MoorLIFE:
Changes to the water table and carbon budget

October 2015

(LIFE08 NAT/UK/00202)

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Suggested citation: Maskill, R., Walker, J.S, Allott, T., Evans, M. and Shuttleworth, E. (2015). MoorLIFE: Changes to the water table and carbon budget. Moors for the Future Report, Edale, Derbyshire.

Acknowledgements: With thanks to all the staff members and volunteers who have assisted with dipwell and water sampling campaigns. Thanks go particularly to Jemma Benson, Gareth Roberts, Tony Rogers, Stuart Rudgyard, Paul Titterton, David Ward, Tom Spencer, Sam Heap and Dave Bowen for all their hard work in all weathers. Also thanks to Cath Wynn, Laura King, Debra Wilson, Brendon Wittram and Sharon Davison for support, Jorge Auñon for GIS work and Claire Hanley-Öpik for formatting.

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1. Executive Summary

1.1. The MoorLIFE Project

The MoorLIFE project was a five-year project that began in 2010 and was the biggest moorland conservation project in Europe at that time. Its aim was to protect active blanket bog within the South Pennines SAC and increase biodiversity through stabilisation and revegetation of eroding surfaces. Its objectives were:

1. Stabilisation of inactive bare peat (through establishment of nurse crop on bare peat);
2. Restore moorland vegetation on these, and previously stabilised sites, and onto active blanket bog communities (through plug planting and application of *Sphagnum* propagules); and
3. To reduce peat and water flow and restore hydrological integrity (through gully blocking).

Works were undertaken across four sites: Bleaklow, Black Hill, Rishworth Common and Turley Holes (Figure 1).

The MoorLIFE project had an extensive, landscape-scale, scientific monitoring programme. It was designed to monitor and assess the impact that the conservation works had on vegetation succession and hydrology. This report focuses on the results of the hydrology and erosion monitoring work undertaken as part of MoorLIFE.

1.2. Impacts 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.

The MoorLIFE monitoring programme has demonstrated that revegetation of bare peat is associated with a rise in water table. Data collected from autumn sampling campaigns of 'manual' dipwells showed that two years following revegetation, water tables at Turley Holes have risen by 22mm. Revegetated bare peat sites on Bleaklow also showed signs of a slight rise in water table of 11mm one year following revegetation. While the Bleaklow results are not statistically significant, this site was monitored just one year following revegetation. This suggests that the rise in water tables observed is a slow, steady increase rather than a rapid, sudden change.

Automated dipwells showed that water table behaviour changed following revegetation. The ranges of water table depth measurements were smaller at each automated dipwell, suggesting that water table has stabilised to some degree. Water tables were not as low following revegetation as they had before works were undertaken. This finding supports evidence gathered from similar studes which suggests that more pronounced differences between bare peat and revegetated sites were observed when water tables were at their deepest.

Comparison of water table depth and behaviour at treatment and untreated control sites demonstrate that the observed changes are associated with the MoorLIFE capital works, rather than natural variation.

1.3. Impacts on sediment loss/accumulation

Sedimentation surveys undertaken within the Woodhead Gully Block monitoring project on MoorLIFE gully blocks demonstrated that 18 months after installation 100% of dams were holding water and 82% were holding accumulated sediment. In addition, significant changes in sediment depth behind stone dams werer observed following their installation. Sediment depth was found to increase 14cm in blocked gullies relative to an unblocked control. The majority of sediment accumulation occurred within 3 weeks of installation.

A number of recent studies provide supporting evidence for the benefits of the MoorLIFE capital works. Comparisons of sediment loss from bare peat sites and revegetated sites on Bleaklow by Shuttleworth *et al* (2015) showed that the historic work of MFFP has been successful in effectively shutting down erosion pathways on sites where peat stabilisation works have taken place. Similar studies by MFFP’s Catchment Restoration Project demonstrated that gullies that had been revegetated and gully blocked had significantly lower sediment loss than gullies that had been untreated.

Given the very similar nature of the MoorLIFE capital works to those monitored above, it is entirely reasonable to expect sediment loss on treated areas of Bleaklow, Rishworth Common and Turley Holes to have been significantly reduced.

Peat anchors installed on other MFFP projects will continue to be monitored to provide long term evidence of the differences in erosion rates on intact and revegetated areas of blanket bog.

Work undertaken by Worrall *et al* (2011) to examine the carbon benefits of undertaking peat stabilisation works on Bleaklow showed a high carbon benefit of revegetation. This study considered a variety of carbon flux pathways and found that most restored sites had improved carbon budgets (decreased source and/or increased sink of carbon) when compared to unrestored, bare peat sites. This improvement was mainly in the form of avoided loss of carbon through pathways such as erosion of sediment. The study concluded that the carbon sequestration benefit of peatland restoration on Bleaklow ranged between 122 and 833 tonnes C/km^2/yr.

In addition, work undertaken by Shuttleworth *et al* (2015) has demonstrated sediment loss from revegetated sites to be several orders of magnitude lower than untreated bare peat sites.

Therefore it can be concluded that the most immediate and significant impact of the MoorLIFE capital works on the carbon budgets of treated blanket bog has been the reduction of sediment loss from areas of bare peat.

In treating these areas of bare peat and preventing significant erosion, adjacent areas of active blanket peat have been protected from the threat of ongoing erosion and potentially further lowering of water tables.

1.4. Impacts on water quality

1.4.1. *Impact of gully blocking treatments on water quality.*

Gully blocking in vegetated blanket bog on Woodhead had no observable impact on water colour or dissolved organic carbon (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 particulate organic carbon (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 statistically significant.

1.4.2. *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.

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

2. Introduction

The MoorLIFE project was a five-year project that began in 2010 and was the biggest moorland conservation project in Europe at that time. Its aim was to protect active blanket bog within the South Pennines SAC and increase biodiversity through stabilisation and revegetation of eroding surfaces. Its objectives were:

1. Stabilisation of inactive bare peat (through establishment of nurse crop on bare peat);
2. Restore moorland vegetation on these, and previously stabilised sites, and onto active blanket bog communities (through plug planting and application of *Sphagnum* propagules); and
3. To reduce peat and water flow and restore hydrological integrity (through gully blocking).

Works were undertaken across four sites: Bleaklow, Black Hill, Rishworth Common and Turley Holes (Figure 1).

The MoorLIFE project had an extensive, landscape-scale, scientific monitoring programme. It was designed to monitor and assess the impact that the conservation works had on vegetation succession and hydrology. This report focuses on the results of the hydrology and erosion monitoring work undertaken as part of MoorLIFE. The objectives of this section of the monitoring programme were:

1. To monitor the impact of revegetation on water tables;
2. To assess the effect of stabilisation on peat capture and accumulation;
3. To monitor the impact of the capital works on water quality (carbon).

Figure 1 - overview of the locations of the four MoorLIFE sites in the north of England.

2.1. MoorLIFE sites

2.1.1. *Turley Holes*

Turley Holes is the most northerly of the MoorLIFE sites, situated approximately 30 km north-west of Bleaklow. The site has the similar expansive areas of bare peat on its slopes, with peat pans dominating on the flatter areas. Peat stabilisation works (geotextiles, heather brash, lime, seed and fertiliser) and diversification (plug planting and *Sphagnum* applications). This site has received treatments of lime, seed, fertiliser, plug plants and *Sphagnum* bead applications as part of the MoorLIFE project.

2.1.2. *Rishworth Common*

Rishworth Common is north of the Peak District National Park and the site is divided by the M62 motorway. In 2010 the area to the south of the motorway had large areas of bare peat which received stabilisation treatments of lime, seed, fertiliser, and diversification treatments of plug plants and *Sphagnum* bead applications. Areas to the north of the M62 were well vegetated, if species poor, and were treated with *Sphagnum* beads in 2014 and 2015.

2.1.3. *Black Hill*

Black Hill was considered here as a previously revegetated site, having undergone initial stabilisation treatments in 2006. Black Hill was the first MoorLIFE site to receive applications of *Sphagnum* propagules in September 2012. No other treatments were applied.

Figure 2 - Aerial views of the four MoorLIFE sites. Clockwise from top left: Bleaklow (Woodhead), Black Hill, Turley Holes and Rishworth Common.

2.1.4. *Bleaklow*

Bleaklow is the second highest hill in the Peak District National Park with a summit of 630m. Extensive areas of bare peat have been successfully revegetated over more than ten years through conservation works (Figure 2). As such some areas of Bleaklow are considered by MFFP as being‘previously’ revegetated. Peat stabilisation works (geotextiles, heather brash, lime, seed and fertiliser); diversification (plug planting and *Sphagnum* applications) and gully blocking were undertaken across the plateau by the MoorLIFE project.

3. Water table

3.1. Introduction

Water table depth and behaviour is strongly associated with the erosion status of blanket peat. Water tables at intact sites are, as expected in blanket bog, consistently close to the ground surface. In contrast, water tables at eroded, bare peat sites are often greater than 300mm below the ground surface (Allott *et al* 2009). Erosion gullies cause both a local drawdown effect and a general site wide water table lowering. This site-wide effect is hypothesised to result from reduced hydrological contributing areas (drainage areas) at eroded sites (Allott *et al* 2009). Water moving through the peat landscape is diverted into gully channels, rather than being able to drain through the blanket peat down the hillslope.

Revegetation 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 evapotranspiration 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.

3.2. Methods

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.

Four scenarios were represented in the water table monitoring:

Treatment sites

These were sites that received full peat stabilisation treatments of brash, lime, seed and fertiliser. This scenario was monitored on Bleaklow, Rishworth Common and Turley Holes.

Previously revegetated sites

Previously revegetated sites were present on Bleaklow (Peaknaze) and Black Hill. These were sites where initial restoration treatments took place between 2003 and 2006. At the start of the MoorLIFE project, previously re-vegetated sites were between four and seven years post initial restoration activities.

Bare peat reference

A number of sites were used as untreated, bare peat reference sites. On Bleaklow, one of MFFP’s long-term bare peat reference sites was used as a comparison for Bleaklow dipwell clusters.

Small areas of bare peat on Turley Holes and Rishworth Common were protected from works to provide on-site reference areas. These small areas were treated at the end of the project. Unfortunately, the bare peat reference site on Rishworth suffered a degree of damage and so monitoring here was discontinued.

Intact reference

Areas of blanket bog that had intact vegetation and little influence from erosion gullies were used as intact reference sites.

While dipwell clusters were established on all four MoorLIFE sites, for clarity, only data from Bleaklow and two on Turley Holes were analysed. The date of seeding was used to divide data into ‘before’ and ‘after’ data. Data from treatment sites was also compared against the bare peat control clusters on each site, using data from matching time periods. Table 1 and Table 2 show the dipwells used and the time periods extracted for analysis.

Table 1 – before and after periods for automated dipwells on Bleaklow, as determined by seeding date. Seeding took place at Bleaklow dipwell clusters between 26th and 27th July, 2013.

Site code	**Before**	**After**
SB	13/01/2011 – 14/08/2012 19/01/2013 – 25/07/2013	15/04/2014 – 26/05/2015
LO	13/01/2011 – 14/08/2012 19/01/2013 – 25/07/2013	15/04/2014 – 26/05/2015
RI	13/01/2011 – 14/08/2012 19/01/2013 – 25/07/2013	15/04/2014 – 26/05/2015

Table 2 – before and after periods for automated dipwells on Turley Holes, as determined by seeding date. Seeding took place on Turley Holes in April 2012.

Site code	**Before**	**After**
BP1	02/09/2010 – 19/03/2012	03/10/2014 – 02/07/2015
BP2	07/09/2010 – 19/03/2012	03/06/2013 – 02/07/2015

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 (with the exception of Turley Holes in 2011, when a six week campaign was undertaken:

Table 3 and

Table 4). Data collected from manual dipwells were used to provide information on the spatial variability of water table.

Table 3- Clusters and treatment types with manual dipwell campaign dates on Bleaklow

Site	Treatment type	Campaign dates	Number of measurement days
SB	Treatment	15/09/2011 – 01/12/201	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
JP	Previously revegetated	18/09/2014 – 04/12/2014	10 / 12
PO	Previously revegetated		12 /12
PE	Intact reference		12 / 12
SH	Intact reference		12 / 12

Table 4 - Clusters and treatment types with manual dipwell campaign dates on Turley Holes

Site	Treatment type	Campaign dates	Number of measurement days
TH T1	Treatment	17/10/2011 – 28/11/2011	6 / 12
THT2	Treatment		6 / 12
TH T3	Treatment		6 / 12
TH BP Ref	Bare peat reference	18/09/2014 – 04/12/2014	6 / 12
TH Intact	Intact		6 / 12
TH Peat pan	Peat pan		6 / 12

3.3. Results

3.3.1. *Manual water table measurements*

This section examines the differences in water tables between individual dipwell clusters on Turley Holes and Bleaklow before seeding had taken place.

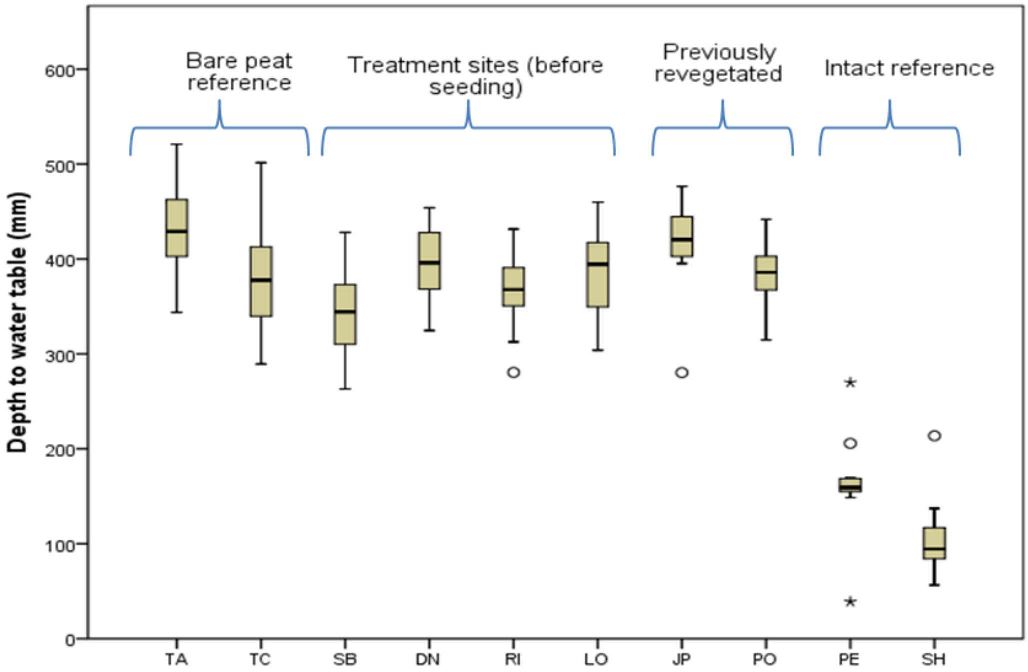
Due to the high degree of variation within dipwell clusters, water table values are based on the mean depth of water measured at each dipwell cluster. Each cluster showed a normal distribution.

Variation in mean water table was also observed between dipwell clusters of the same erosion/treatment state.

Individual clusters showed considerable variation on both Bleaklow and Turley Holes (Figure 3) in 2011. On Bleaklow water tables at treatment and bare peat control were very similar before seeding. Treatment sites on Turley exhibited greater differences in ranges and means of water table.

Variations between sites of the same erosion/treatment status is 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, statistical analysis is undertaken on erosion status rather than individual dipwell clusters – the results of which are presented in the following section.

a)



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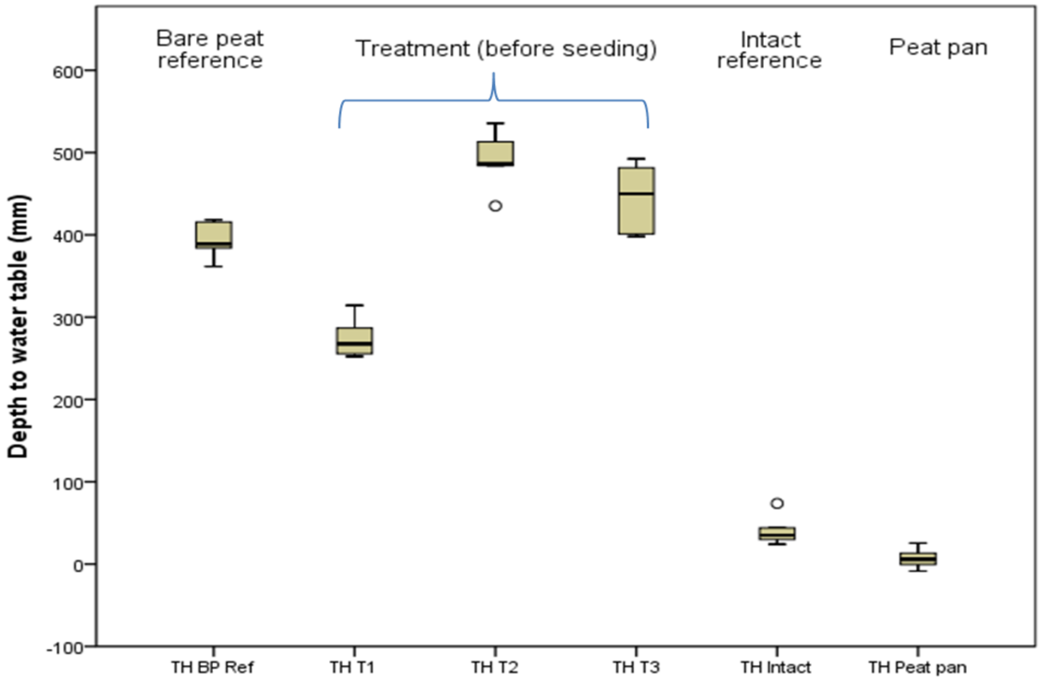


Figure 3 - distribution of water tables at a) Bleaklow and b) Turley Holes in 2011 (before seeding).

3.3.2. *Spatial variation in water tables prior to revegetation*

This section examines differences in water table in areas of different erosion/treatment status before seeding of treatment areas. On Bleaklow a comparison is made between bare peat, intact and previously revegetated areas. On Turley Holes, a comparison is made between bare peat, intact and peat pan areas.

3.3.2.1. Bleaklow

Significant differences existed between the vegetation scenarios (intact blanket bog, previously re-vegetated and bare peat: F = 223.465, df = 2, $p < 0.001$).

Bare peat and late-stage re-vegetated sites exhibited the deepest mean water tables (

Table 5; Figure 4), 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 5 –mean depths to water tables at dipwell clusters on the three erosion/treatment scenarios monitored 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

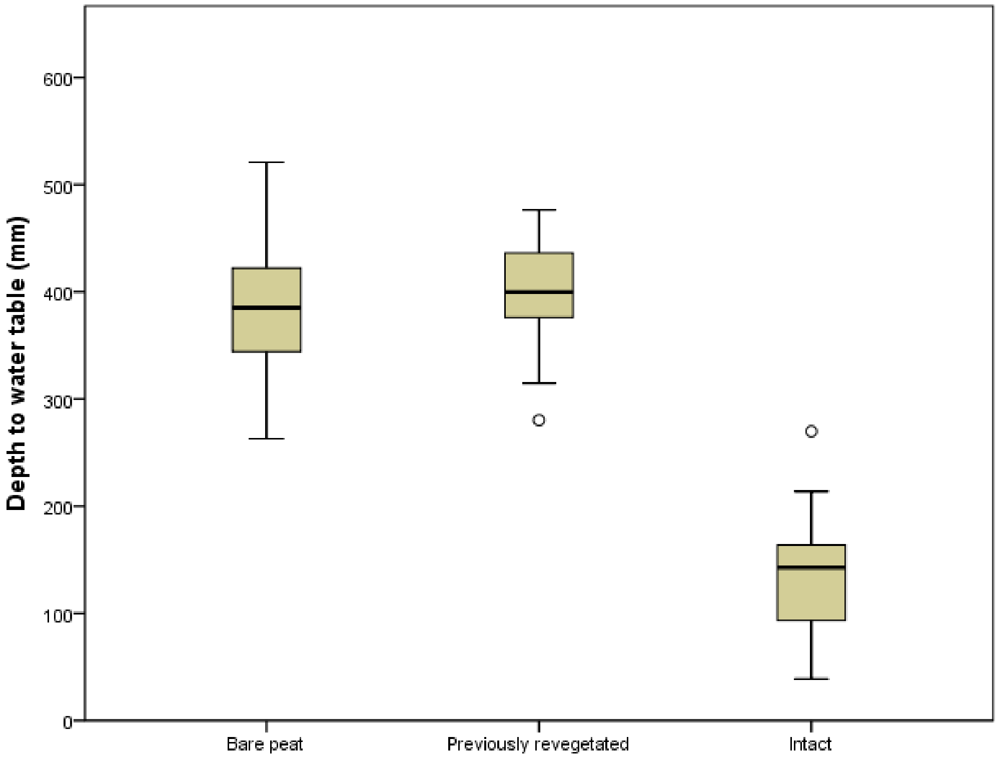


Figure 4 - Distribution of water table depths at bare peat, previously revegetated and intact sites on Bleaklow in 2011

3.3.2.2. Turley Holes

Significant differences existed between the vegetation scenarios on Turley Holes (intact blanket bog, bare peat and peat pan: F = 111.925, $p < 0.001$).

The bare peat sites on Turley exhibited significantly deeper water tables than both the intact and peat pan sites (

Table 6; Figure 5) ($p < 0.001$). The peat pan site exhibited shallower mean water table and a lower range than the intact site. However, mean water table at the intact and peat pan sites were not statistically different ($p > 0.05$).

Table 6 – depths to water tables at dipwell clusters on the three erosion/treatment scenarios monitored in 2011.

		Intact	**Peat pan**	**Bare peat**
2011	**Max**	74	26	536
	Mean	40	7	407
	Median	35	6	416
	Min	24	-9	252
	Range	50	34	283

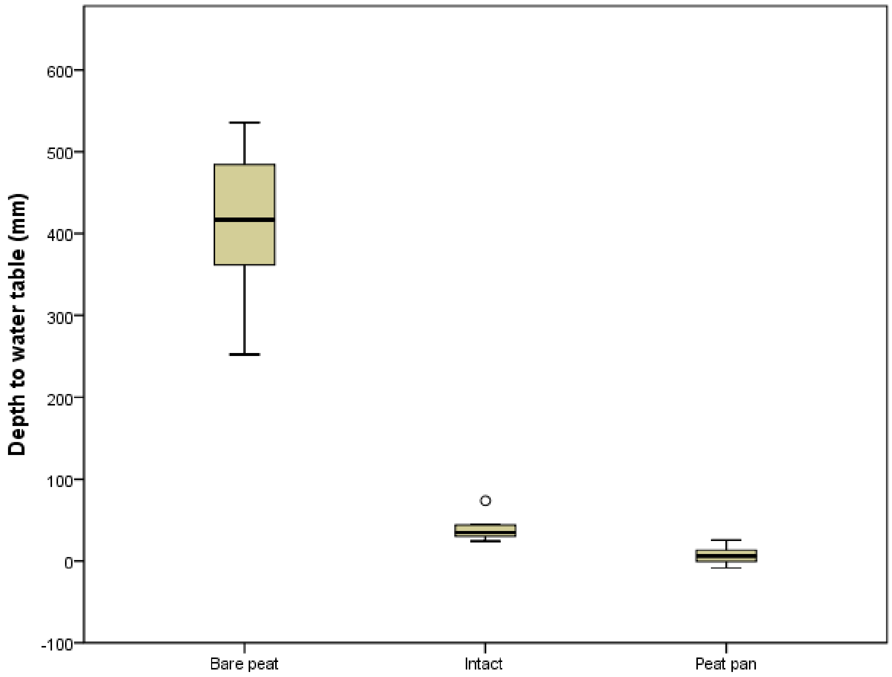


Figure 5 – distribution of water tables on bare peat, intact and peat pan sites on Turley Holes in 2011

3.3.3. *Changes in water tables following re-vegetation*

In this section treatment sites are compared with untreated bare peat sites.

3.3.3.1. Bleaklow

In 2011, pre-treatment sites and bare peat control sites showed a similar range of water table depths; between 263 and 460 mm, and 289 and 521 mm at the treatment and control bare peat sites respectively (Table 7; Figure 6). However, pre-treatment sites exhibited significantly higher water tables than the bare peat control sites ($t = -2.632$, $p < 0.05$) due to the fact that the control bare peat site water tables were consistently deeper on all measurement days (Figure 7).

Initial examination of water tables in 2014 indicates that both sites were wetter than in 2011 during the measurement periods. The control site showed increased variability in water tables, whereas treatment sites maintained a similar range. Since peatland water table depths are controlled by precipitation and evapotranspiration, variation in these factors is a significant influence on variation in water table between years. Therefore, a direct comparison of water tables before and after re-vegetation is not appropriate here as we cannot be sure what is due to treatment or other factors.

Table 7 – water table metrics (mm) for treated sites and untreated control sites on Bleaklow in 2011 (before works) and 2014 (one year after seeding).

		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

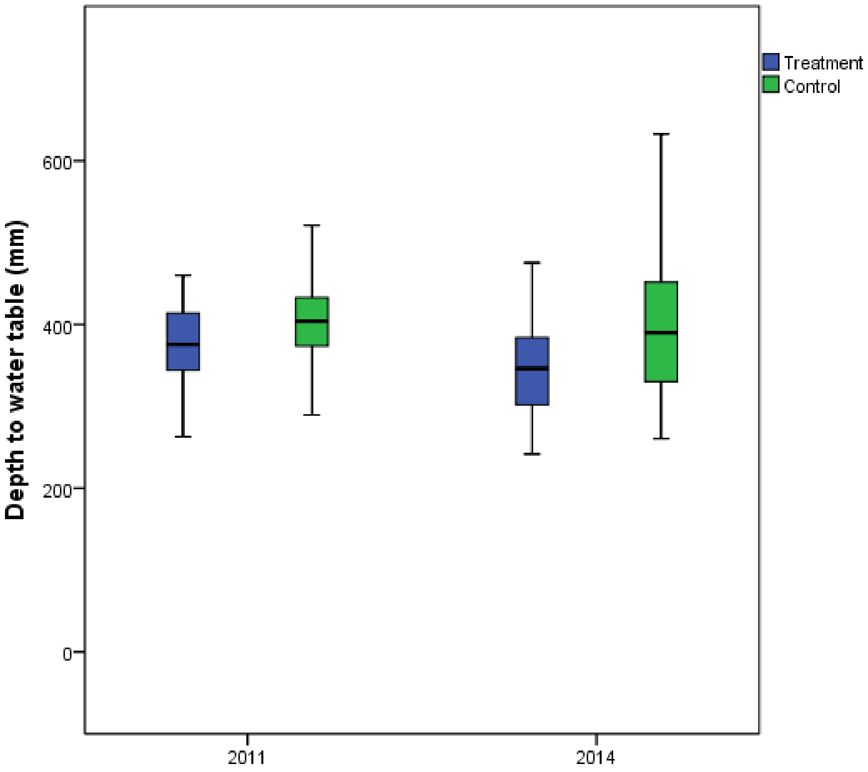


Figure 6 - depth to water table in 2011 (before seeding) and 2014 (after seeding) at treated and untreated bare peat control sites on Bleaklow.

Figure 7 –Treatment and control comparison of depth to water table for Bleaklow study site

Consequently, the differences between water tables at treatment 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, mean water table depth at the treatment sites was, on average 24mm shallower than that of the control sites. In 2014, water table depth at the treatment sites was, on average 35mm shallower than that of the control sites – a relative decrease in depth of 11mm (Figure 8) although not statistically significant ($t = -1.412$, $df = 22$, $p > 0.05$).

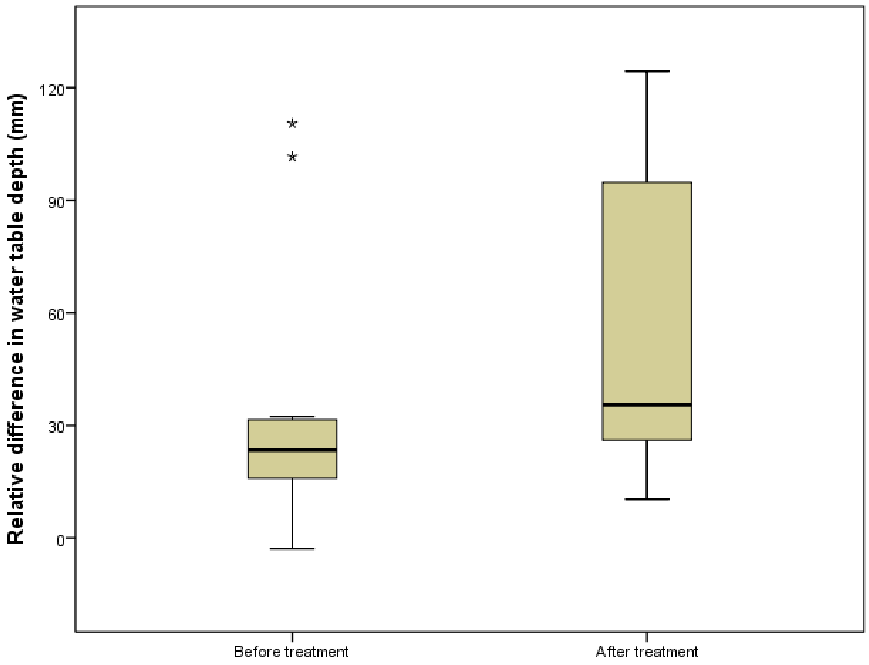


Figure 8 – Relative difference in water table depth following MoorLIFE revegetation at Bleaklow

3.3.3.2. Turley Holes

In 2011, the range of water table depths exhibited at the bare peat control site were noticeably different from those recorded at the treatment sites (Table 8)

While water tables at the treatment sites were consistently deeper than the bare peat control site, mean water table depths of the two scenarios were not significantly different (Figure 9; $t = 0.390$, $p > 0.05$).

In subsequent monitoring years it was observed that the treatment and bare peat control sites behaved in a similar manner. Water tables in 2013, were closer to the surface, and in 2014 showed signs of being deeper again. This is likely to be linked to meteorological variation between years.

Table 8 – summary figures for treated and untreated control sites on Turley Holes in 2011 (before revegetation), 2013 and 2014 (one and two years after seeding).

		Treatment	Control
2011	**Max**	536	418
	Mean	411	394
	Median	440	389
	Min	252	362
	Range	283	57
2013	**Max**	525	450
	Mean	377	350
	Median	401	352
	Min	182	225
	Range	343	224
2014	**Max**	580	505
	Mean	407	406
	Median	433	381
	Min	250	342
	Range	330	163

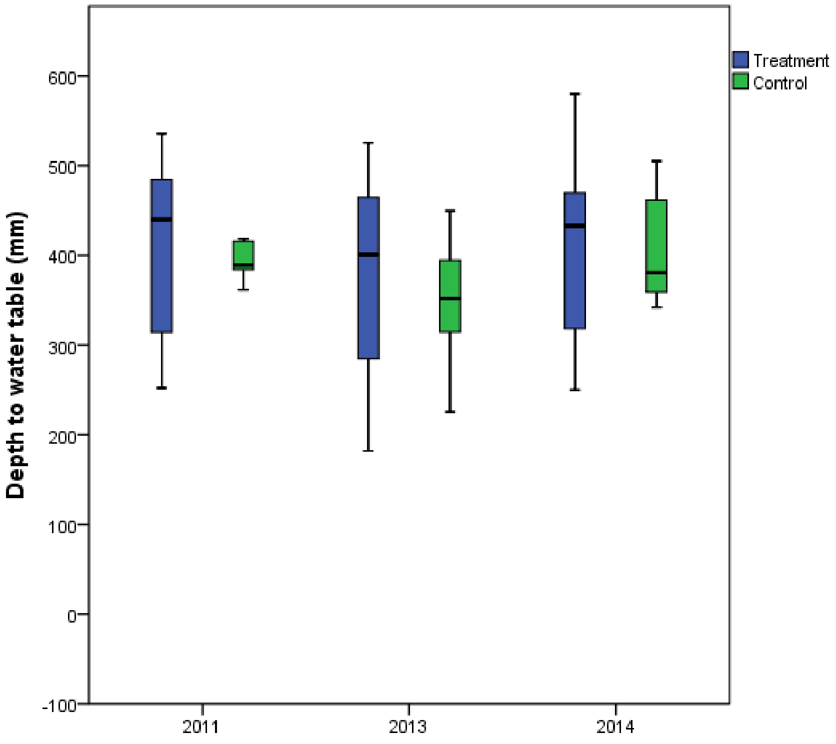


Figure 9 – water table depths at Turley Holes

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

In 2011, the mean water table depth at the treatment sites was, on average 13mm deeper than the bare peat control sites. In 2014, two years after seeding, the water table depth at the treated sites was an average of 4mm deeper than the bare peat control, a relative decrease in water table depth of 8mm. While a box-and-whisker plot (Figure 10) suggests a change in behaviour, there was no significant difference in the mean difference in water tables before and after treatment (t = -0.886, p > 0.05).

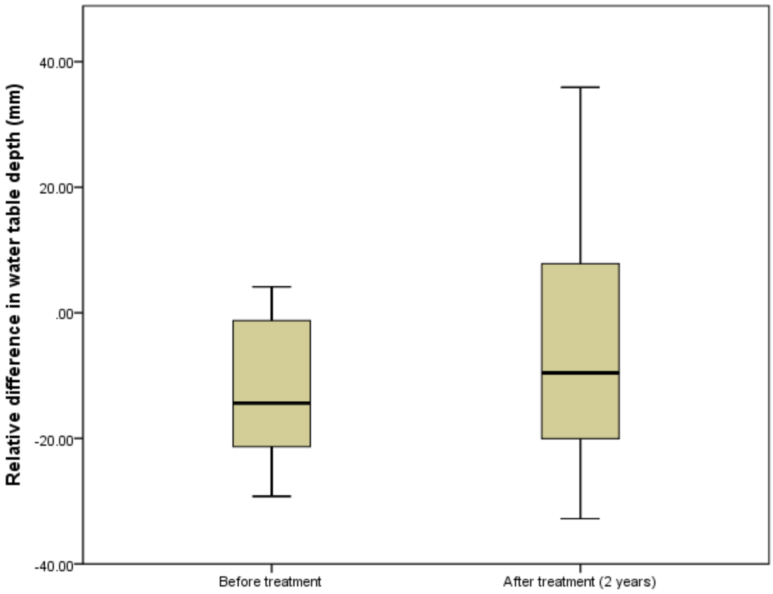


Figure 10 – relative difference in water table depth before and after treatment

Upon closer examination of individual dipwell cluster behaviours at Turley Holes, one cluster (TH T1) was (TH T1) was observed to have behaved in a consistently differently manner to other treatment clusters (

treatment clusters (

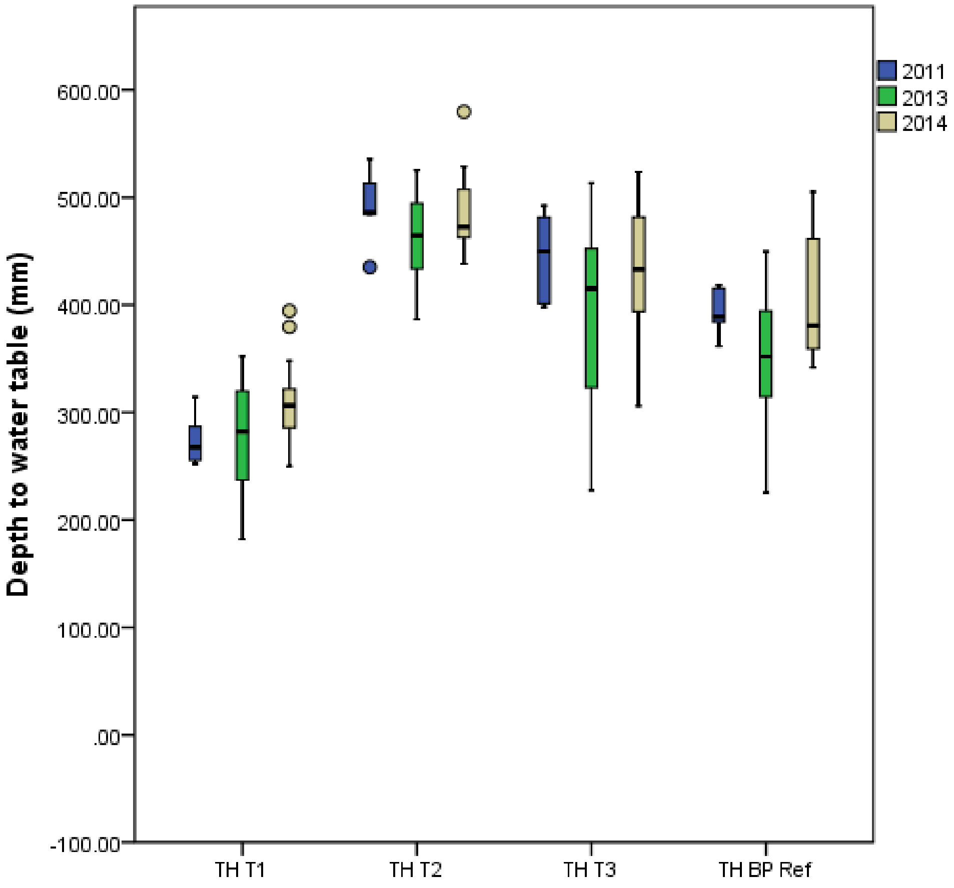


Figure 11). This added an extra layer of ‘noise’ into an already variable data set, and potentially masking any change due to treatments. Because of the difference in behaviour exhibited at TH T1, this analysis was run again, this time excluding this cluster.

Excluding TH T1, a repeat analysis indicated a relative increase in water table at the treatment site of treatment site of 22mm. This was found to be significant ($t = -2.177$, $p = 0.045$;

Figure 12).

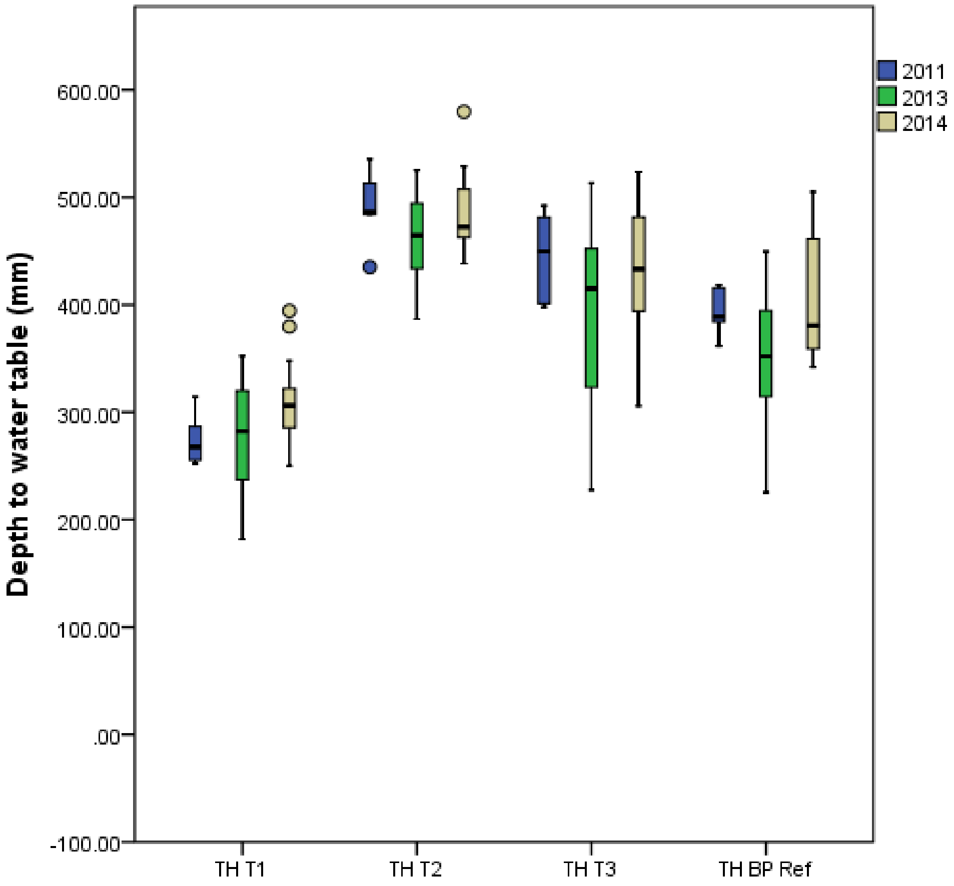


Figure 11- water table depths of treatment and bare peat control dipwell clusters on Turley Holes throughout the monitoring period. One cluster (TH Treatment 1) was observed to have behaved in a consistently differently manner to other treatment clusters

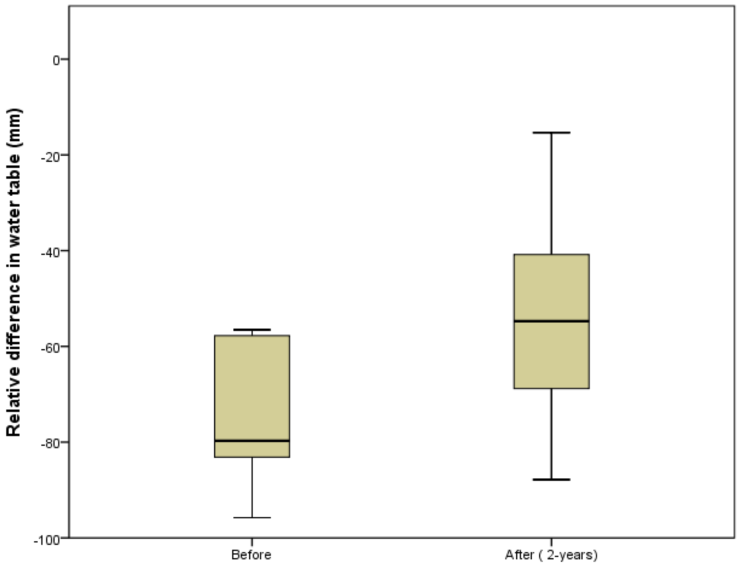


Figure 12 Relative difference in water table depth following MoorLIFE revegetation at Turley Holes

3.3.4. *Changes in temporal variation*

Continuously logging dipwells enabled the analysis of changes in behaviour of water table.

16 months and 18 months pre-treatment data were collected by automated dipwells on Bleaklow and Turley Holes respectively.

Post-treatment data on Bleaklow represented a period of between 9 and 22 months after seeding (13 months data). Post-treatment data on Turley Holes represented a period of between 29 and 40 months after seeding (9 months data).

Data from loggers represents data from an individual dipwell and not of the site as a whole. The summary statistics for individual dipwells are shown in Table 9 and Table 10. Water tables measured by individual dipwells had higher maximum and median water tables in the period after seeding. Range of depths occupied by water tables decreased.

Table 9 - summary statistics of automated dipwells in treatment areas before and after revegetation on Bleaklow.

	SB		**RI**		**LO**	
	Before	**After**	**Before**	**After**	**Before**	**After**
Max	935	748	907	727	596	485
Q3	665	517	634	526	433	346
Median	481	353	555	453	309	191
Q1	349	233	495	389	206	75
Min	-1	-1	81	104	9	-1
Range	936	749	826	623	587	486

Table 10 - summary statistics of automated dipwells in treatment areas before and after revegetation on Turley Holes.

	TH BP1		**TH BP2**	
	Before	**After**	**Before**	**After**
Max	962	791	895	616
Q3	619	547	456	373
Median	546	502	345	290
Q1	489	468	271	258
Min	73	16	60	66
Range	889	775	835	551

The time series of the automated dipwells on Bleaklow show that while the water table at the three treatment dipwells occupied different depths within the peat profile, the water table behaved in a very similar way at all three (Figure 13 – time series of Bleaklow dipwells. The water table recorded at the bare peat control dipwell (TC) was generally deeper than at the three treatment dipwells. The water table at the control dipwell was not as responsive as the three treatment dipwells.

The time series of the automated dipwells on Turley Holes show that the two treatment dipwells and the bare peat control dipwell occupied similar ranges of peat water table depths and behaved in similar ways with concurrent rises and falls in water table (Figure 14).

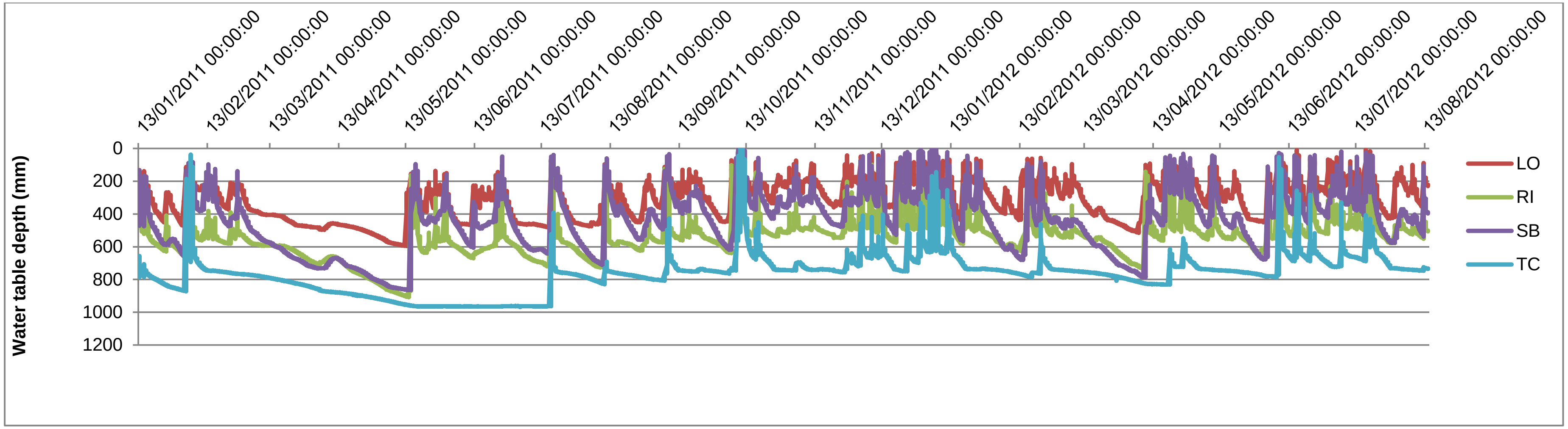


Figure 13 – time series of Bleaklow dipwells

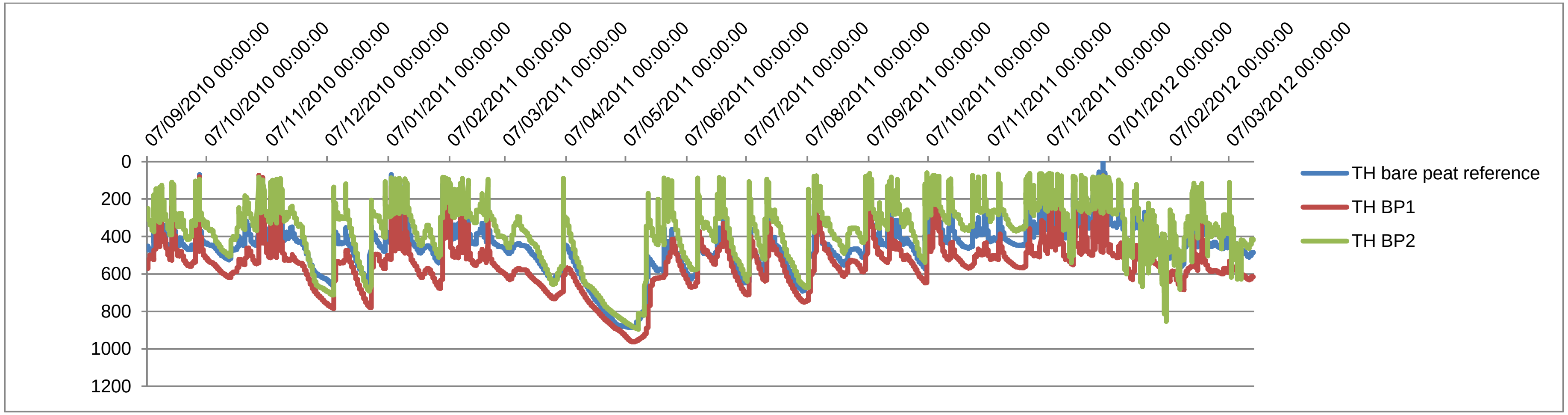


Figure 14 – time series of Turley Holes dipwells

Figure 15 and Figure 16 show the cumulative frequency distributions of dipwells on Bleaklow and Turley Holes respectively. Data from all five analysed automated dipwells showed indications of a rise in water table, relative to untreated bare peat.

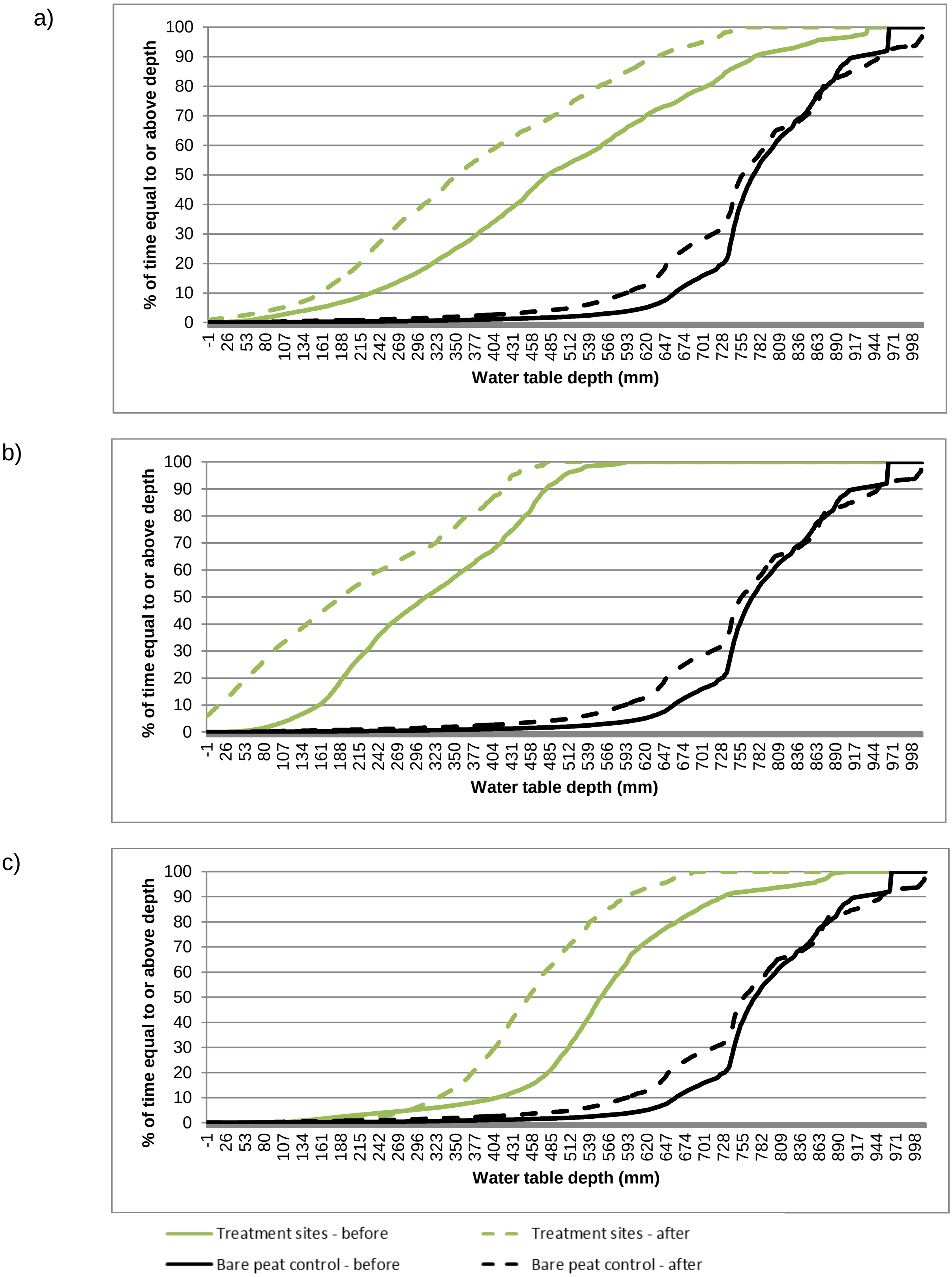


Figure 15 – cumulative frequency distribution for four treated sites on Bleaklow: a) SB, b) LO and c) RI.

On Bleaklow, water tables at the untreated bare peat site were slightly higher, with a higher proportion of time spent at depths above 750mm, but little change at deeper depths. Water tables at treated sites all show shifts to shallower depths, to a greater degree to that observed at the untreated site.

Similarly, on Turley Holes, water tables at the treated dipwells show different behaviour to that observed at the untreated bare peat site. At untreated sites, water tables are generally deeper in the period following seeding. At treated sites, water tables are shallower, particularly at the lower depths.

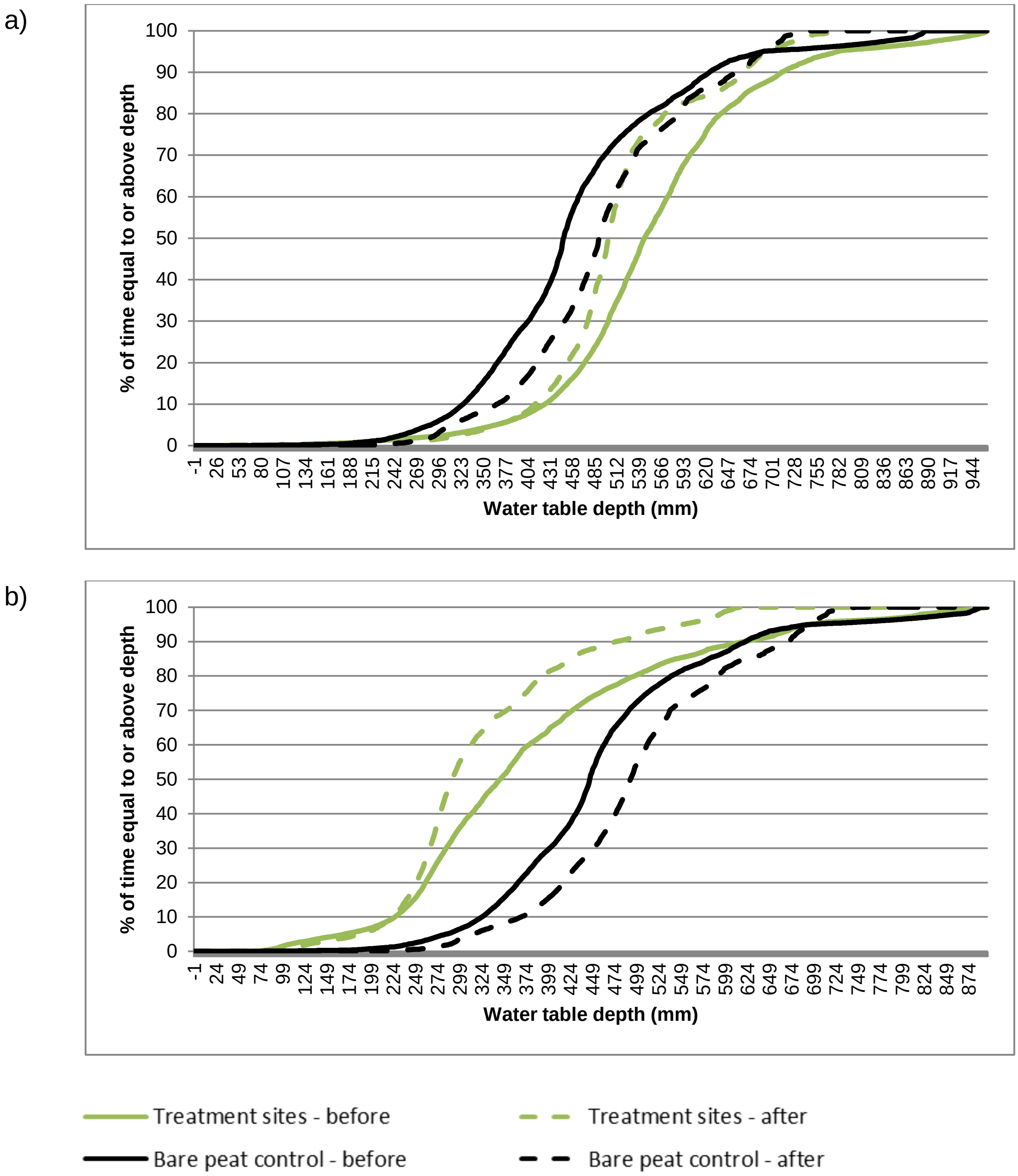


Figure 16 – cumulative frequency distribution for two treatment sites on Turley Holes: a) TH T 1 and b) TH T2

3.4. Discussion

Data collected from both automated and manual dipwells indicate that water tables have become shallower in the time period following revegetation treatments on both Bleaklow and Turley Holes.

At Bleaklow, the rise in water table one year after revegetation was 11mm relative to the control site, although not statistically significant. Data collected from automated dipwells however does indicate that one year after seeding, water tables at treated sites are exhibiting observable changes in behaviour. Median and maximum water table depths have decreased at all sites, indicating that water tables are higher.

Water tables at Turley Holes in 2014 (two years after revegetation)exhibited a statistically significant rise in water table of 22mm relative to the untreated control. Turley Holes was seeded over a year earlier than Bleaklow, so vegetation would be at a later stage of development and maturity. Automated dipwells on Turley Holes also show indications that water table behaviour has changed. In the period following revegetation, water tables at the treated site were wetter than before. In the same period, water tables at the untreated control were actually drier than in the period before seeding took place.

Had revegetation had no impact on water tables, it would be expected that water tables on treated site would have exhibited patterns of behaviour similar to those of the untreated bare peat sites. Instead, treated sites are showing clear signs of higher water tables.

4. Sedimentation loss/accumulation

4.1. Introduction

The presence of expansive areas of bare peat threatens adjacent active blanket bog habitat due to high rates of erosion and gullying in bare peat areas, which infringes on areas of intact blanket peat.

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).

Eroding bare peat threatens adjacent active blanket bog habitats by contribution to lowered water table Revegetation protects the peat from erosion and slows overland water flows (Allott *et al* 2015; Holden *et al* 2008).

4.2. Results and Discussion

The original methodology planned for monitoring peat accumulation/erosion on MoorLIFE sites involved use of peat pins. These were made of 50mm lengths of 5mm stainless steel rods, bent over at one end to form a hook. The hooked end was marked with tape. The pins were inserted into the ground so that the bottom of the tape was 10cm from the surface of the peat. Pins were clustered in groups of 12 over a 4m^2 area. Pins were to be measured during two day campaigns, twice a year, for the duration of the project. Erosion pins were established on Bleaklow, Rishworth Common and Turley Holes prior to works taking place.

However, surveyors making return visits frequently found that many erosion pins were disturbed either by human or animal activity. In addition, it could not be ruled out that freeze-thaw action was pushing the erosion pins upwards. These difficulties were also observed on the Peatlands for the Future monitoring project (Maskill *et al* 2012), and little useful data was available from erosion pins on this project.

Due to the uncertainty surrounding this method, and the need for more regular checks, it was decided not to continue using erosion pins.

Alternatives to erosion pins

The landscape-scale monitoring programme established by MFFP covers multiple projects that provide added value to the monitoring within MoorLIFE. Projects established since

MoorLIFE have utilised alternative methods of erosion and sediment monitoring such as peat anchors and Time Integrated Mass Flux Sampler (TIMS) units.

Peat anchors

Peat anchors were established within the Kinder Catchment Monitoring Project (Maskill *et al,* 2015a) and the Catchment Restoration Fund (CRF) monitoring programme (Crouch *et al*, 2015). Scenarios monitored included stabilised bare peat, intact and untreated bare peat sites.

The peat anchors were assembled using M12 connecting studs, M12 threaded rod, Lanocote grease, quick-setting waterproof glue following a methodology from Lindsay (2010). The anchors were treated with blue Rustoleum Nyoxide® anti-corrosive paint to resist rusting and affecting the surrounding vegetation with leachate.

On site, each peat anchors were installed by pushing through the peat and then tapped with a mallet into glacial till/base rock beneath. An appropriate length was left standing proud of the bog surface in order to have something to measure the bog surface against.

Measurements were taken from the bog surface to the top of the crowning connector.

Peat anchors were found to be a more appropriate method than peat pins because of their more robust design and the long length under the peat surface, which made them much more stable and less likely to be disturbed.

Both Kinder Catchment and CRF monitoring projects collected measurements over the course of approximately one year. The data were found to be noisy, with no observable results.

This was not an unsurprising result as peat anchors are a long-term monitoring method. The peat anchors remain *in situ* to enable continued monitoring.

TIMS units

The CRF monitoring project also used TIMS units to monitor sediment loss within erosion gullies. This project found that sediment loss from gullies that had been revegetated and gully blocked, or only revegetated, was significantly lower (99% and 98% respectively) than that of unblocked, bare peat gullies (Crouch *et al*, 2015).

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 MoorLIFE treatment sites are different topographically, it has undergone much of the same treatments as these other monitored sites, and so our expectation would be for these catchments to follow the same trajectory.

Sedimentation surveys

MFFP had additional funding from United Utilities to undertake surveys of gully blocks on Woodhead installed by the MoorLIFE project. 18 months after installation 100% of surveyed dams were holding water and 82% were holding accumulated sediment.

In addition, significant changes in sediment depth behind stone dams were observed following their installation. Sediment depth was found to increase 14cm in blocked gullies relative to an unblocked control. The majority of sediment accumulation occurred within three weeks of installation.

Carbon benefit of peat stabilisation

Work undertaken by Worrall *et al* (2011) to examine the carbon benefits of undertaking peat stabilisation works on Bleaklow showed a high carbon benefit of revegetation. This study considered a variety of carbon flux pathways and found that most restored sites had improved carbon budgets (decreased source and/or increased sink of carbon) when compared to unrestored, bare peat sites. This improvement was mainly in the form of avoided loss of carbon through pathways such as erosion of sediment. The study concluded that the carbon sequestration benefit of peatland restoration on Bleaklow ranged between 122 and 833 tonnes C/km^2/yr.

5. Water quality

5.1. 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. Erosion is a key pathway of carbon loss from peatland systems, and drying of peat is linked to high levels of colour and DOC. In addition, water quality is of particular interest to the water companies that are MoorLIFE's associated beneficiaries, as one of the multiple benefits of peatland management. Work undertaken by United Utilities' SCaMP project have found that appropriate management of peatland catchments can lead to improved raw water quality entering water treatment works.

The capital works undertaken within MoorLIFE 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 original proposal within the MoorLIFE monitoring programme was to monitor soil water quality during two day campaigns undertaken twice each year. Water samples were to be analysed for colour (DOC) and turbidity (POC).

This methodology was revised early in the MoorLIFE programme, with water samples collected from streams and gullies draining treatment, bare peat reference, and intact blanket bogs. This was done in two campaigns, coinciding with the autumn/winter dipwell campaigns in 2012 and 2014.

In 2012 samples were sent to an external lab to be tested for DOC, POC, TOC and colour in Hazen. These samples were also filtered and tested in-house for absorbance using a spectrophotometer. In 2014, water samples were only tested in-house, with the intention of using Absorbance at 400 as a proxy for DOC, based on relationships established in 2012.

However, it became apparent that there were a number of issues with this sampling campaign which were outside of MFFP's control.

Seasonal variation in DOC concentration (and thereby colour) is observed within peatland catchments (Worrall *et al* 2005). During this annual cycle, DOC is typically at its lowest in spring and increases through summer months due to lower water tables and increased production. DOC is flushed out during the late autumn/early winter when water table is high.

In the UK, 2012 was an extremely wet year – the second wettest on record (Met Office 2015). This is likely to have had an impact on the seasonal cycle. This has made a straightforward comparison between the 2012 and 2014 sampling campaigns particularly difficult. While the presence of an untreated bare peat system to act as a control should have helped this, often these systems were not running, and so few samples were collected in the 2014 campaign.

In addition, since the beginning of the MoorLIFE project, studies of water samples collected from MFFP's Making Space for Water sites have shown a significant impact of lime applications on water colour and DOC concentrations (Evans *et al* 2015). Following lime applications, DOC concentrations were observed to decrease for a period of approximately 6 months. This effect was most noticeable following the initial application, and was reduced following subsequent applications. A potential mechanism suggested was 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).

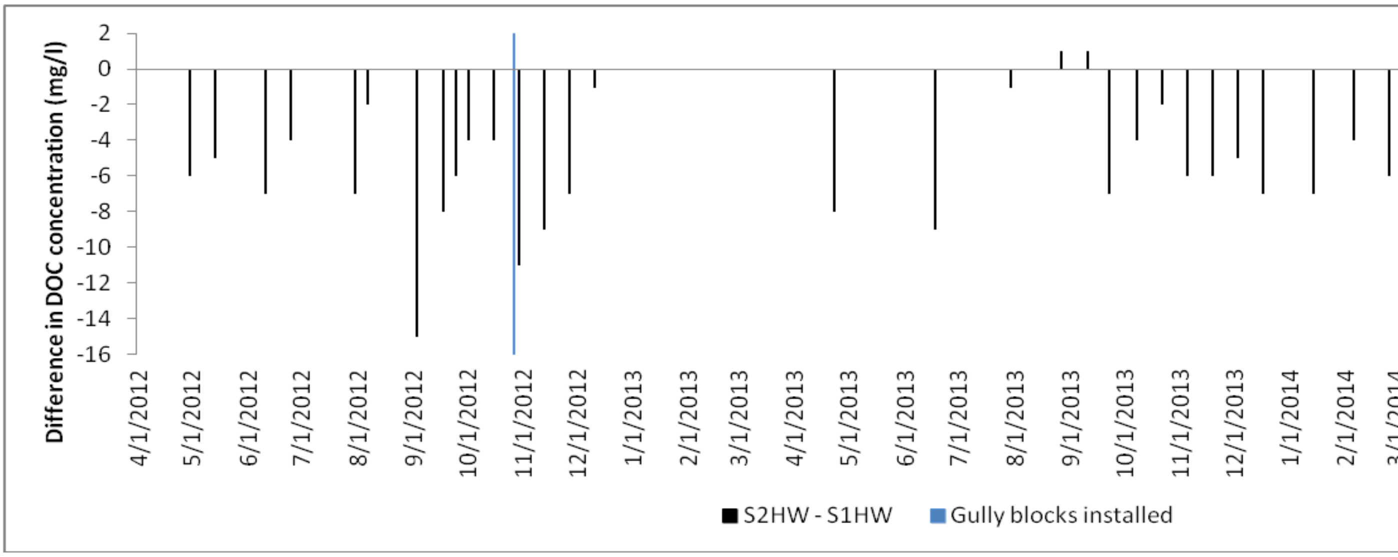
In light of these complications, data collected from MoorLIFE water sampling points is not presented here, but could be used as part of a long-term monitoring programme.

In 2011/12, MFFP secured additional funding from the Environment Agency and United Utilities to monitor water quality at sites on Woodhead, Bleaklow. These sites directly monitored the impacts of gully blocks and areas of bare peat which received lime, seed and fertiliser treatments revegetation through the MoorLIFE project (Maskill *et al* 2015b). A summary of these findings is presented below.

5.2. Key findings from the Woodhead Gully Block Monitoring Project

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



(Figure 17 and Figure 18). This finding is not unexpected, since the primary mechanism by which gully blocking would impact on DOC would be a raising of the water table. The primary purpose of stone gully blocks is to trap sediment, and 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.

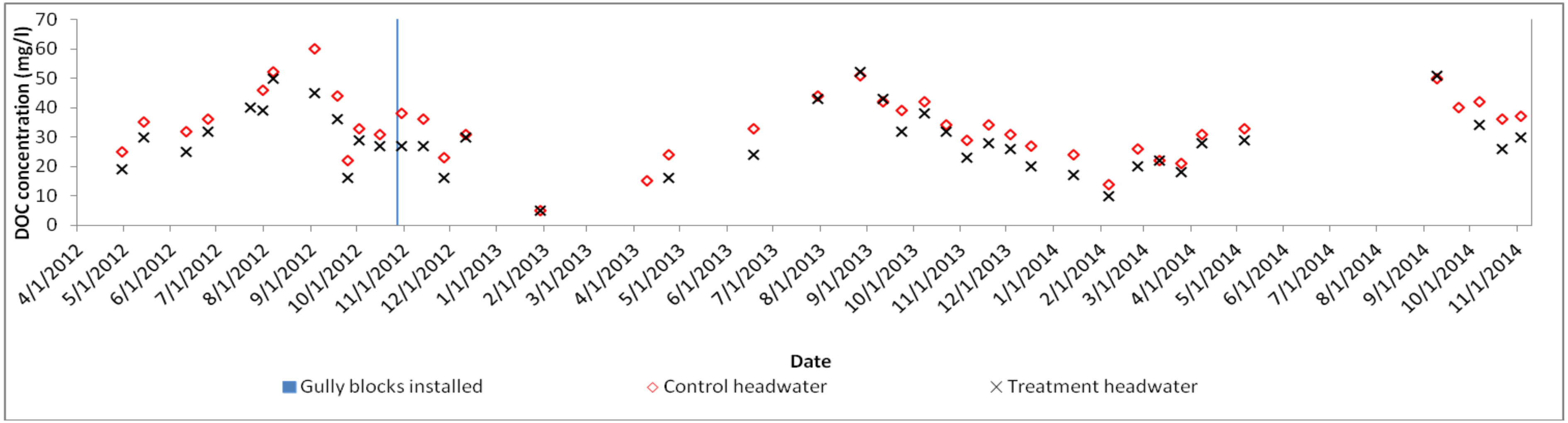


Figure 17 - DOC concentration in Smithy Clough - untreated control and blocked gully.

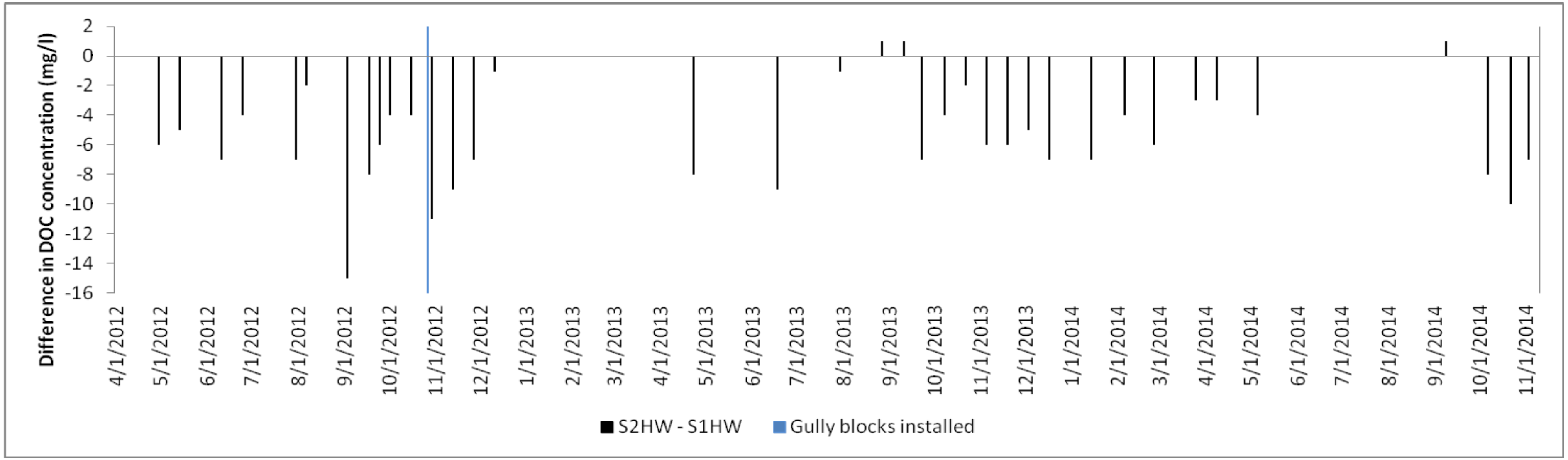


Figure 18 -difference in DOC concentrations between unblocked control and blocked gullies in Smithy Clough

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 (Figure 19 to Figure 22). 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).

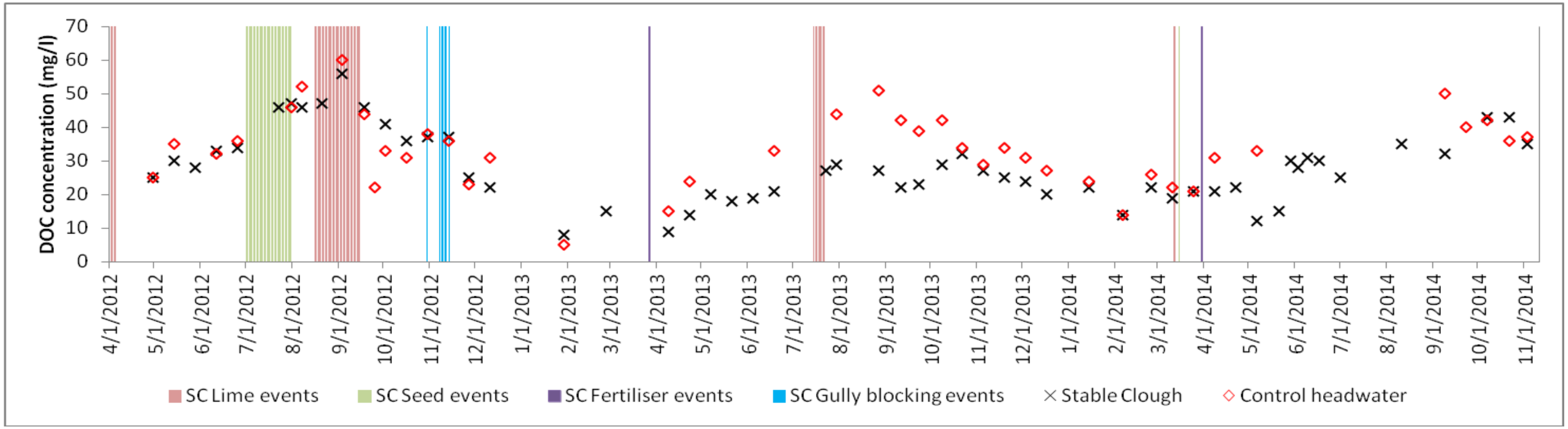


Figure 19 – DOC concentrations from Stable Clough and the control (system 1) gully

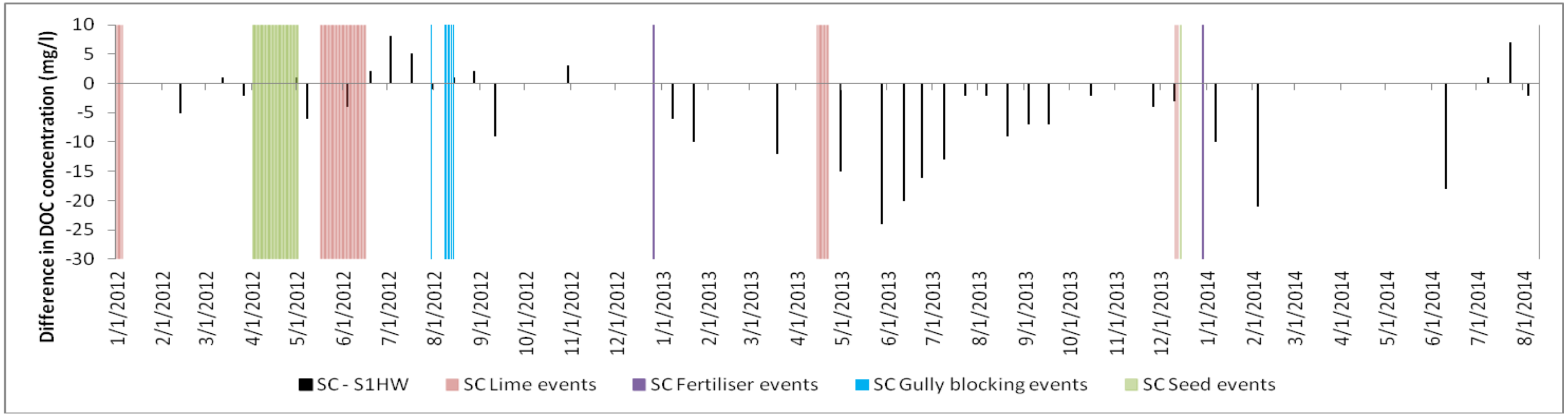


Figure 20 – Differences in DOC concentrations between Stable Clough and the control headwater site (system 1).

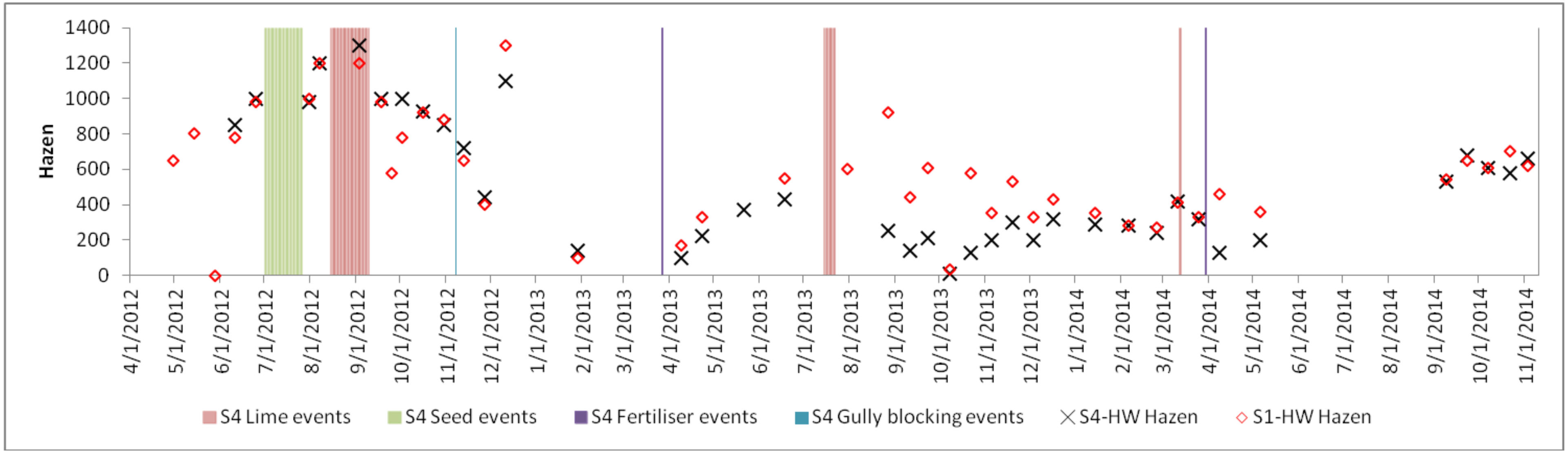


Figure 21 – colour in Hazen at the treated system 4 against the control system 1.

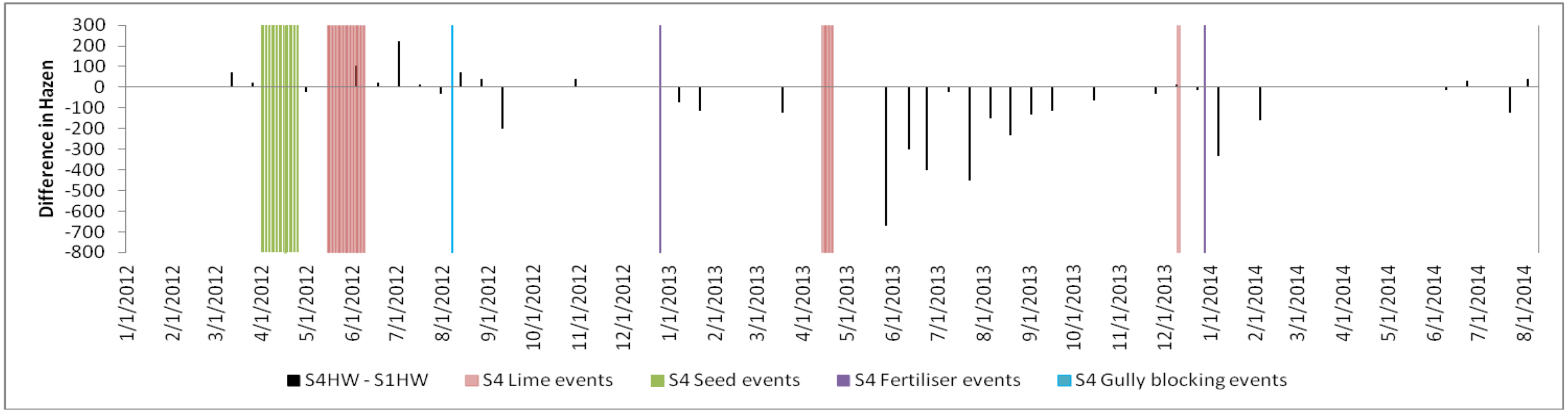


Figure 22 – residuals of system 4 and system 1 (treatment – control)

6. 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.* Edale, Derbyshire: Moors for the Future Partnership

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.

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, 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.

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.

Lindsay, R. (2010) Peatbogs and carbon: a critical synthesis to inform policy development in oceanic peat bog conservation and restoration in the context of climate change. Environmental Research Group: University of East London.

Maskill, R., Walker, J.S and Allott, T. (2012). Kinder ‘Peatlands for the Future’ Project Monitoring Report. Moors for the Future Partnership, Edale, Derbyshire.

Maskill, R., Walker, J.S, Benson, J., Allott, T., Evans, M. and Shuttleworth, E. (2015a). Kinder Catchment Project, Monitoring Report. Moors for the Future Partnership, Edale.

Maskill, R., Walker, J.S., Benson, J., Allott, T., Evans, M. and Shuttleworth, E. (2015b). Woodhead Gully Block Monitoring: Final Report. Moors for the Future Partnership, Edale.

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.

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., Burt, T., and Adamson, J. (2005). Fluxes of dissolved carbon dioxide and inorganic carbon from an upland peat catchment: implications for soil respiration. Biogeochemistry 73: 515-539.

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. Earh Surface Processes and Landforms 36, 11, 1487 – 1498.