Similar patterns of water colour were observed. Peaks of colour were particularly high in 2012, where in the control system, water colour reached 1200 Hazen, and 1400 Hazen in Stable Clough.

The following summer in 2013, the control gully colour peak was lower at 920 Hazen, a 23% reduction. In Stable Clough, water colour was also lower, peaking at just 380 Hazen: a 73% reduction in water colour.

System 4 – water colour

Figure 41 shows the colour in Hazen at system 4 within Stable Clough – which showed an 84% reduction in peak colour between 2012 and 2013. Figure 42 shows the difference between system 4 and the control.

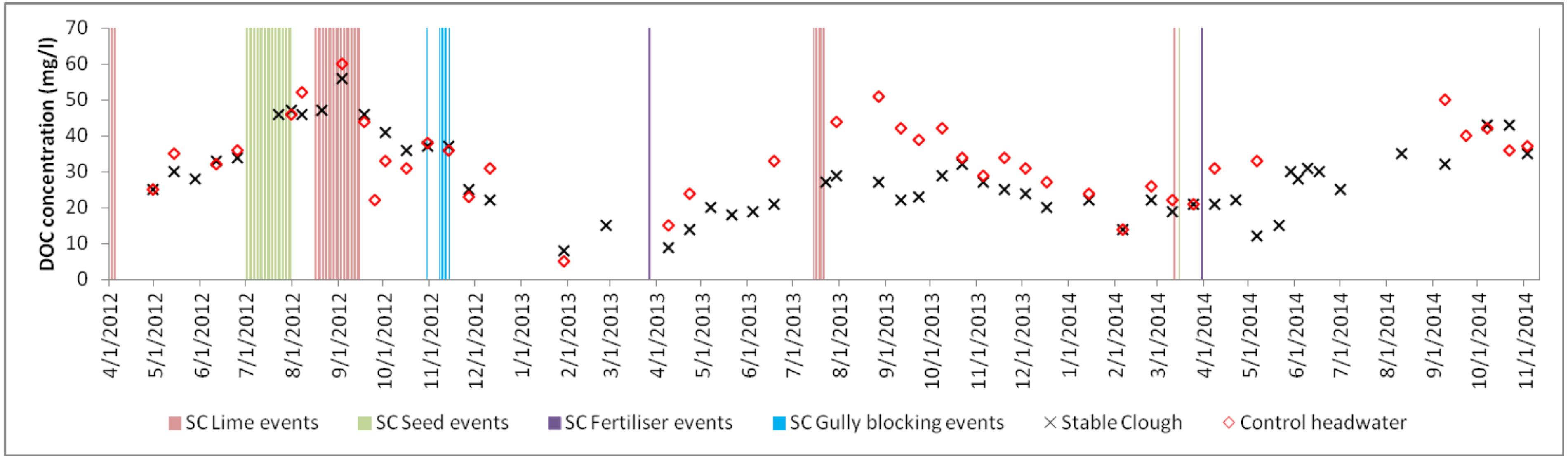

Figure 39 – DOC concentrations from Stable Clough and the control (system 1) gully

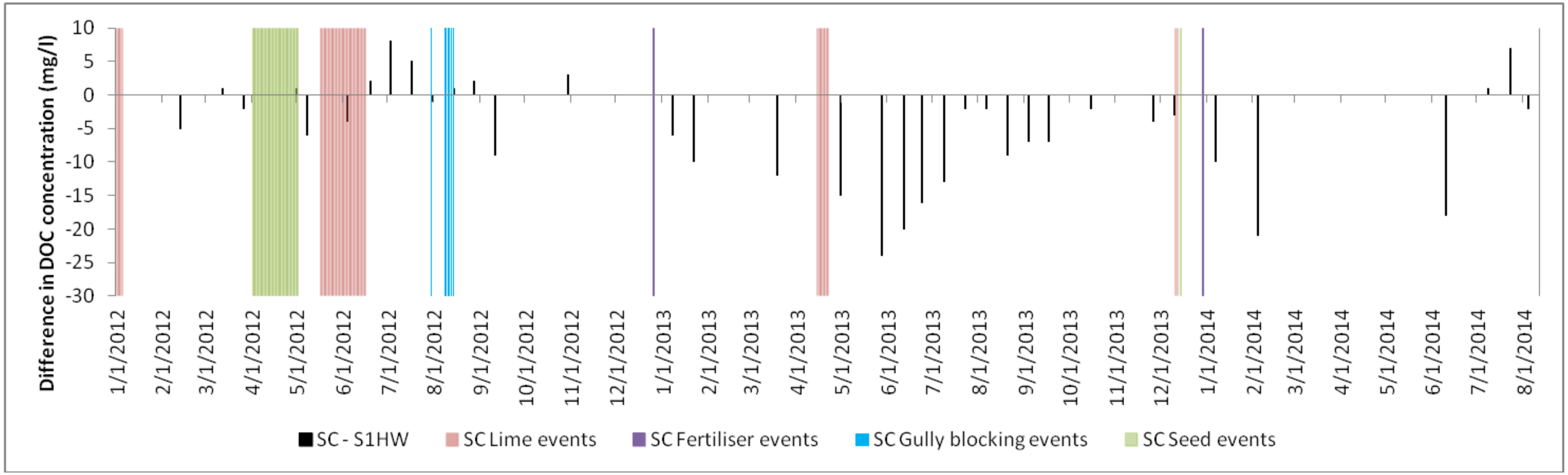

Figure 40 – Differences in DOC concentrations between Stable Clough and the control headwater site (system 1).

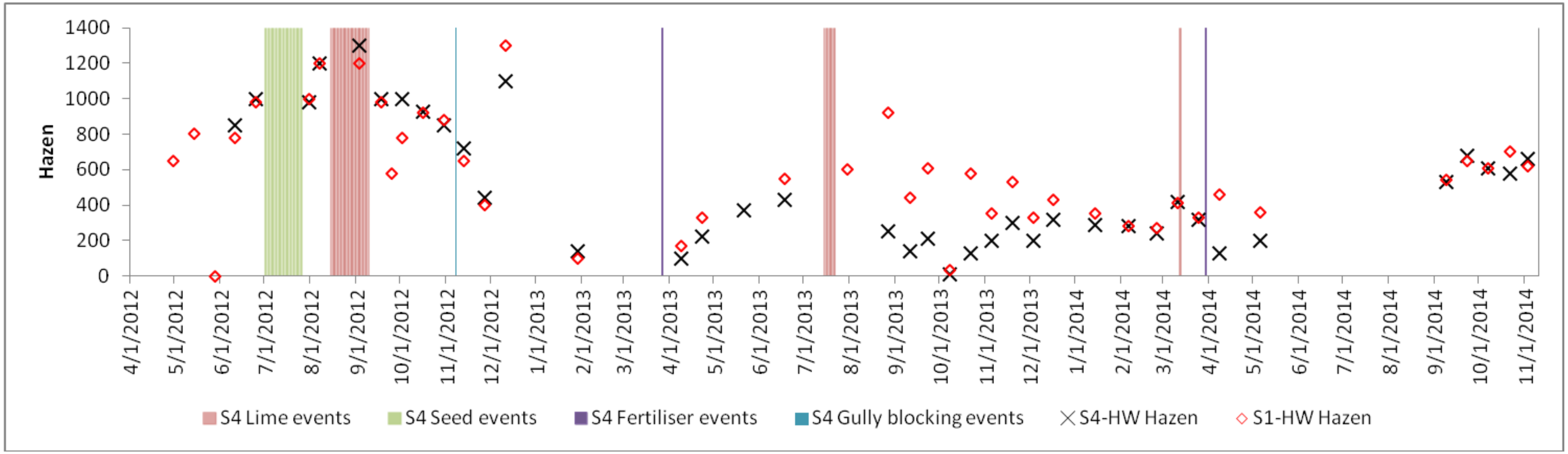

Figure 41 – colour in Hazen at the treated system 4 against the control system 1.

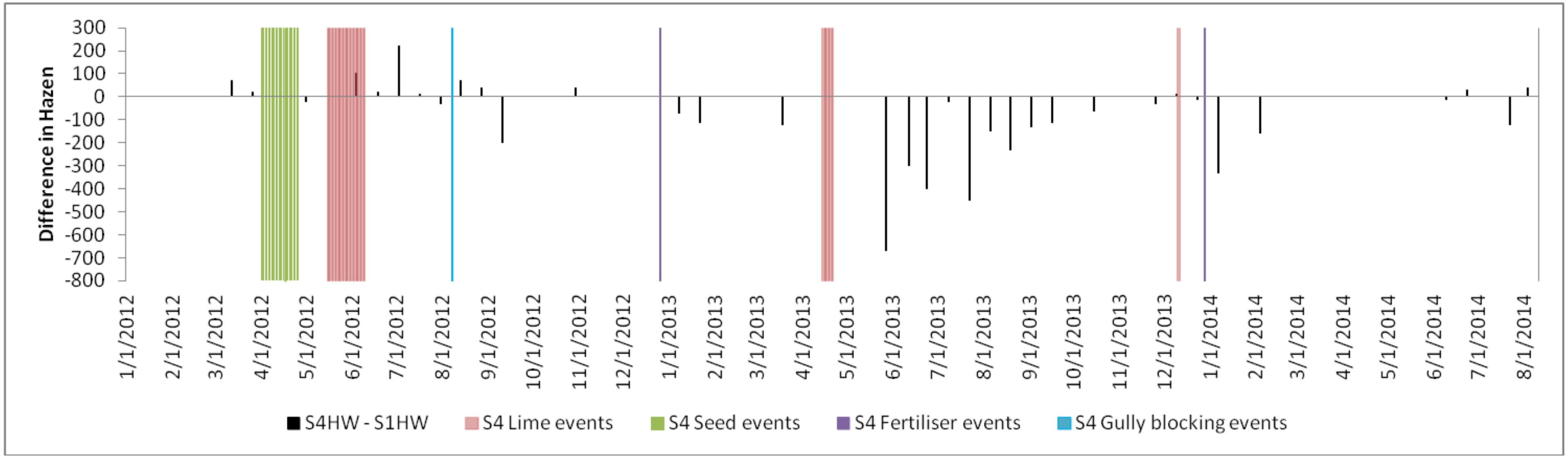

Figure 42 – residuals of system 4 and system 1 (treatment – control)

Conductivity and Total Dissolved Solids

Conductivity and Total Dissolved Solids (TDS) of water flowing through gullies clearly show a change following lime and fertilizer treatments in July 2013, and again in March 2014, as shown from data collected from the monitored gullies within the Stable Clough catchment (Figure 43 and Figure 44). These return to levels matching the control after approximately four months in 2013, and two months in 2014.

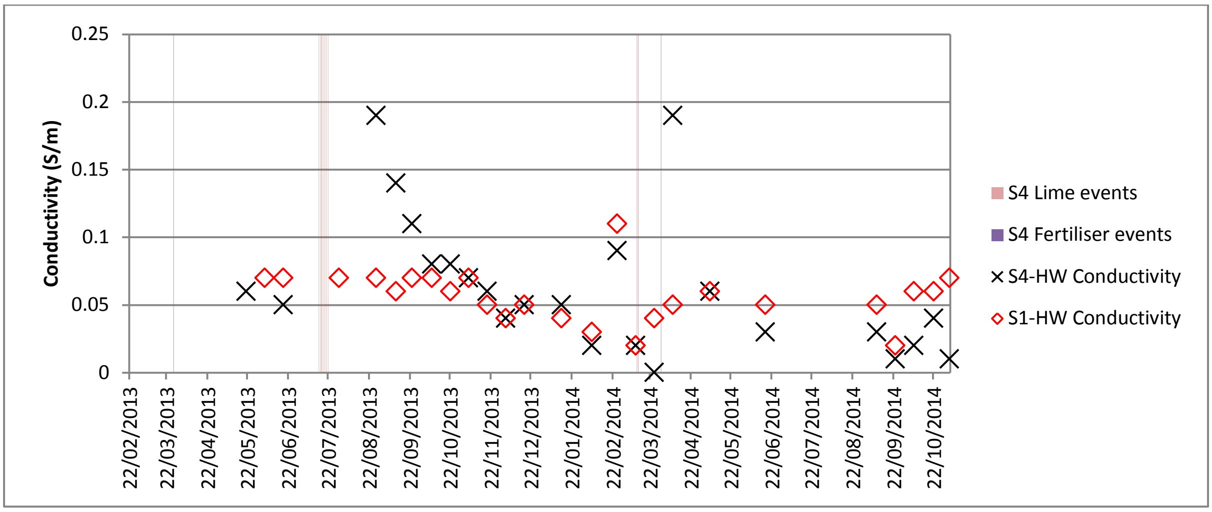

Figure 43 Conductivity at the control (system 1) and treated (system 2) catchments in 2013.

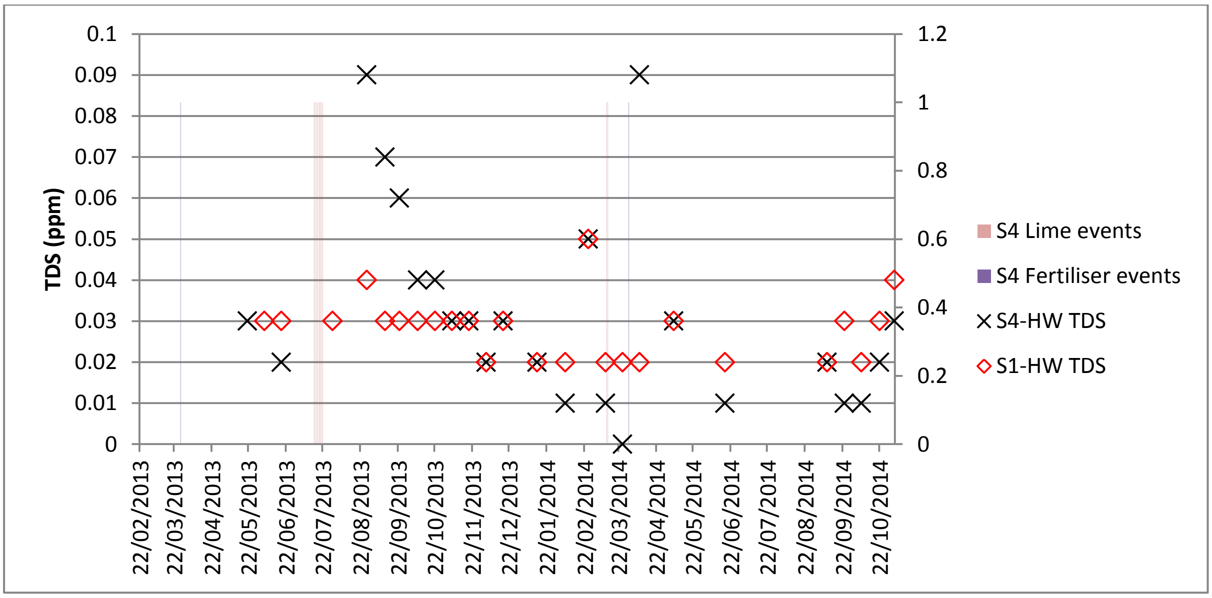

Figure 44 – Total dissolved solids (TDS) at the control (system 1) and treated (system 2) catchments in 2013.

6.3.3. Impact of works on POC

Figure 45 shows the POC concentrations observed at the two Smithy Clough gullies and the Stable Clough catchment over the monitoring period. Sample sizes for system 4 were small and so an analysis of change in POC occurrence was not undertaken.

The proportion of water samples collected that recorded POC concentrations above detection levels was higher before gully blocking than after gully blocking at all sites with the exception of the control headwater site (Figure 45). In the treated headwater catchment POC was detected in 67% of samples before gully blocking and 35% after. This decrease was not significant ($\chi^2(1) = 2.994$, $p > 0.05$).

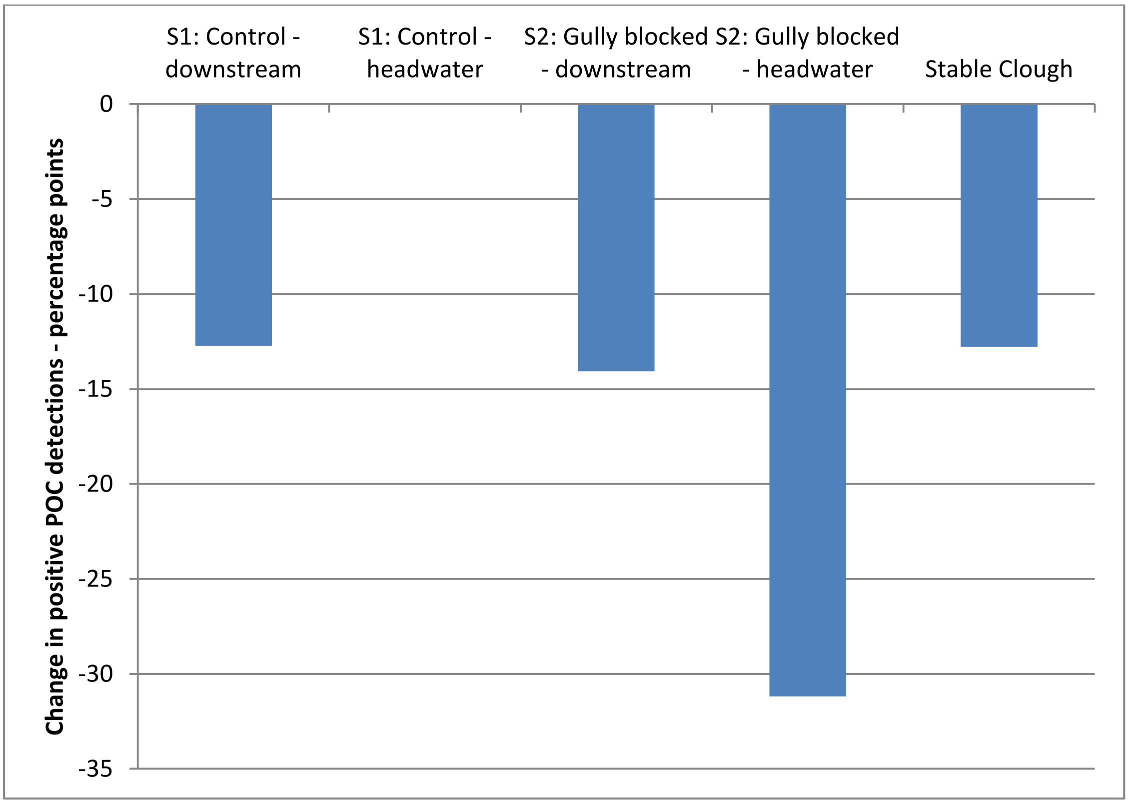

Figure 45 – change in POC occurrence at monitored sites following gully blocking.

6.3.4. Storm sampling

Descriptive figures for each storm event are shown in Table 13.

Of the 17 storm events sampled, here we focus on the three with the highest discharges captured through storm sampling period. These events took place on 10th August 2014, 14th August 2014 and 7th November 2014. The two August events tail-end events of Hurricane Bertha, the November event was a result of heavy rain from an active weather system. These three events generated. The hydrographs (Figure 47 to Figure 52) demonstrated the peaks in DOC flux and POC that occur during these large storm events.

6.3.4.1. Changes in POC during storm events

The storm sampling demonstrated the variability of POC concentrations during storm events, and the episodic nature of POC release. The highest POC concentrations over the whole study were recorded during the storm sampling campaign– this was 44 mg/l during the storm on 7th November, 2014. This was is in contrast to 19 mg/l as the highest POC concentration recorded from spot samples.

6.3.4.2. Changes in DOC during storm events

The maximum DOC concentrations recorded in water samples collected from storm sampling and spot sampling were identical (65 mg/l in both studies), indicating that DOC export was less episodic than that of POC.

The storm hydrographs showed that DOC concentrations decreased with increasing discharge during storm events. However, the relationship between DOC concentration and discharge was very weakly positive ($r^2 = 0.064$, $p < 0.05$). This suggests that while there is a dilution effect during storm events, it is not very big. No relationship was found for individual storm events, and no seasonal relationships were detected.

When DOC concentration was converted to instantaneous flux measurements (DOC concentration multiplied by the discharge at the time of the sample), the hydrographs show that the patterns in DOC flux closely matched that of discharge.

6.3.4.3. Changes in TOC during storm events

The highest TOC concentration was recorded from storm samples. The highest value recorded was 75 mg/l, compared to 66 mg/l recorded as the highest through spot sampling.

While no significant relationships were found between POC and discharge or DOC and discharge, there was indication of a seasonal pattern in the relationship between TOC and peak storm discharge. This relationship was significant for the autumn 2014 storm events ($r^2 = 0.921$, $p < 0.05$) but not for the summer 2014 events ($r^2 = 0.013$, $p > 0.05$) (Figure 46).

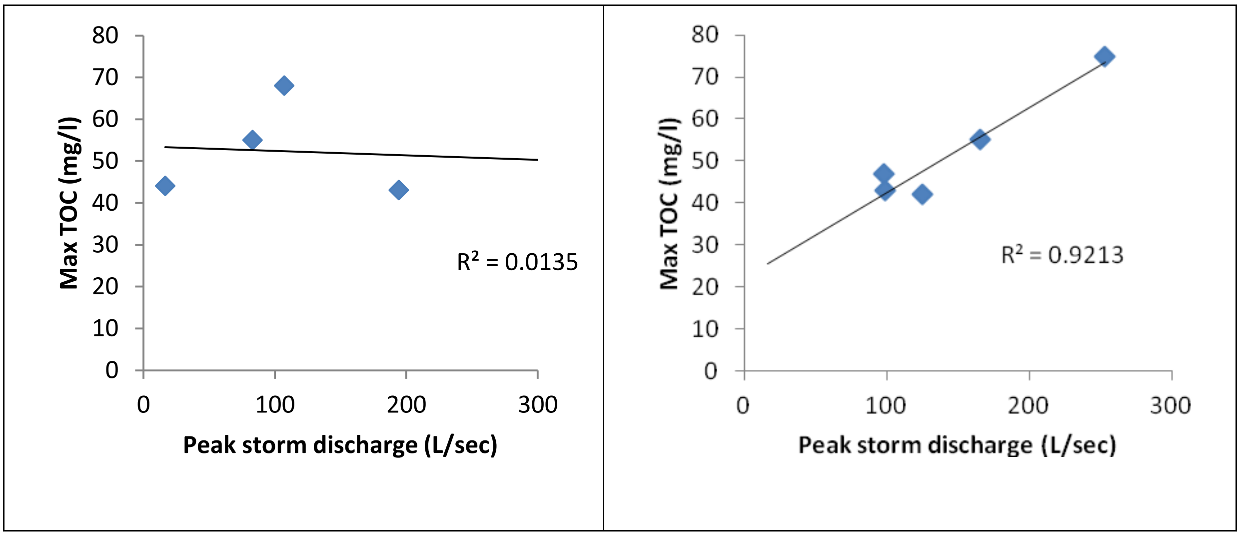

Figure 46 – Relationship between Max TOC concentration and peak storm discharge in summer 2014 (left) and autumn 2014 (right)

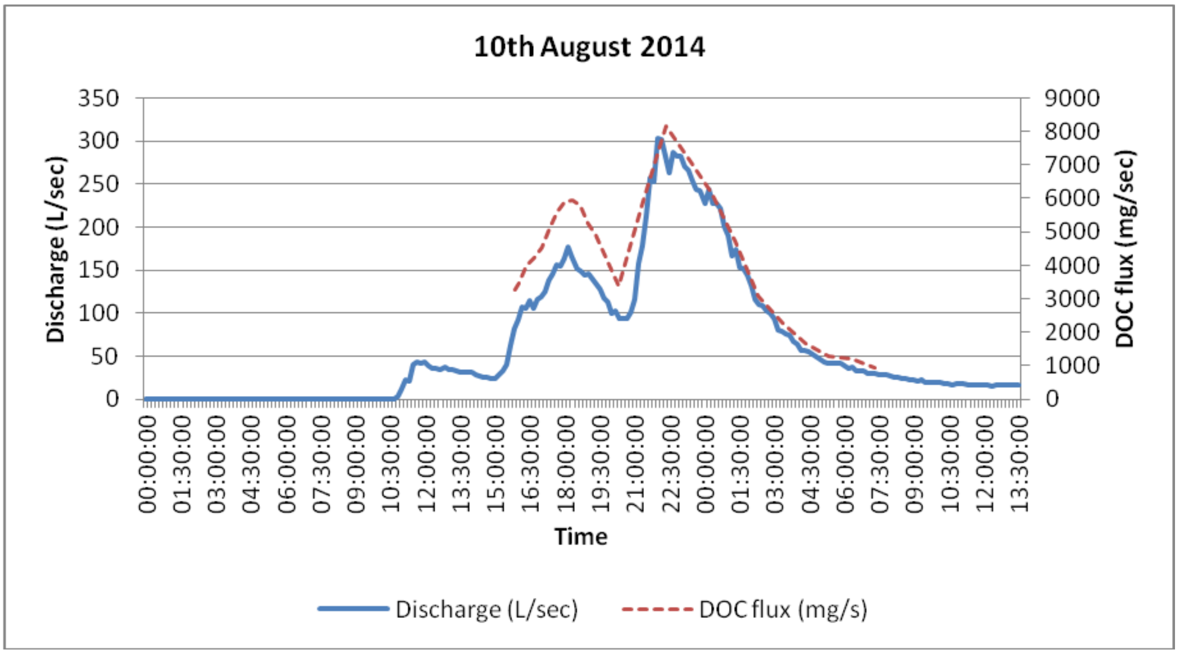

Figure 47 – 10th August DOC flux

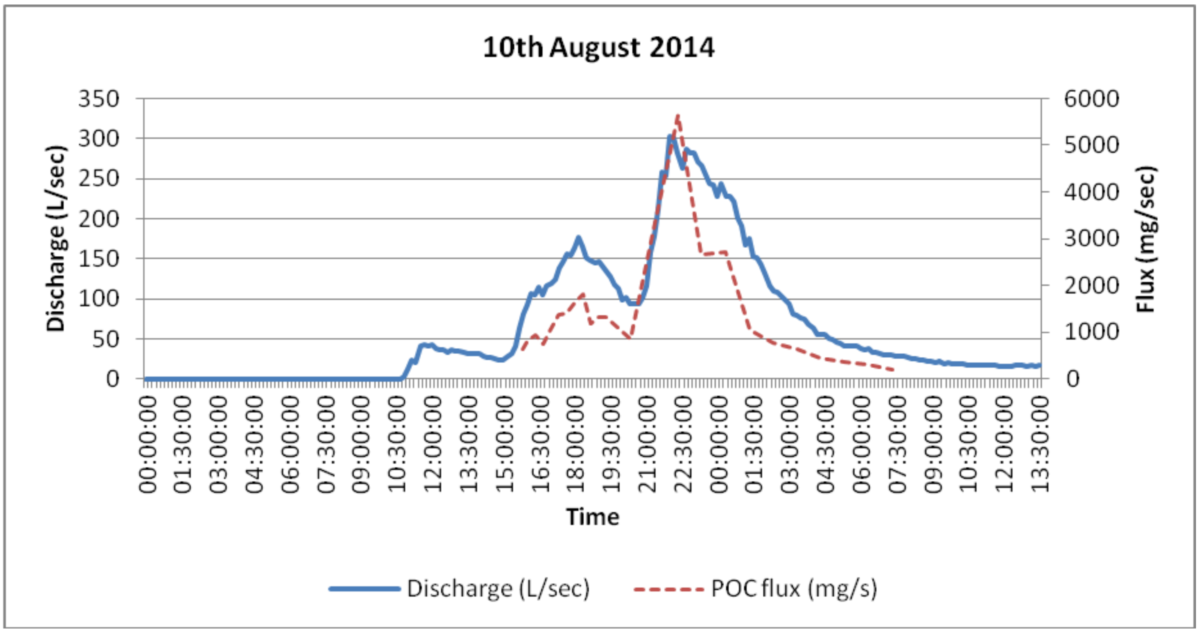

Figure 48 - 10th August POC flux

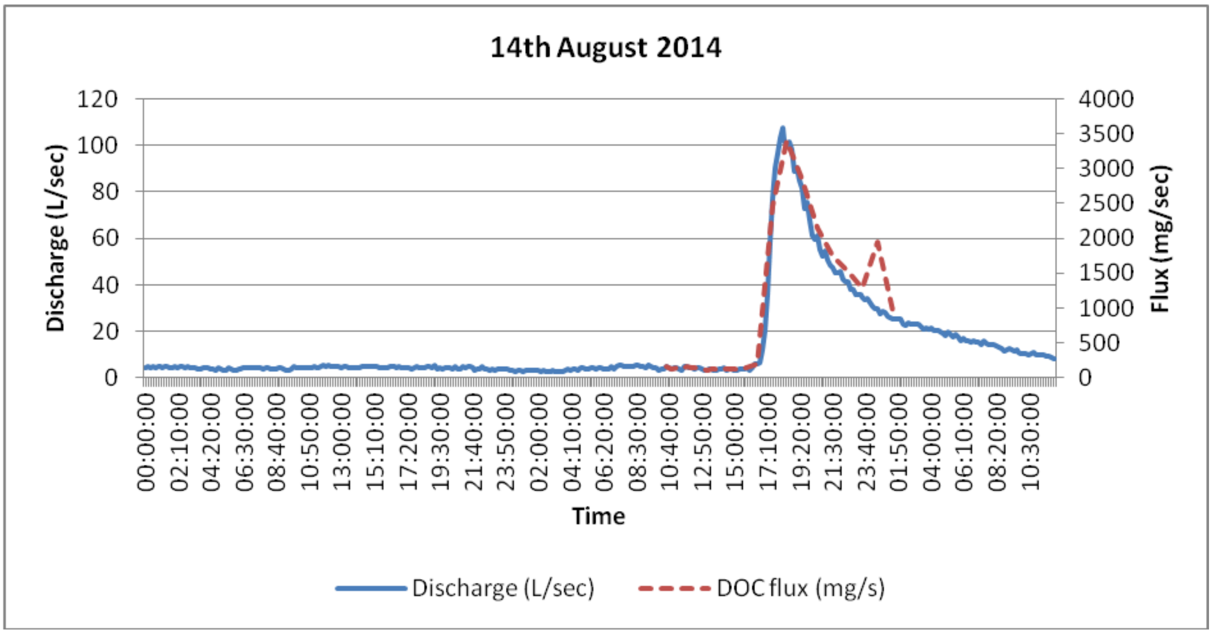

Figure 49 – 14th August DOC flux

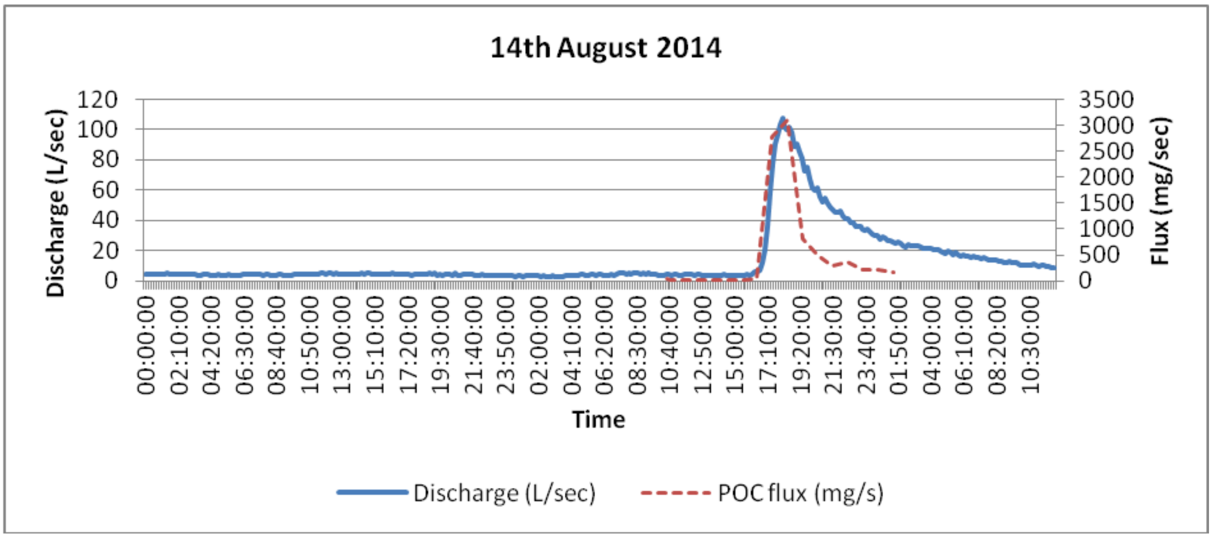

Figure 50 14th August POC flux

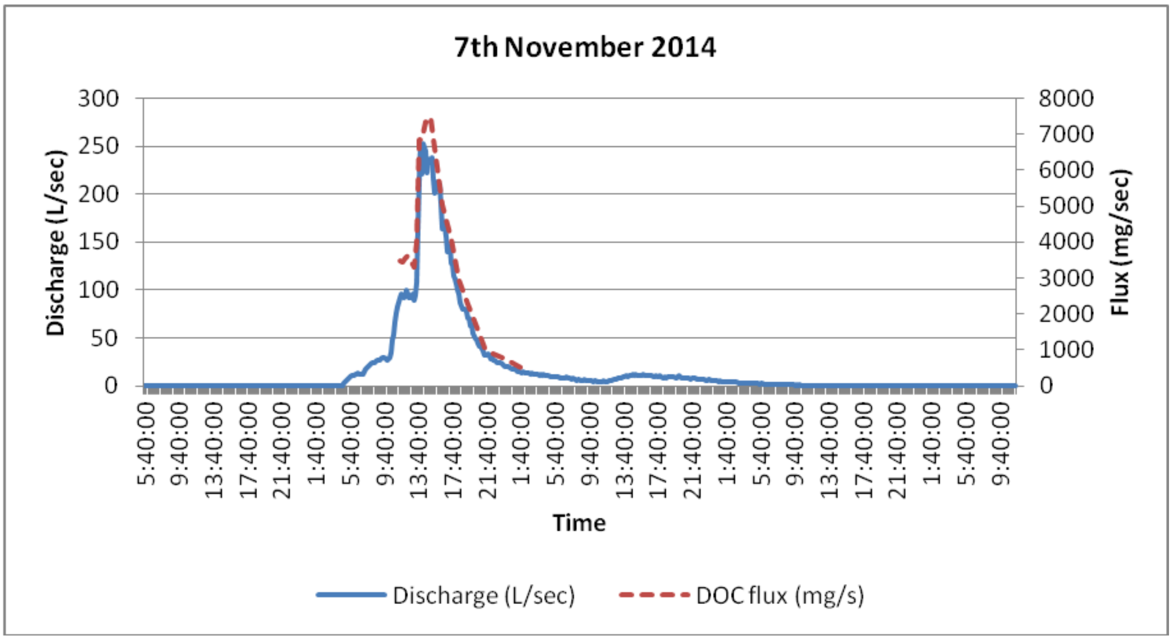

Figure 51 – 7th November DOC flux

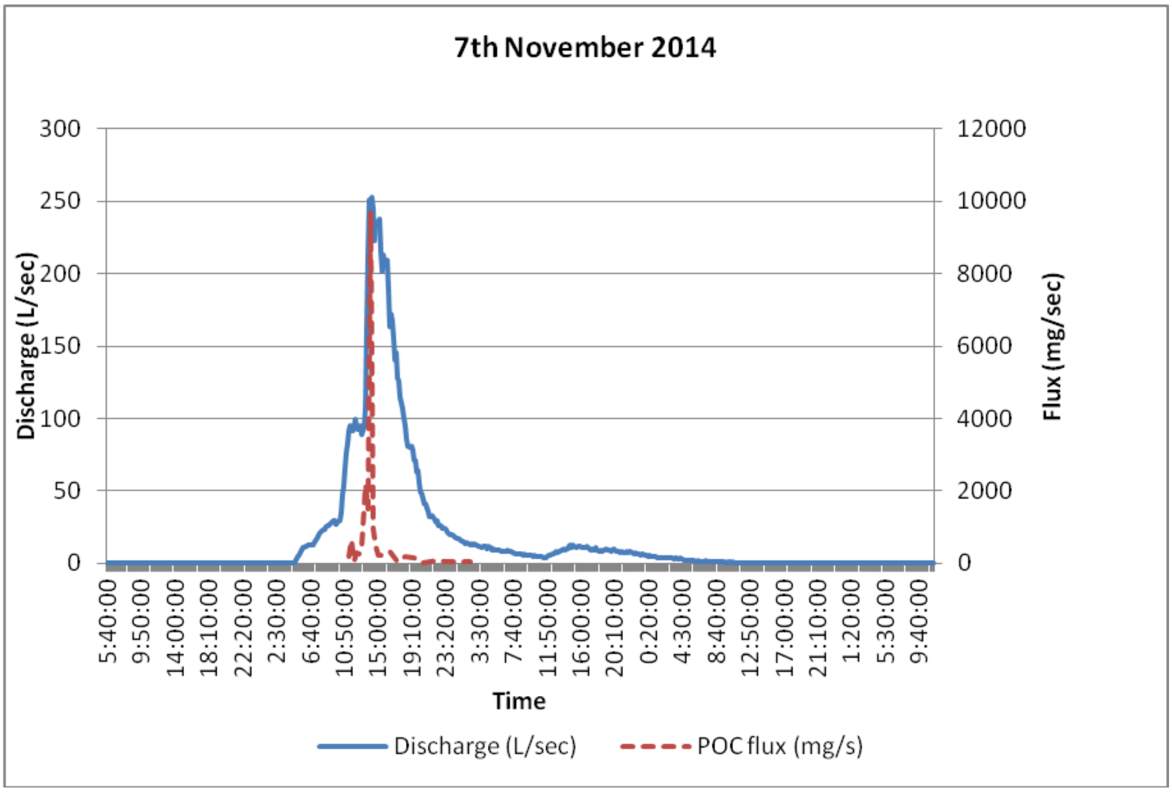

Figure 52 7th November POC flux

6.3.4.4. Carbon flux during storm events

Table 13 shows the total POC and total TOC loss in kilograms for the sampled portion of storms. On average, POC made up 16% of the total organic carbon, suggesting that DOC is a more significant component of the organic carbon.

The large storm event on 10th August, 2014 was responsible for nearly 300kg of organic carbon being lost into the fluvial system over a 14.5 hour period. One of the smaller storms sampled, on 19th July 2014 recorded much lower DOC and POC flux can be seen (Figure 53 and Figure 54). During this storm just under 7kg of TOC was lost into the Stable Clough catchment over a 14 hour period. Just 9% of this was POC.

One of the smaller storms sampled, on 19th July 2014, a much lower DOC and POC flux can be seen (Figure 53 and Figure 54). During this storm just under 7kg of TOC was lost into the Stable Clough catchment over a 14 hour period. Just 9% of this was POC.

In addition, the hydrographs exhibit slightly different behaviour: during the larger storms, POC and DOC appear to peak after peak discharge.

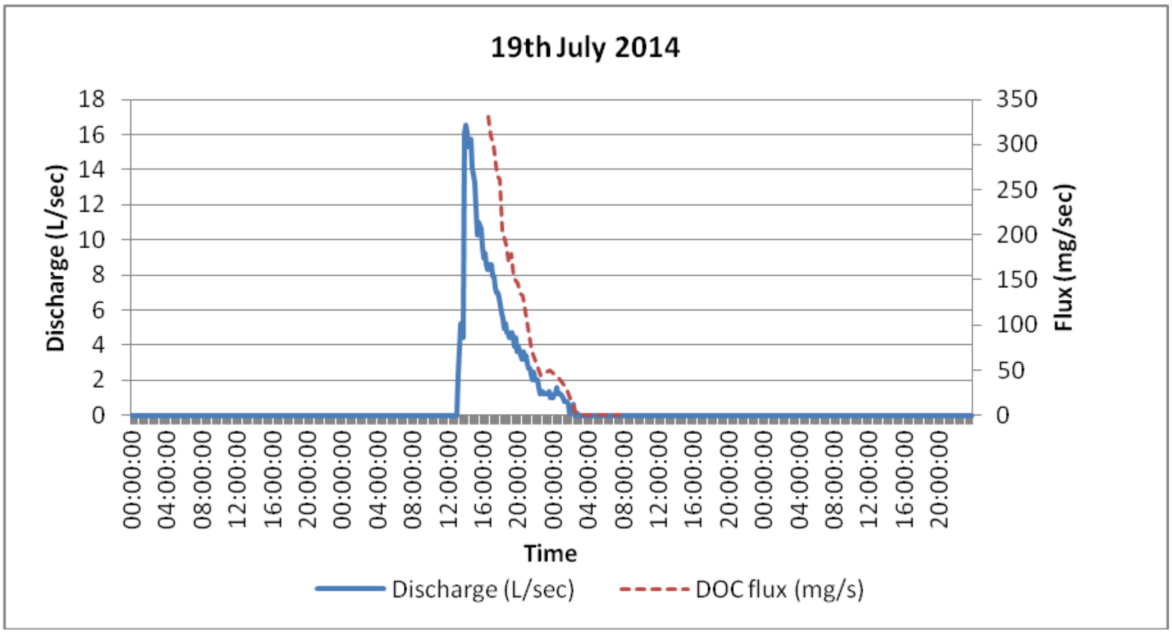

Figure 53 – 19th July DOC flux

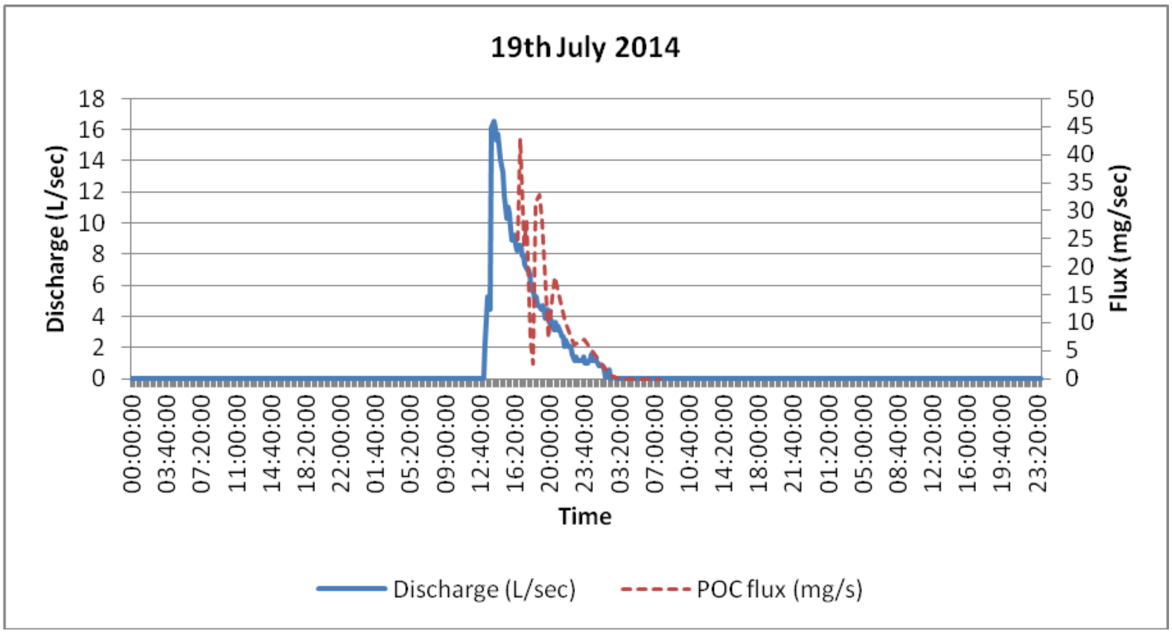

Figure 54 19th July POC flux

Table 13 - Descriptive figures for storm events – missing DOC/TOC/POC values indicate that samples were not sent to labs for analysis.

Date of storm	Peak storm flow (L/sec)	Mean E4/E6 ratio	Maximum colour (Hazen)	Maximum POC (mg/l)	Maximum DOC (mg/l)	Maximum TOC (mg/l)	Max POC flux (mg/s)	Max DOC flux (mg/s)	Max TOC flux (mg/s)	Total POC flux (mg/s)	Total DOC flux (mg/s)	Total TOC flux (mg/s)	Total POC loss during storm event (kg)	Total TOC loss during storm event (kg)	Proportion of organic carbon that is made up of POC
28/03/2014	70.2	7.9													
22/04/2014	13.7	6.7													
07/05/2014	154.4	5.6													
23/05/2014	194.5	6.0		19	30	43	2956	4862	6690	11477	41885	50152	17.6	76.9	22.9
09/06/2014	53.0	6.4													
19/07/2014	16.6	6.7		7	40	44	43	331	355	308	3016	3217	0.6	6.8	9.6
10/08/2014	303.5	6.1	690	20	40	50	5634	8170	13804	33160	103963	136641	72.1	297.2	24.3
14/08/2014	107.3	9.0	660	36	65	68	3108	3408	6516	8666	20431	28123	19.5	63.3	30.8
26/08/2014	83.2	6.7	790	16	44	55	1332	3505	4577	7388	38185	45425	17.0	104.5	16.3
06/10/2014	165.5	6.8	710	8	48	55	1124	7780	8608	11246	89735	100989	25.0	224.7	11.1
13/10/2014	98.3	6.6	800	13	44	47	717	3853	4112	6671	58466	64622	15.7	151.9	10.3
21/10/2014	125.3	7.2	670	12	34	42	1227	3476	4294	10581	79641	90171	24.3	207.4	11.7
02/11/2014	16.1	7.4													
07/11/2014	252.9	7.0	720	44	38	75	9737	7459	16597	18253	88022	106442	41.1	239.5	17.1
12/11/2014	50.9	6.7													
14/11/2014	99.3	7.7	570	10	41	43	779	3772	3910	2512	39021	41297	5.8	96.0	6.1
21/11/2014	106.3	6.5													

6.4. Discussion

Gully blocking – impact on DOC/colour

Gully blocking with stone had no observable impact on water colour or DOC concentration during the monitoring period, and there was no observable change in POC concentrations. This finding is not unexpected, since the primary mechanism by which gully blocking would impact on DOC would by raising of the water table. The primary purpose of stone gully blocks is to trap sediment. This aim was achieved on Woodhead. Data collected from automated dipwells on Woodhead have been inconclusive in assessing the impact of stone gully blocks on water tables due to the limitations of monitoring unique locations.

If water tables have increased, this would only be in a small area around gully blocks, rather than an increase in water table across the wider landscape.

Gully blocking – impact on POC

A smaller proportion of water samples contained POC after gully blocking than before in treated systems. However, this difference was not statistically significant for any site. Therefore it is not possible to conclude from this study that gully blocking with stone and in isolation of other treatments had an effect on POC. The pre-treatment period provided relatively few samples, and so this may have restricted the ability of the study to detect a change. In addition, the storm sampling demonstrated that high volumes of POC are released during storm events. While spot sampling has been useful for colour and DOC content of water samples, its use in monitoring POC has been limited since many samples are collected during low flows.

The Catchment Restoration Fund monitoring programme undertaken by MFFP used Time Integrated Sediment Flux units (TIMS) to monitor the volume of POC transported in gullies from various restoration scenarios (Crouch et al 2015). This study found that in 2013, POC transport in gully flow in revegetated and blocked gully systems was 99% lower than in unblocked, unvegetated gully systems on The Edge, Kinder Scout. Also on Kinder, on Seal Edge, blocked and revegetated gullies in bare peat were reported to have 57% lower POC transport than in revegetated-only systems in 2013. This was maintained in 2014 with a 68%

lower POC transport in blocked and revegetated gullies compared to revegetated-only. This second site suggested that gully blocking in addition to revegetation treatments gave added benefit in reducing POC loss.

Re-vegetation – impact on POC

No significant change in POC occurrence was detected at Stable Clough. However, much of the published work on the impact of revegetation on sediment loss indicates that MFFP's historic work has been highly successful in trapping sediment through protection of the peat surface from erosive processes and filtering organic particles from overland flow (Shuttleworth *et al,* 2015). Several years following revegetation, the sediment yields have been reduced to rates comparable to those of intact peatland. While Woodhead is different topographically, it has undergone much of the same treatments as other monitored sites, and so our expectation would be for these catchments to follow the same trajectory.

Continued monitoring of POC and sediment, and introduction of alternative sediment monitoring methods (such as TIMS units) is recommended to inform such trajectories, and to be able to inform future management of the site.

The main source of sediment from revegetated sites is from gully walls (Shuttleworth *et al* 2015). This is likely to be the case on Woodhead, with many, if not most gullies being steep sided and with bare peat walls. Within the Stable Clough catchment, revegetation treatments will be most effective on the flatter areas of peat, and revegetation of gully bottoms is likely to result in the trapping of sediment. This is less likely to be the case in systems 1 and 2 where no revegetation works have taken place, and recolonisation of the gully floors with vegetation is slow.

Re-vegetation – impact on DOC/colour

The application of lime as part of the revegetation work resulted in temporary decreases in colour of up to 43%. This can be clearly seen in the reduction of peak Hazen in summer/autumn 2013 in comparison to that of the Smithy Clough gullies which were not treated with any lime or fertiliser applications. Further fertiliser treatments were undertaken up to March 2015 on Woodhead – beyond period of analysis – and so it would be several more months, if not years, before the longer-term effects of revegetation works can be begin to be evaluated. The effect of liming has been studied as part of the MFFP Making Space for Water project and a United Utilities funded PhD project on Kinder Scout. The potential mechanism supported by this work is reduced solubility of DOC and particles falling out of suspension in the water due to calcium ions binding with humic substances (Evans *et al* 2015).

In order to understand the longer-term impacts of the conservation activities on water colour, a longer monitoring programme that captures several more years of seasonal variation will be required. Studies such as UU's SCaMP monitoring have found a significant, but slight, decrease in water colour after 7 years of monitoring post-works

The longest monitoring dataset of the impact of blanket bog restoration works on water colour(a proxy for DOC) comes from United Utilities' 'Sustainable Catchment Management Programme (SCaMP). Up to two years post treatment, an increase in raw water colour was found; however, monitoring data between 3 to 6 years post restoration a slight, but statistically significant decrease in raw water colour has been recorded, although this was not a consistent trend across all sites. While preliminary, these results are extremely encouraging (Hammond & Ross, 2014).

Storm sampling

Storm sampling highlighted the episodic nature of POC release, and demonstrated that even through gully blocking and revegetation works, there is still some POC loss through the fluvial system. Further work needs to be done to understand this POC loss in the context of other sites. The absence of pre-works storm sampling and the absence of an untreated control mean that no comparisons can currently be made to understand the scale of POC loss.

While a weak, positive relationship was found between discharge and POC concentration, this is complicated by the hysteresis of storm events. Sediment source will also be an important factor. The hysteresis of the August storm events demonstrated that one discharge value can have two POC concentrations – high on the rising limb, and low on the falling limb – as the supply of readily available sediment is exhausted during a single storm event. Time between storms will also be important, as shown again by the two August 2014 events sampled.

POC contributed between 10% (baseflow) and 16% (storm flow) of the fluvial carbon flux – a lower value than calculated for the unrestored Upper North Grain on the southern slopes of Bleaklow (Pawson *et al,* 2008).

6.5. Recommendations

- A review of POC monitoring would lead to improved monitoring for individual sites.
- Simultaneous storm sampling in control system and another revegetated system to compare POC flux differences between different types of treatment scenario.
- Modified spot sampling regime – either weekly, or use autosampler to take more regular samples – e.g. intensify sampling effort during autumn period.
- Investigation of new technologies – e.g. Spectrolysers - to enable continuous water quality monitoring.

7. References

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 Partnership, Edale, Derbyshire

Allott, T., Evans, M., Agnew, C., Milledge, D. & Pilkington, M. (2013). Storm hydrograph characteristics of intact, eroded and re-vegetated peatland catchments: a preliminary analysis. A progress report for the 'Making Space for Water' project. Moors for the Future Partnership, Edale.

Allott. T., Shuttleworth, E., Evans, M., Agnew, C., Pilkington, M., Spencer, T., Milledge, D., Gorham, J., Mellor, J., Jones, A., Richards, R., Maskill, R., Walker, J. (2015). Restoration of blanket bogs; flood risk reduction and other ecosystem benefits. Annex 5: Flood risk. Moors for the Future, Edale.

Bunce, R.G.H., Barr, C.J., Gillespie, M.K., Howard, D.C., Scott, W.A., Smart, S.M., van de Poll, H.M. & Watkins, J.W. 1999. *Vegetation of the British countryside the Countryside Vegetation System.* ECOFACT Volume 1. London: Department of the Environment, Transport and the Regions.

Clark, J. M., Lane, S., Chapman, P. And Adamson, J. 2007 Export of dissolved organic carbon from an upland peatland during storm events: implications for flux estimates. *Journal of Hydrology, 347 (3-4)*

Crouch, T., Walker, J.S. and Morley, K. (2015) Peatland Restoration Project: Rivers Alport and Ashop Monitoring Report. Moors for the Future Partnership, Edale.

Evans CD, Monteith DT, Cooper DM 2005. Long-term increases in surface water dissolved organic carbon: observations, possible causes and environmental impacts. *Environmental Pollution,* 137**,** 55-71.

Evans, M., Stimson, A., Allott, T., Pilkington, M., Shuttleworth, E., Holland, N., Spencer, N., Spencer, T., Maskill, R., Walker, J. (2015). Restoration of blanket bogs; flood risk reduction and other ecosystem benefits. Annex 4: Dissolved Organic Carbon concentrations. Moors for the Future Partnership, Edale.

Hill, M.O., Mountford, J.O., Roy, D.B. & Bunce, R.G.H. 1999 *Ellenberg's indicator values for British plants.* Huntingdon: Institute of Terrestrial Ecology

Hammond & Ross (2014) United Utilities Sustainable catchment management programme: Water quality monitoring results July 2012. Report to United Utilities. Penny Anderson Associates, Buxton. Penny Anderson Associates

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

JNCC, (2009), Common Standards Monitoring Guidance for Upland Habitats, Version July 2009

Marsh, T.J., Parry, S., Kendon, M.C. and Hannaford, J. 2013. The 2010-12 drought and subsequent extensive flooding. Centre for Ecology and Hydrology. Wallingford, UK

Maskill, R., Walker, J., Allott, A. (2012) *Kinder 'Peatlands for the Future' Project Monitoring Report.* UK: Moors for the Future Partnership.

Met Office (2015) 2012 – a wet year. http://www.metoffice.gov.uk/learning/learn-about-the-weather/weather-phenomena/case-studies/2012-a-wet-year. Accessed September 2015.

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

Shuttleworth, E.L., Evans, M.G., Hutchinson, S.M. & Rothwell, J.J. (2015). Peatland restoration: controls on sediment production and reductions in carbon and pollutant export. Earth Surface Processes and Landforms, 40, 4, 459-472.

Worrall, F., Rowson, J.G., Evans, M.G., Pawson, R., Daniels, S., and Bonn, A. (2011) Carbon fluxes from eroding peatlands – the carbon benefit of revegetation following wildfire. Earth Surface Processes and Landforms, 36, 1487-1498.

Whiteley, A. (2010). An Evaluation of Artificial Gully Blocking Techniques in the southern Pennines. MSc. dissertation submitted to the University of Manchester.