Annex 2

Water table trajectories on bare peat stabilisation sites

Prepared by

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Peatland Restoration and Trajectories of Water Table Change

Report to the Moors for the Future Partnership

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Analysis of a large dataset of measured water tables at restored peatlands sites in the southern Pennines suggests that relative to bare peat control sites water table increases at restored sites. Rates of change vary by site but a conservative estimate of the average rate of change is 19mm per year. Evidence from older restored sites indicates that these rates of change may persist for 10 years or more. Direct monitoring at longer timescales is required to confirm this. There is some evidence that the hydrology of the surface peats is recovering leading to reduced variability and potentially increased resilience of the peatland system. Further work is required on this issue. Both continuous dipwell monitoring and campaign studies have contributed valuable understanding to this study, and a combined strategy is recommended for future monitoring particularly at key long term sites.

1.0 Introduction

Over 12 years, since 2003, major landscape scale restoration has been undertaken in the eroded peatlands of the Bleaklow and Kinder Scout plateaux in the southern Pennines. The 'Peak District Prescription', consisting of aerial seeding of utility grass seed, together with brashing, liming and fertiliser application, has been applied over extensive areas of bare peat. As part of the monitoring of restoration effect, water table data has been collected at restoration sites of varying ages since 2010.

Although the re-vegetation does not explicitly target water table modification, unlike for example gully blocking which is commonly undertaken alongside, the dramatic modification of surface cover has the potential to modify surface water exchange and transfer processes. These changes to the water balance of a site might lead to changes in water table. This project draws on the available water table data with the aim of defining trajectories of water table change associated with re-vegetation of bare peat.

2.0 Data Sources

This report is based on measured water table datasets collected and supplied by the Moors for the Future Partnership on peatland restoration sites across the south Pennines between 2010 and 2015. Water table depth at all sites was measured in 1 metre dipwells made of 30mm (internal diameter) polypropylene pipe drilled at 100mm intervals). Two main types of data were assessed: 1) Manual dipwell campaign data which comprised weekly or fortnightly measurement of water table depth at clusters of 15 dipwells during Autumn campaigns (September-December), and 2) Automated dipwell data is from single dipwells at each site and is based on trutrack capacitance probe data logged at sub hourly intervals. For the purposes of these analyses continuous data has been aggregated to hourly intervals.

Datasets were selected from the full suite of measured data according to the following requirements:

1) There should be available data from a bare peat control site comparable to the restoration site.
2) Sufficient data are available post-restoration
3) For continuous datasets there is a requirement that there are comparable control and restoration data for sufficient continuous periods.

4) Suitable calibration data are available for continuous datasets
5) Data quality and collation sufficient that the analyses could be completed in the time committed for this project.

The analyses presented below are derived from the datasets outlined in Table 1 which met these criteria for one or both of the manual and automated measurement campaigns.

	Site Code(s)	Restored	2010	2011	2012	2013	2014	2015
Bleaklow	D, L, R, SB	2013	-	M,	M, A*	M, A	M, A*	-
Turley Holes	TH 1-3	2012	-	M, A	M, A*	M, A*	M, A	-
Rishworth Common		2012	-	A*	M, A*	M	M, A*	A*
Kinder Scout (MS4W)	O, N	2011	M	M,A*	A*	A*-	M, A*	M, A*
Black Hill			-	-	M	M, A*	M, A*	-
Bleaklow	JP, Po	2003	-	M	M, A*	M, A*	M, A*	-

Table 1 Summary of key data sources used in the production of this report. M indicates autumn manual dipwell campaign and A represents continuous logged dipwell data. * indicates data for that year is partial. Green shading is data for post restoration years, orange shading is pre-restoration data. Note some single dipwell data exists beyond these timeframes for some sites, this table summarises relatively complete coverage useful for this project.

3.0 Manual dipwell data

3.1 Data

Manual measurement water table data is available from 17 dipwell clusters on re-vegetated ground, and from four bare peat control sites. The dipwell clusters are from five areas: Bleaklow, Turley Holes, Rishworth Common, Kinder Scout, and Black Hill. Each area has control data with the exception of Rishworth Common and Black Hill for which the Turley Holes data were used. The available data and its relation to the period of time since restoration is outlined in Table 2 below.

	2010	2011	2012	2013	2014	2015
Bleaklow (recent)	-	0	0	1	2	-
Turley Holes	-	0	1	2	3	-
Rishworth Common	-	-	1	2	3	-
Kinder Scout (MS4W)	0	1	-	-	4	5
Black Hill	-	-	7	8	9	-
Bleaklow (late stage)	-	8/9	9/10	10/11	11/12	-

Table 2 Available manual dipwell data and number of growing seasons after restoration

The manual dipwell measurement protocol involves simultaneous (same day) measurement of dipwell clusters (15 dipwells) at each site. The analysis of this data follows the approach developed by Allott et al. (2009) and applied recently in the final report of the Making Space for Water (MS4W) project (Pilkington et al. 2015). For each measurement occasion at each cluster a mean of the 15 measured depths is taken to give a water table for the site. The median of these mean cluster values taken across all the measurement occasions during the autumn campaign is then calculated to represent the median water table at the site during that period. Measured water tables show significant variation between eroded bare peat sites and intact sites in line with the findings of Allott et al. (2009). Throughout the study period, annual median depth to water table varied between -9 and 162 mm at the intact control sites, and between 267 and 510 at the bare control sites. Figure 1 shows the range of observed water tables at the intact (Site P) and bare peat (Site TR A) control sites on Bleaklow over a four year period. Median depth to water table for all sites by year is presented in Appendix 1.

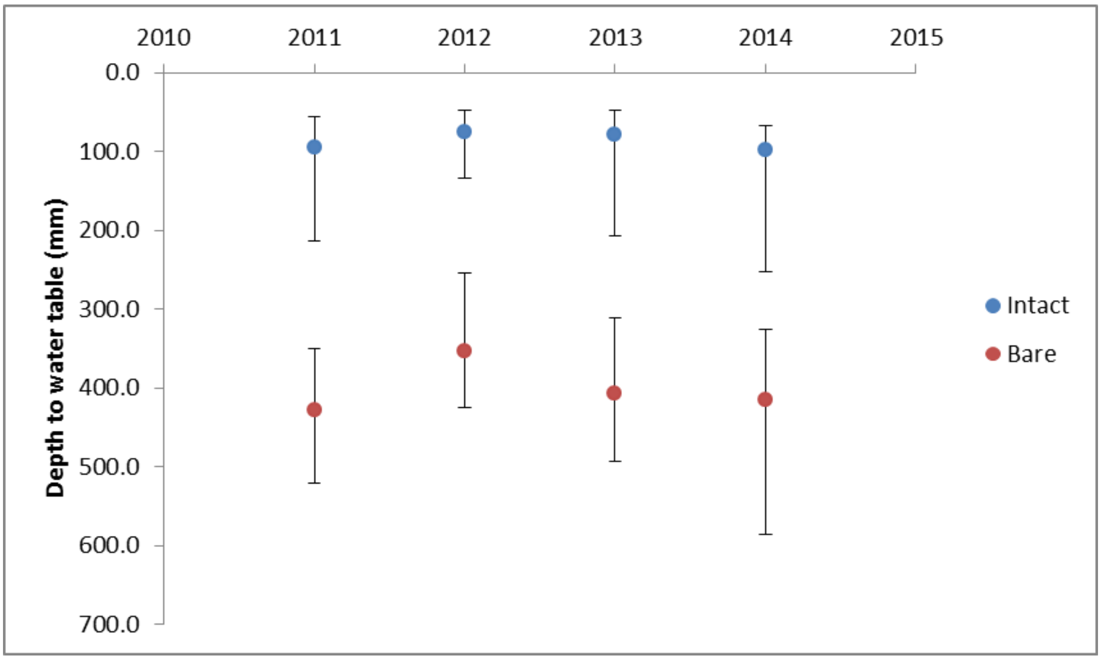


Figure 1 Water table depths at intact (Site P) and bare peat (Site TR) sites on Bleaklow demonstrating the typical scale of water table depression associated with bare and eroded sites.

Simple change in water table at the restored sites cannot be taken to represent change associated with the intervention because this does not account for inter annual hydroclimatic variability. It is for example apparent from Figure 1 that 2011 and 2014 has lower water tables than 2012 and 2013.

Therefore, in order to assess change in water table associated with restoration, rather than simply inter-annual change in hydroclimate, the analyses presented in this report are based on water table measured relative to a local bare peat control site. This is preferable to comparing to an intact site because these sites have stable high water tables so that in wet years there will be an apparent increase in restored site water table if these are used as a control. Comparing with eroded bare peat sites provides a better assessment of changes associated with the restoration process. There is one caveat to this approach: because the water tables are measured relative to the ground surface, erosion at the bare peat sites has the potential to be recorded as lower depth to water table at the bare control site. Any increases in water table at restored sites recorded in this dataset should therefore be regarded as minimum values since erosion at the bare sites would be observed as a negative change in the difference between restoration and control site water tables reported here. This means that the approach adopted is conservative with regard to identifying positive change in water tables at restored sites.

3.2 Water table change recorded by manual dipwell campaigns

The data for each site are presented graphically in Appendix 2 (Figures A2.1 to A2.6.). These figures present change in water table at the treatment site relative to the control site. The Y axis is D control – D treatment where D is the depth to water table in mm. Higher values on the Y axis reflect reductions in depth to water table (i.e. higher water table) at the treatment site or increases (i.e. lower water table) at the control site. Of the 17 dipwell clusters assessed, 14 show an increase in the difference in median water table depth between the control site and the restoration site. For these sites, the water table is relatively closer to the surface at the restored sites than the controls. The rate of change for each site is presented in Table 3. Rates of change in mm/yr, derived from the trend line fitted through the annual data points, range from -14 to 83 mm with an average across the sites of 24 mm/yr. This average rate encompasses sites at varying stages of restoration. There is no clear relation between the rate of change and the period post restoration. We might expect a progressive decline in rate of change over time but the data do not support this. In fact the average rate of change for late stage restoration sites (38mm/yr) exceeds that for early stage sites (20 mm/yr) but the sample sizes are small and these findings should be treated with caution.

There is considerable variability in hydrological recovery between sites apparent in these data, but the overall trend across diverse sites with multiple control sites is that post restoration there is a small but ongoing positive change in water table relative to control sites. The magnitude of these changes on an annual basis is small. Given that reductions in median water table at eroded sites are on the order of hundreds of mm the annual recovery indicated by these data is limited, but the indication that it is ongoing over several years means that there is the potential at longer timescales for water table recovery at a scale which could influence peatland function.

					Rate for change (mm/yr)	
Area	**Time frame (yrs)**	**ID**	**Difference (mm)**	**Direction**	**Diff between start and end**	**Based on trend line**
Bleaklow (recent)	0 to 2	D	10.6	Increase	53	53
		R	4.5	Increase	23	22
		L	6.8	Increase	34	34
		SB	1.2	Increase	6	6
Turley Holes	0 to 3	TH1	-3.6	Decrease	-12	-14
		TH2	0.4	-	1	2
		TH3	6.8	Increase	23	18
Rishworth Common	0 to 3	RC1	5.2	Increase	17	27
		RC2	10.2	Increase	34	48
		RC3	9.1	Increase	30	40
Kinder (MS4W)	0 to 5	N1	5.3	Increase	11	9
		N2	6.5	Increase	13	15
		O	0.3	-	1	-1
Black Hill (late stage)	7 to 9	BH1	7.2	Increase	36	36
		BH2	16.6	Increase	83	83
Bleaklow (late stage)	9 to 12	JP	9.7	Increase	32	33
		Po	0.1	-	0	1
				Mean	**23**	**24**
				Early stage	18	20
				Late stage	38	38

Table 3 Change in water table relative to control for each dipwell cluster analysed at each of the five sites

4.0 Automated dipwell data

4.1 Data treatment

The automated dipwell data are derived from logged capacitance probes situated at 1 m depth within the dipwells. An important element of assessing the continuous data is calibration of the sensors. Previous experience of these sensors in this environment shows that whilst they provide a reliable linear response, there is the potential for drift and manual calibration is necessary. The supplied data had some calibration data but the nature of this varied between sites. The Kinder Ccout sites have good calibration data with multiple calibrations averaged for each quarter and applied to the data for that quarter. The calibration data for Bleaklow was more variable with some suggestion from the field notes that some calibrations had been affected by removal of the loggers prior to measurement. The scale of the variance in some of the calibration data was on tens of mm so that the treatment of calibration is vital to identifying trends. The best calibrated Kinder Scout data was used as supplied in calibrated form. The following approach was taken to the Bleaklow data: 1) Because sensor drift is typically a gradual process major temporary deviations in the calibration were assumed to be error unless they coincided with removal/replacement of the logger. 2) The remaining data was patchy in temporal coverage and so the calibrations were applied to the data from the mid-point between adjacent calibration points (so that the calibration at time t was applied from half way between t and t-1 to half way between t and t+1). Data from Rishworth, Turley Holes and Black Hill were not used because of uncertainties over calibration which whilst potentially resolvable were could not be addressed within the timescales of this project.

The issues with calibration mean that the absolute values of water table from the continuous data are probably less secure than those derived from the manual data. However, it should be noted that the continuous data has two advantages: 1) because measurement is relative to the dipwell rather than the ground surface the potential effects of erosion at control sites are removed and 2) the short term relative changes recorded by the logging dipwells are unaffected by calibration issues allowing us to examine water table behaviour at high resolution.

4.2 Trends in continuous data

Continuous data is available for the MS4W sites on Kinder Scout. Sites O and N were restored in summer 2011 and data span 2012 -2014. Further continuous data is available from sites L, R, SB, and D on Bleaklow which were restored in 2013 (2013 and 2014 data available) and from sites JP and Po (also on Bleaklow) which were restored in 2003 (2012-2014 data available). In addition, bare peat control sites were available from Bleaklow (site TR) and from Kinder Scout (Site F). The continuous data therefore allow us to assess change in the short and medium timescales post restoration.

In order to account for inter year variation in hydroclimate changes in water table post restoration are assessed as change relative to a control site. Because the available data span only relatively short periods post restoration and because there are various gaps in the datasets the approach taken was to assume that changes in water table post restoration are linear over periods of 1-3 years (this is consistent with the evidence from the manual dataset). Lines of best fit were fitted through the data to assess trends over the period of observation.

Figures A 3.1 to 3.3 plots the residual (control WT– treatment site WT) against time for each of the study sites. The trend in relative water table derived from the best fit lines are tabulated in Table 4. Six of the eight sites show an increasing trend in the difference between control and restoration water tables. Rates of change vary from -21 mm/yr to +145 mm/year with an average value of 36.7mm. As with the manual data, there is no clear relation of rate of change to period post restoration. The overall rate of change is greater than that identified in the manual data which may relate to the fact that the manual data represent minimum rates of change. However, with the small sample size and relatively noisy continuous data this cannot be unambiguously demonstrated.

It is important to note that comparison of the trends from individual sites with the trends recorded by the manual dipwell campaigns for the same site show several discrepancies between the two datasets. These might indicate differences in behaviour between the autumn manual campaign period and the longer term data collected by the continuous data, although analysis of the continuous data does not strongly support this (See section 4.5 below). Another explanation for this behaviour is consideration of the representativeness of single dipwells at a site. Allott et al. (2009) suggested a minimum of 15 dipwells were required to characterise water table at a site (the basis for the design of the manual campaigns in this study). The cost of logging equipment for continuous monitoring means that replication at a site is difficult. It is therefore preferable to regard the 8 sites as a series of replicates across the ‘restored’ peatland landscape of the Southern Pennines, rather than attempt to make site by site comparisons between data types. On this basis the data in Table 4 support the findings from the manual data that re-vegetation is associated with small but ongoing increases in water table relative to bare peat control sites.

Site	Years post Restoration	Regression equation y=	Significance of x coefficient	95% confidence on slope	Rate of WT change (range) mm/year	Rate WT change (mean) mm/year
D	1	0.0016x+59	<0.0001	0.0013 – 0.0020	12 – 17 increase	14
R	1	0.0035x + 242	<0.0001	0.0031 – 0.0039	27 – 34 increase	31
L	1	0.0030x + 430	<0.0001	0.0026 – 0.0033	23 – 29 increase	26
SB	1	0.0017 + 67	<0.0001	0.016 – 0.017	141 – 149 increase	145
O	3	0.0064x+401	<0.0001	0.0062 to 0.0065	54 – 57 increase	56
N	3	-0.0005x+88	<0.0001	-0.00074 to -0.00030	3 – 7 decrease	-5
Po	Late stage	0.0055 + 345	<0.0001	0.0053 – 0.0057	46 – 50 increase	48
JP	Late stage	-0.0024 + 513	<0.0001	-0.0025 - -0.0023	21 - 20 decrease	-21
All sites						**37**

Table 4 Rate of change in relative water table (control-treatment) derived from linear trend lines through continuous data (see Figures A3.1-3.3). Positive slopes on the trend lines indicate increasing difference between control and treatment water tables.

4.3 Variability of WT

In order to assess whether restoration has had an effect on water table variability, the annual variability of water table at the four Kinder Scout (MS4W) sites was analysed (Sites P, O, N and F) using the annual mean and standard deviation of water table. Because of missing data, complete annual data are not available for each year at every site. To make a reasonable comparison these calculations only included periods where every site recorded data. This yielded data for three periods: 2012 (1/4/12 – 31/12/12), 2013 (1/1/13 – 25/6/13 and 28/8/13 – 31/12/13), and 2014 (1/1/14 – 19/2/14 and 20/5/15 – 30/9/14). The data for these periods are plotted in Figure 2. Because the three 'years' have variable periods of missing data variation between the 'years' is a function of the different sampling periods as much as it is a reflection of inter annual variability in hydroclimate. However, because the data are directly comparable, the relative trends in variability between control and treatment sites can be assessed.

Figure 2 A and B show that the deepest water tables and the highest variability in water table are associated with the bare peat site (F). In 2012 (the first after treatment) the two treatment sites (N and O) are intermediate in water table depth and variability between the bare (F) and intact (P) control sites. Over the three years post treatment it is apparent that the site O shows decreased variability and in fact converges with site P (intact) in 2014. Because of the gaps in the data and the limited number of sites analysed here, these data do not provide a complete picture of change in water table variability. However it is notable that site O shows reduced variation in WT to levels similar to the intact control site after three years. The other treatment site (N) does not exhibit this behaviour which is consistent with the observation (in Table 4) that significant increase in WT has not been recorded in the continuous data at this site.

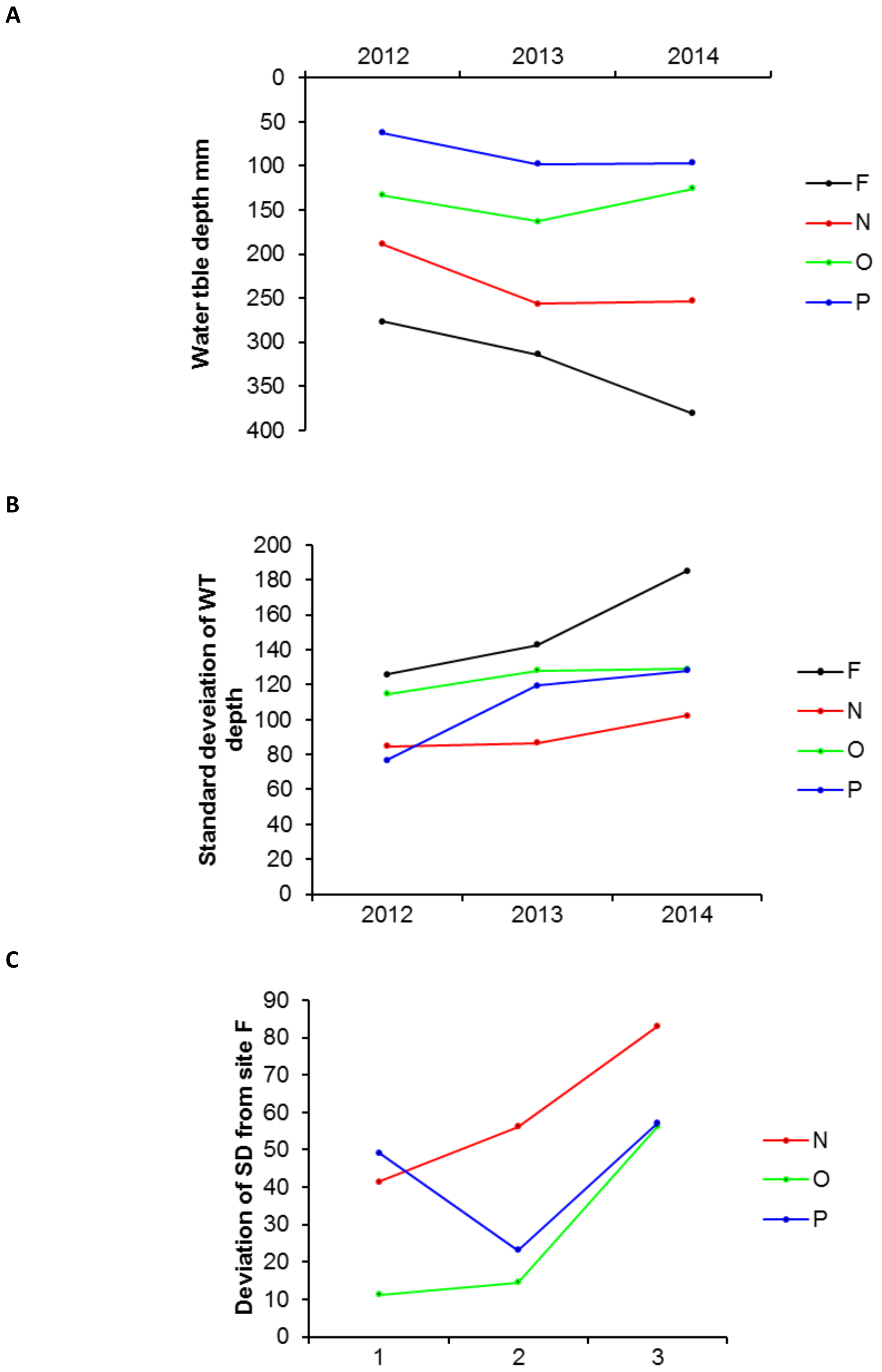


Figure 2 Mean water table (A) and Standard deviation of water table (B) for the MS4W sites. P = intact control, F = bare peat control, N = revegetated, O = revegetated.
n.b. each year has missing data as noted above. This means that the interannual variability is partly due to sampling as well as to changes in hydroclimate. The key to interpreting these plots is the relative change in control and treatment sites. This is plotted directly in (C) relative to the bare control (Site F)

4.4 Drawdown behaviour

The continuous dipwell data offers the opportunity of examining water table behaviour over short timescales and so a means to assess potential change in processes underlying water table behaviour. Of particular interest are drawdown events for two reasons:

- Peatland systems show characteristic drawdown of water table during dry periods. Rate of change of water table during these periods is controlled by evapotranspiration and also by lateral drainage. Lateral drainage is controlled by the hydraulic conductivity and macropore structure of the peat, so that if restoration is producing long term recovery in peat structure this should be apparent in drawdown behaviour.
- Drawdown occurs during dry periods. Predictions of future climate change indicate that peatlands are likely to be under significant moisture stress (Clark et al 2010). An assessment of the response of restored systems to drawdown is therefore an important component of understanding the resilience of restored systems to climate change.

Analysis of individual drawdown events is labour intensive. Therefore, within the constraints of this study, analysis has been undertake on a single restored site. Site O on Kinder Scout was restored in 2011 and continuous data is available for 2010 and 2011-2014. The bare peat control site for site O is the adjacent Kinder Scout site (F). In order to assess potential change in drawdown behaviour over time individual drawdown events were identified in the records (e.g. Figure 3) and two parameters extracted:

- Depth of drawdown defined as the difference in depth between WT at the start of the drawdown event and the deepest WT achieved prior to rapid increase in WT at the next rainfall event.
- Rate of WT depth decline which is the depth of drawdown per unit time. For each event these parameters were extracted for both the restoration site(O) and the bare peat control site (F). Figure 4 show the range of derived values expressed as a difference between the parameters for the two sites. Data are not presented for 2014 because the number of suitable drawdown events in the record was too small.

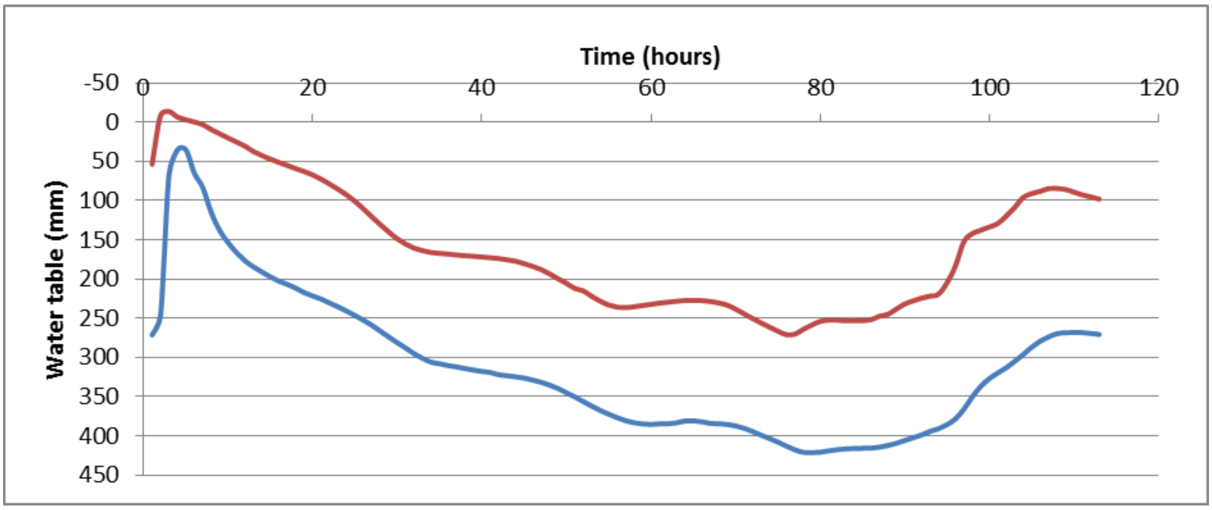
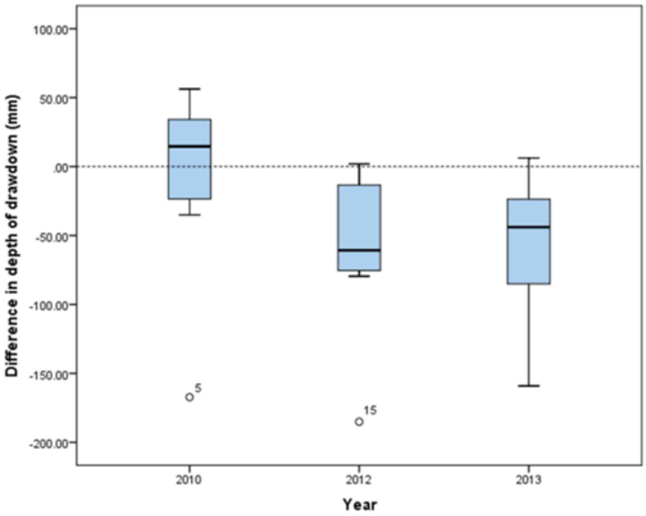


Figure 3 Example of a post restoration drawdown event (24/5/13) at site O (red line) compared with the control (Site F, blue line)

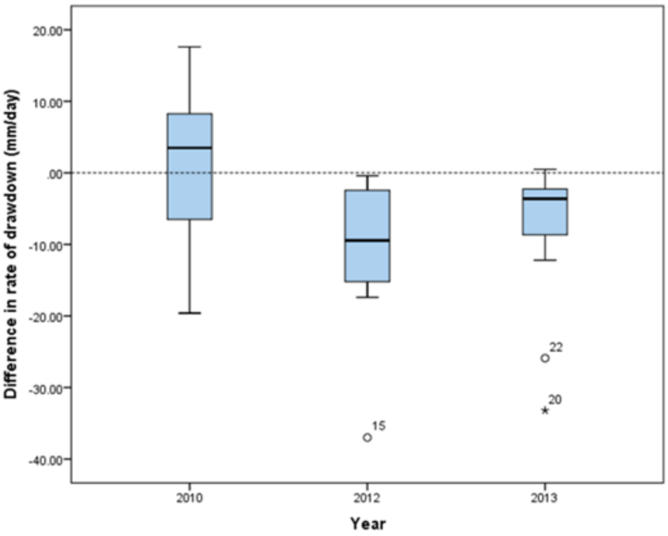
Figure 4 (a and b) demonstrate that in 2010 (prior to restoration) there was very little difference between the drawdown behaviours at the two sites. The unrestored site O showed slightly deeper median drawdown and a slightly greater median rate of drawdown than the bare peat control (F), but this relationship was not consistent and site F experienced deeper and faster rates of drawdown during three out of seven drawdown events. In 2012 and 2013 there was an apparent shift in behaviour, with the restored site showing *consistently* less deep and less rapid drawdown in response to periods of dry weather. Over the two years the average change in depth of drawdown was 60mm - similar to the rate of change for the overall continuous data recorded at site O (Table 4). Statistical comparison of the 2010 data with the 2013 data shows a significant difference in drawdown depth (P=0.026, 2-tailed Mann-Whitney U test) but not in rate (P = 0.083 2-tailed Mann-Whitney U test). However, evidence of consistently slower drawdown following re-vegetation in clear in Figure 4b.

Analysis of the nature of the drawdown events shows differences in the magnitude over the three years (Figure 5). 2010 and 2013 are significantly different (P=0.046, 2-tailed Mann-Whitney U test) with 2013 subject to some substantially longer duration drawdown events than 2010. It is possible therefore that the differences in response are variations in response at the restored site before and after restoration are due to different types of drawdown event rather than a restoration effect. At present the data are not conclusive either way. Changes in water table behaviour before and after restoration hint at changed hydrological response due to restoration but further data spanning a wider range of drawdown events from subsequent years are required to confirm this suggestion.



A

	Depth difference (mm)			
	Mean	Median	Max	Min
2010	-11	15	56	-167
2012	-60	-61	2	-185
2013	-56	-44	6	-33



B

		Rate difference (mm/d)			
	N	Mean	Median	Max	Min
2010	7	1	4	18	-20
2012	8	-11	-9	0	-37
2013	11	-8	-4	1	0

Figure 4 A) Boxplots of differences in drawdown depth (A) and rate (B) between site O (treatment) and site F (control) before and after restoration in 2011. Negative values indicate lower values at site O.

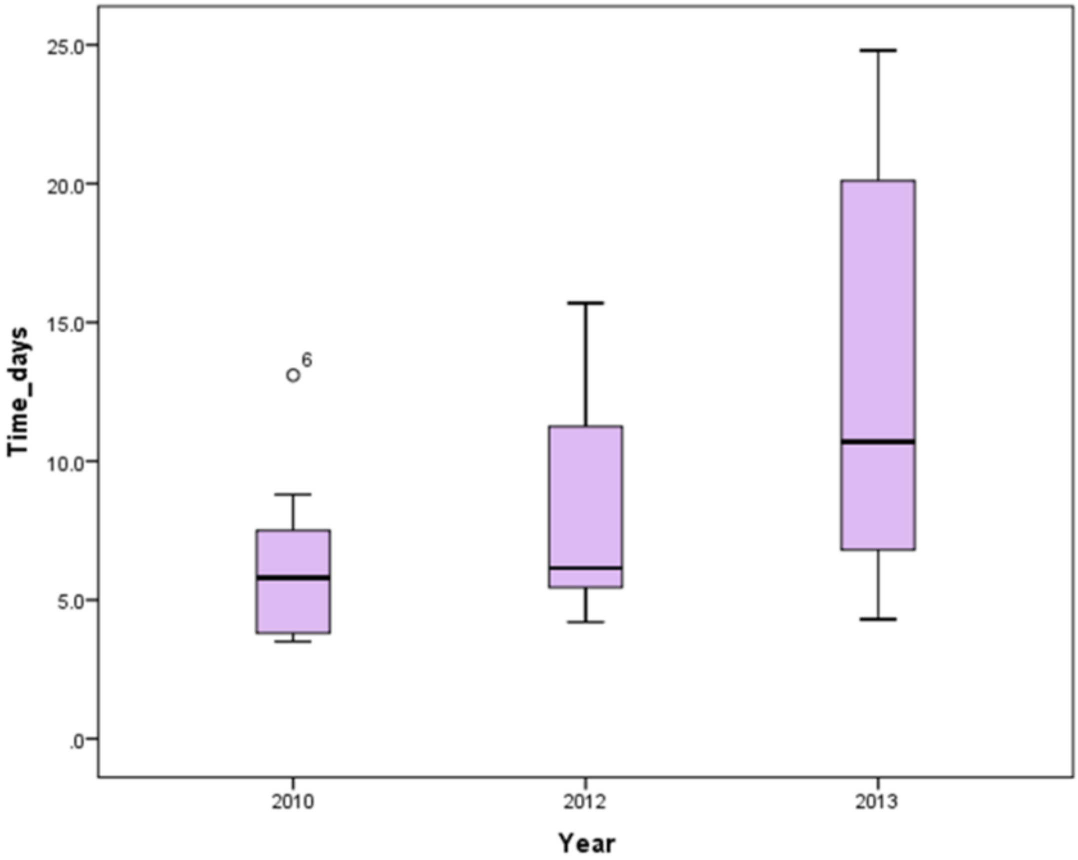


Figure 5 Duration of measured drawdown events by year.

4.5 Representativeness of autumn campaign data

The manual dipwell campaign data reported above was sampled between September and December. There are logistical advantages in limiting the period of the year during which water table monitoring occurs. However, it is important to establish the degree to which these data are more widely representative across the year. The continuous data provide an opportunity to make this assessment. Table 5 shows the difference between mean and median water tables calculated from a full year of continuous data and values derived from continuous data spanning the 4 month period September to December. For the sites on Bleaklow and at Turley Holes the data are from 2011. On Kinder Scout data spanning 2012-2014 are used for the comparison.

Statistical comparison of the autumn data with the full year using the Mann Whitney U test (2 tailed) reveals a significant difference between the datasets for all but one site. The mean deviation of the mean is 11.8mm indicating autumn average water tables are higher those of the whole year. This is unsurprising given that the full year dataset includes the major periods of summer drawdown. However, the effect size is relatively small. The median water table which has previously been shown

Site	Median (mm)	Mean (mm)	Standard Deviation	P 2 tailed Mann Whitney
O (2012-2014)	1	9	33	<0.0001
N (2012-2014)	9	30	33	<0.0001
D (2011)	-11	-11	40	<0.0001
JP (2011)	22	55	15	<0.0001
L (2011)	-17	7	12	0.002
Po (2011)	0	27	34	0.0008
R (2011)	-4	13	22	0.194
SB (2011)	-27	-24	50	<0.0001
TR BP1 (2011)	15	18	8	<0.0001
TR BP2 (2011)	-3	-6	16	<0.0001
All site average	**-1.5**	**11.8**	**16**	

Table 5 Differences in mean, median and standard deviation of water table depth between 12 month data and the autumn (Sept-Dec) period.
Positive deviation indicates autumn average water tables above annual average.

to be a less sensitive and potentially more robust indicator (Allott et al. 2009) shows that water tables are slightly closer to the surface during the autumn (1.5mm) compared to the annual median. The mean standard difference in standard deviation of water table depth between autumn and annual data is 16mm. Therefore, whilst it cannot be said that the autumn data is statistically representative of the full year median water table in particular appears to be a relatively robust measure so that the measured variations between annual and autumn median water table are within the range of measurement error. It should be noted that these data are largely based on a single year and that larger deviations might be expected in particularly dry summers but the Kinder Scout sites with three years of data tell a similar story.

5.0 Water table trajectories

In order to assess the range of water table trajectories apparent in the data this section brings together the evidence from the manual and automated dipwell datasets.

5.1 Constructing water table trajectories

Figure 6 (a and b) plots the period since restoration against the relative change in water table compared to the local bare peat control site. The Y axis of these plots has been normalised so that the water table changes are relative to the pre-restoration condition, i.e. at the time of restoration the deviation is zero. In order to combine different data types on these plots the following approach has been taken:

- The recently restored sites are simply plotted directly on the graphs.
- For the late stage restoration sites, the trend in water table apparent during the measured period is assumed to apply to the whole period of restoration in order to define a Y axis position for the points. Effectively D (water table deviation) at time t_{10} is M + 10R where M is the measured change in year 10 and R is the annual rate of change derived from the measured late stage data. The dotted lines on the plots linking the late stage data to the origin indicate this assumption.
- Confidence intervals have been calculated on this plot using the manual data. Water table was modelled at each site over a 12 year period by extrapolation of the linear trends in the site data. The modelled dataset could then be used to derive confidence intervals.
- In Figure 6 b the slope of the best fit line through the continuous data as derived in Section 4 has been added to a plot of the trajectory derived from the manual data. The linear rate of change derived from the continuously measured data is assumed to be representative through the time period spanned by the graph. The bold lines represent periods where the we have measured data and where the lines become dotted they indicate extrapolation of the data to determine the Y axis position as described above.

5.2 Interpreting Water table trajectories

Figure 6 demonstrates considerable variation in site to site response of water table to restoration. This is unsurprising for three reasons: 1) no account has been taken of site topography which is known to be an important control on water table (Allott et al 2009); 2) the changes in water table are small and there is inevitable noise in the data given the challenge of collecting it; 3) the known variability of peatland hydrology at small spatial scales and the potential presence of peat pipes at these sites which can lead to variable spatial responses of water table. Nevertheless, the clear pattern emerging from the data is one of increasing difference between control and restoration sites. When combined, the manual dipwell data (Figure 6a) produce an average rate of change of 24 ± 12 mm/year (95% confidence interval). The trajectories derived from the continuous dipwell data (Figure 6b) produce an average rate of change of 37 ± 33 mm/year (95% confidence interval). While this is considerably (~50%) higher than the mean rate of the manual campaign, the error is also greater. 75% of the automated data falls within the range of the manual data, and the 95% confidence intervals for the different methods overlap.

A major assumption of the approach adopted here is that, at the timescales considered, water table changes linearly over time. We might expect that as restored systems approach a new equilibrium of ecosystem function, the rate of change would decline. However, comparison of the trajectories of early and late stage restoration suggests that more rapid changes are being observed after 10 years of restoration than in the first few years. An alternative explanation is that there is a real ongoing change in the water balance at these sites driven by processes operating at long timescales. Possible mechanisms include vegetation succession leading to changes in surface character and infiltration capacity, and/or progressive recovery of peat structure and hydrological function. Longer term monitoring at recently restored sites is required to assess these issues more fully. At present the conclusion from these data is that the positive impacts of re-vegetation on water table, although relatively small on an annual basis, continue to accrue for periods in excess of 10 years.

It is important to note that at the larger landscape scale water table is strongly impacted by the effects of erosion and the impact of gullying on upslope contributing area for sites (Allott et al 2009). Therefore, whilst the positive impacts of re-vegetation demonstrated here are evidence for hydrological recovery associated with re-vegetation, complete restoration of water table behaviour in heavily degraded systems will be slow and constrained by long term changes to peatland topography.

Two important implications of these findings indicate the importance of supporting long term monitoring at these sites. The first is that given the relatively small rates of annual change, longer term observations will provide increased confidence in these results by improving the signal to noise ratio in the data. The second is that the implication of ongoing change in water table over a decade is inferred from analysis of the older restoration sites. Ongoing monitoring of recently restored sites will provide confidence that the changes observed here are not a result of site to site difference in water table behaviour.

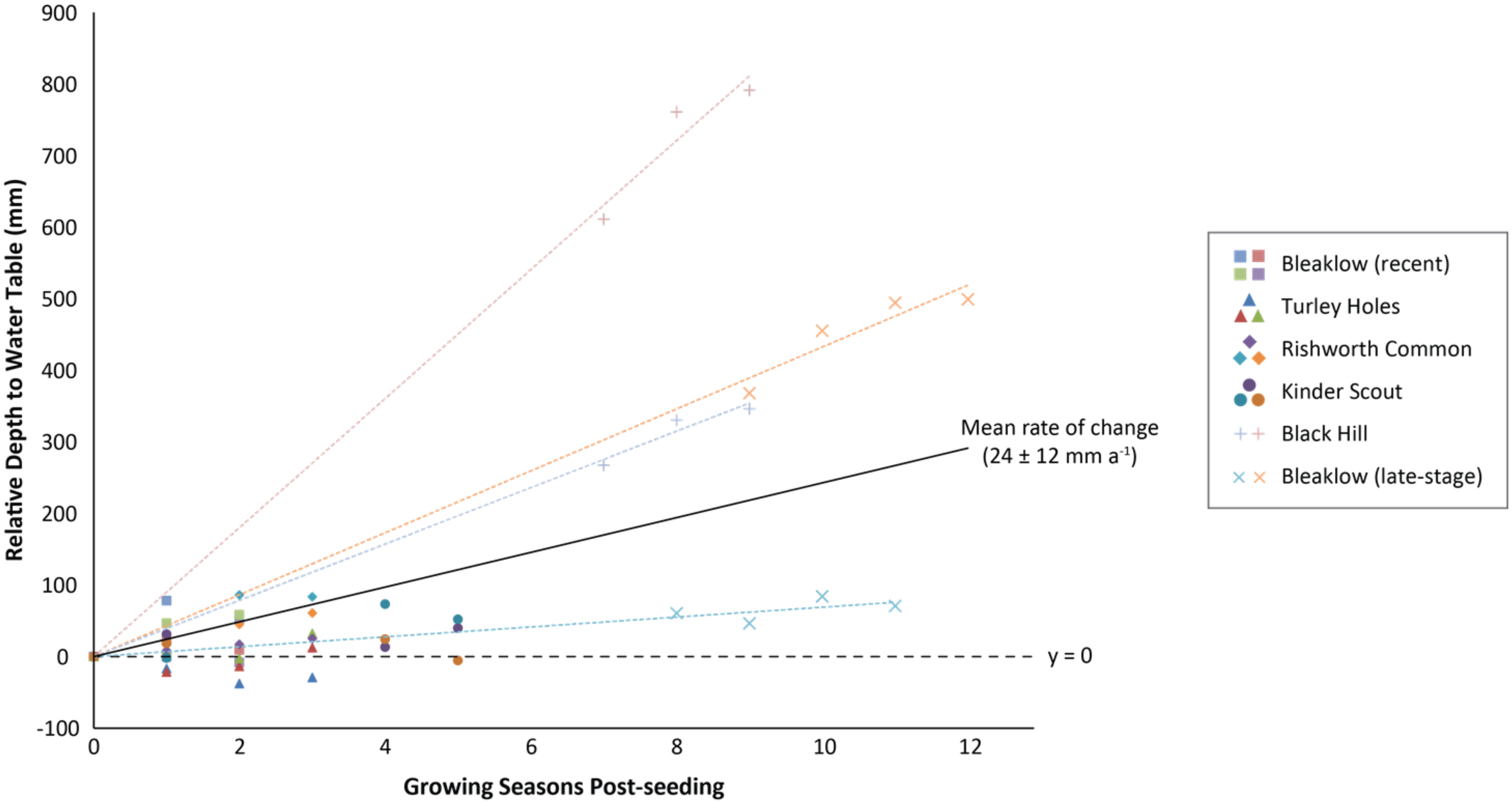


Figure 6 a Trajectories of water table change relative to control sites based on manual campaign data. 'Late stage' data are plotted in Y axis positions based on extrapolation of the local trend to the origin (indicated by the dotted lines, see text).

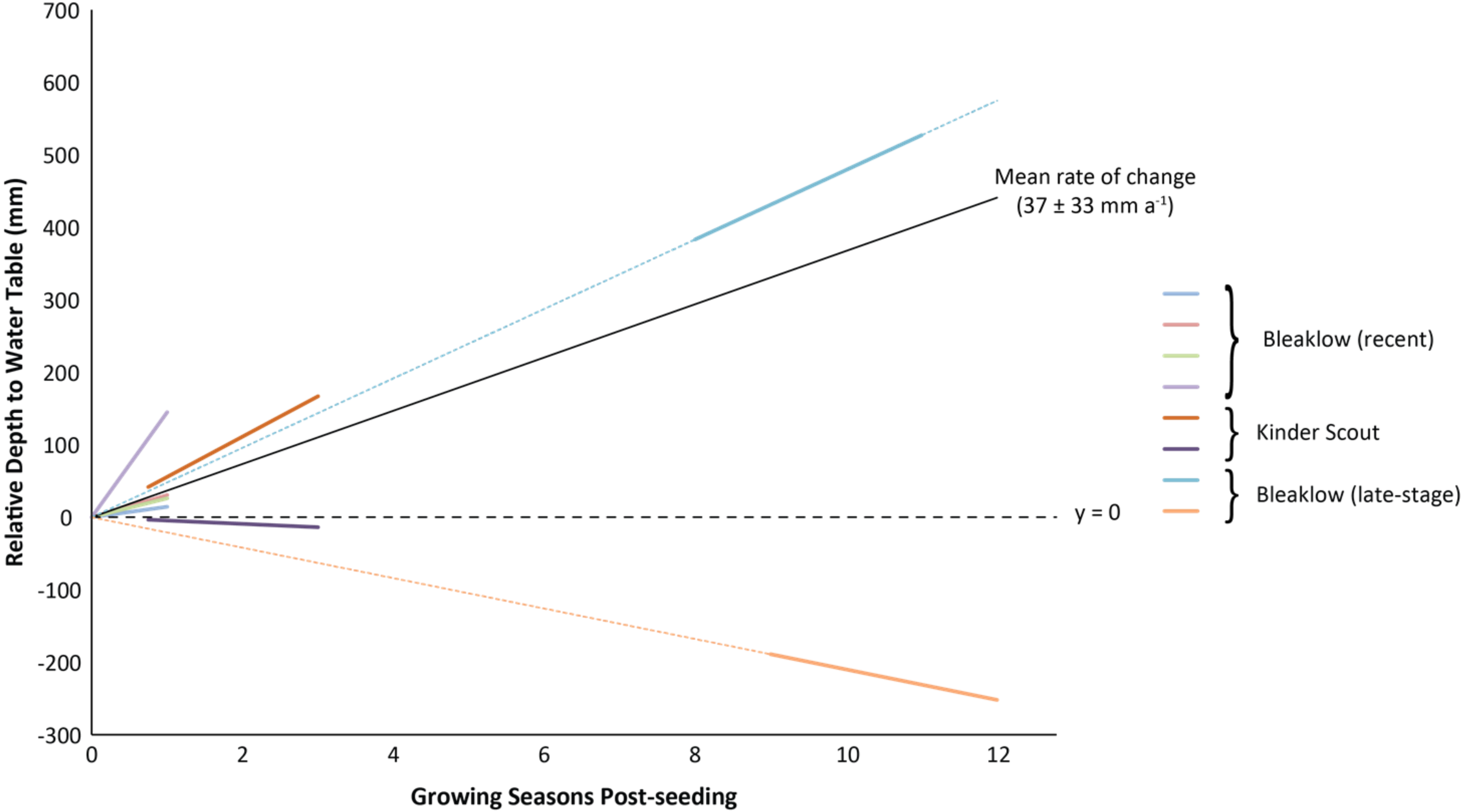


Figure 6 b Trajectories of water table change relative to control sites derived from continuous monitoring. Solid lines indicate the trends derived from the continuous data or the period of monitoring. 'Late stage' data are plotted in Y axis positions based on extrapolation of the local trend to the origin (indicated by the dotted lines, see text).

6.0 Implications for ongoing monitoring

The analysis undertaken for this project has required a careful assessment of the quality and representativeness of the water table data from the existing monitoring programme. The following section reports some conclusions from this assessment in regard to approaches to ongoing monitoring of the restoration sites.

These findings indicate the importance of supporting long term monitoring at these sites. Firstly, given the relatively small rates of annual change, longer term observations will provide increased confidence in these results by improving the signal to noise ratio in the data. Secondly, the implication of ongoing change in water table over a decade are inferred from analysis of the older restoration sites. Ongoing monitoring of recently restored sites will provide confidence that the changes observed here are not a result of site to site difference in water table behaviour.

6.1 Manual dipwell data (autumn campaigns)

- The manual dipwell data is well collated and appears to provide a robust and reliable approach to monitoring.
- The autumn campaigns mean that the monitoring effort is focussed within a constrained time period.
- The simple approaches appear to provide good quality data using trained volunteer labour.
- Because of the potential for erosion around the dipwells at the control bare peat sites the manual dipwell approach is likely to provide minimum estimates of water table increase and may exaggerate water table decreases. For the current data this issue means that estimates of water table increase associated with the re-vegetation are conservative.
- For future monitoring campaigns it would be valuable to ensure that peat anchor data on surface recession at the bare peat sites is presented and analysed together with the water table data in order to assess the magnitude of this effect.
- Analysis of continuous automate data reported in section 4.5 demonstrates that the autumn data produces on average higher and less variable water table than data for the whole year. This is unsurprising since the largest variation in water tables is likely to be associated with summer drawdown events.
- Median water table is a robust measure for which the variation between autumn and summer data is minimised.

6.2 Automated dipwell data(annual data)

- Automated dipwells produce high data volumes. This has some drawbacks in terms of data management but does offer the potential to analyse the finer temporal dynamics of water table behaviour.
- The cost and data handling requirements of continuous measurement tend to preclude replication. Previous analysis of the manual data has suggested that extensive replication is required to accurately assess water tables. Consequently the continuous data is best viewed and analysed as a series of treatment replicates rather than attempting to assess inter-site differences.
- Calibration is a critical issue for the continuous data. In order to detect small changes in water table over periods of several years it is important that data is corrected for potential instrumental drift.
- Calibration of long term data presents significant logistical challenges. Changes in personnel, precision of measurement in difficult field conditions, and the requirement to remove and service equipment mean that the calibration of the current dataset has the potential to introduce significant noise into the measurements.
- The high resolution data provided by continuous dipwells has the potential to demonstrate changes in water table dynamics indicative of hydrological recovery in the restored peatlands. The drawdown analysis presented here, whilst not conclusive, is indicative of the potential of this approach.
- Continuous data plays an important role in understanding the representativeness of the campaign data.

6.3 Future Monitoring

- The manual campaign data has proved an effective approach to demonstrating changes om water table at restoration sites, and subject to the recommendations above appears to be a suitable approach for compliance monitoring where the requisite person power can be deployed, perhaps in the form of volunteer labour.
- Continuous logging of water table data is not a fire and forget method of monitoring, careful attention needs to be paid to calibration and consistency of method. However, the potential of this approach to describe changes in water table dynamics related to restoration mean that it is a valuable method.

- A mixed approach of campaign monitoring with continuous measurement at selected sites is recommended for future monitoring campaigns
- Maintenance of long term records at sites with a long post restoration record (such as the Kinder Scout MS4W sites) is essential to demonstrate that the long term water table recovery which the current spatial data indicate is observable at single sites.

7.0 Key Findings and Conclusions

- Both continuous and manual dipwell data suggest that water table is raised relative to bare peat control sites post re-vegetation of the peat surface.
- Rates of recovery are small and variable. A conservative estimate of rate of increase is 19 mm per year with observable increases occurring up to 11 years post restoration (the limit of the available data). Over 10+ years post restoration the cumulative changes in water table are relevant in terms of peatland function.
- There is evidence that the process of hydrological restoration is ongoing post re-vegetation, with some evidence of reduced variability and reduced rate of drawdown in dry periods and potentially of higher rates of water table change for late stage sites. Further monitoring is required to firmly establish the validity of these initial indications; in particular longer term single site data will confirm patterns inferred from space for time studies and allow direct assessment of the form of the long term trend.
- Both continuous and campaign monitoring of water table have limitations but both add distinctive understanding to this analysis. There is merit to continuing a combined monitoring strategy, particularly at key long term sites.

8.0 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. Report to the Environment Agency. Moors for the Future Report No. 17. Moors for the Future Partnership, Edale, 47pp.

Clark, J., Gallego-Sala, A., Allott, T., Chapman, S., Farewell, T., Freeman, C., House, J., Orr, H., Prentice, I., Smith, P., 2010. Assessing the vulnerability of blanket peat to climate change using an ensemble of statistical bioclimatic envelope models. Clim. Res. 45, 131–150. doi:10.3354/cr00929

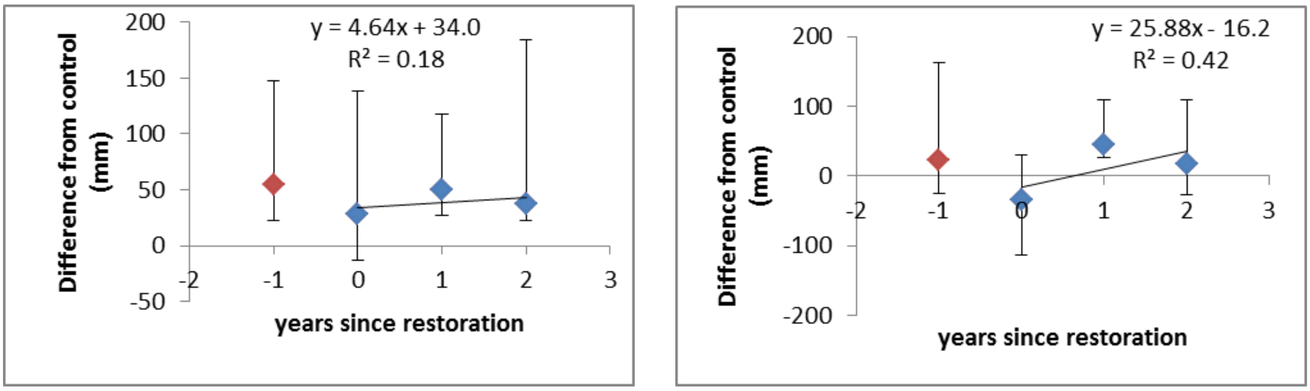
Pilkington, M., Walker, J., Maskill, R., Allott, T. and Evans, M. (2015). *Restoration of Blanket bogs; flood risk reduction and other ecosystem benefits*, Final report of the Making Space for Water project: Moors for the Future Partnership, Edale.

Appendix 1 Water table depth data

Figure A1.1 Median depth to water table by site for each annual monitoring campaign. (Bold denotes values before restoration at treatment sites.)

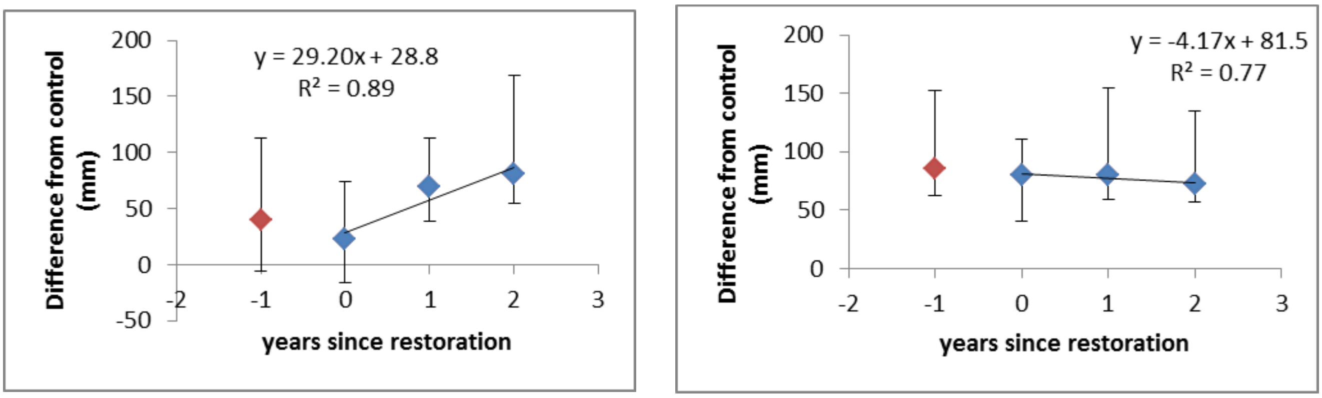
			Depth to water table (mm)					
	Area	**ID**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Recently re-veg	Bleaklow (recent)	D		**396**	**387**	359	383	
		R		**368**	**288**	336	328	
		L		**394**	**329**	331	324	
		SB		**344**	**275**	322	310	
	Turley Holes	TH1		**277**	236	282	307	
		TH2		**486**	431	465	473	
		TH3		**450**	389	415	433	
	Rishworth Common	RC1		**391**	353	395	445	
		RC2		**316**	286	269	330	
		RC3		**275**	248	272	314	
	Kinder (MS4W)	N1	**508**	534			372	292
		N2	**444**	487			250	189
		O	**388**	384			228	200
Late stage re-veg	Black Hill	BH1			462	414	453	
		BH2			462	309	339	
	Bleaklow (late stage)	JP		421	256	277	289	
		Po		386	333	331	369	
Bare control		TR A		429	354	407	416	
		TR C		378	293	361	350	
		F	495	510			342	267
		TH BP		386	333	349	381	
Intact control		Pe		162	27	10		
		S		94	75	79	99	
		TH int		35	-9	35	91	
		RC int		11	15	47	73	

Appendix 2 Manual Dipwell Plots



Site D

Site R

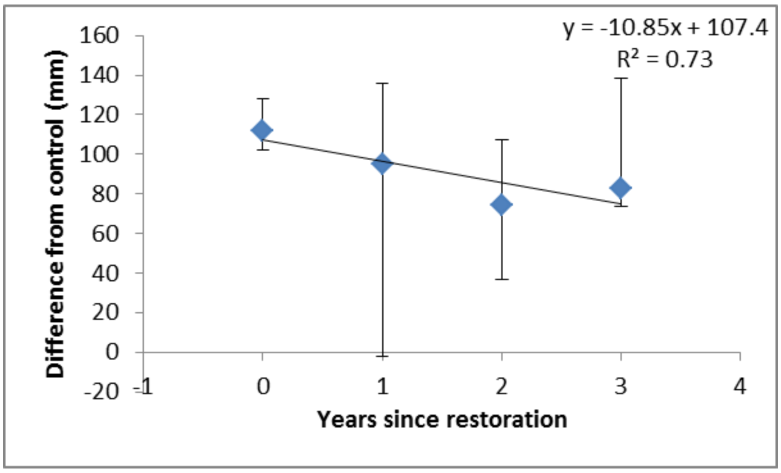


Site L

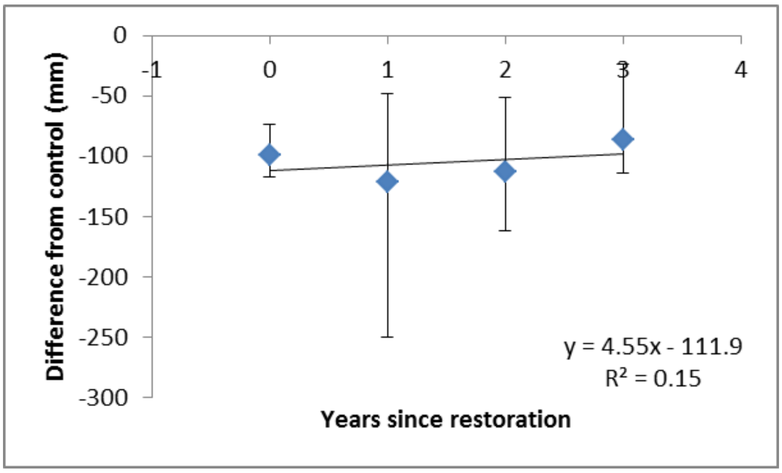
Site SB

Figure A 2.1 Difference from control for re-vegetated sites on Bleaklow (Re-vegetated July 2013). Manual dipwell data spanning 4 years. Y axis is D control – D treatment where D is the depth of water table below the surface in mm. Increases in the Y axis value reflect decreases in depth to WT at the treatment site (higher water tables) or increases (lower water table) at the control site. Rate of change is calculated using the fitted lines through the post restoration data (blue markers). Points are median water table and error bars are the range of measured mean water tables for the site through the autumn sampling campaign.

Site TH1



Site TH2



Site TH3

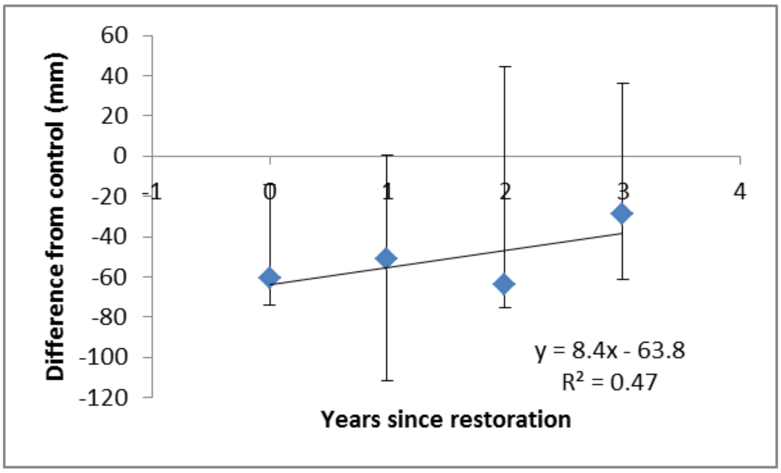
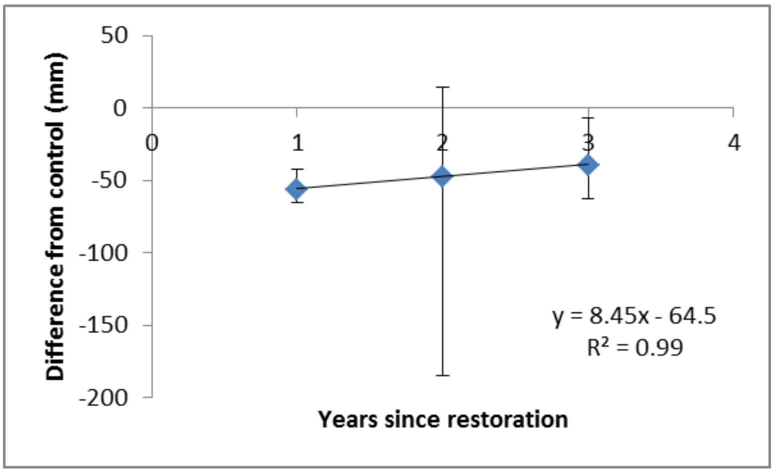
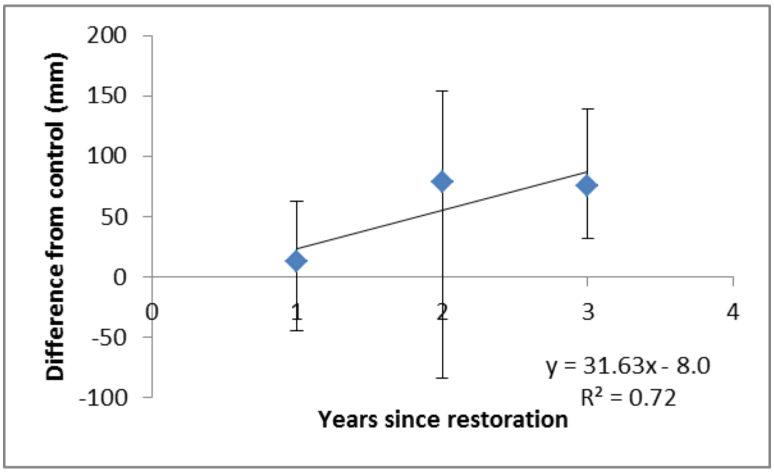


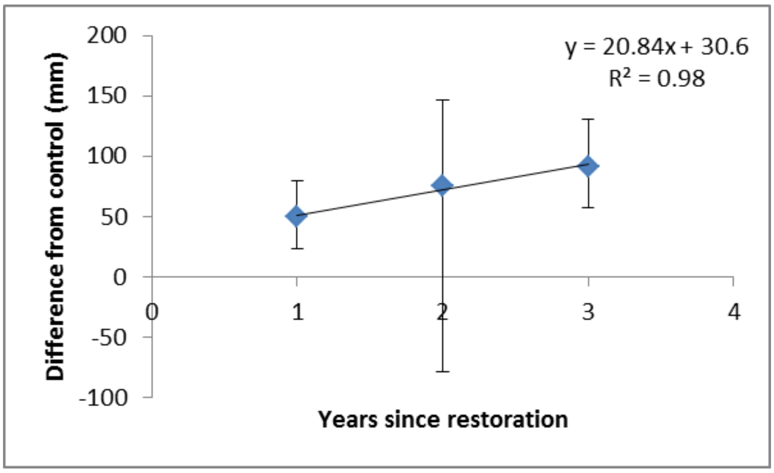
Figure A2.2 Difference from control for re-vegetated sites on at Turley Holes (Re-vegetated April 2012). Rate of change is calculated using the fitted lines through the post restoration data. Points are median water table and error bars are the range of measured mean water tables for the site through the autumn sampling campaign.



Site RC1



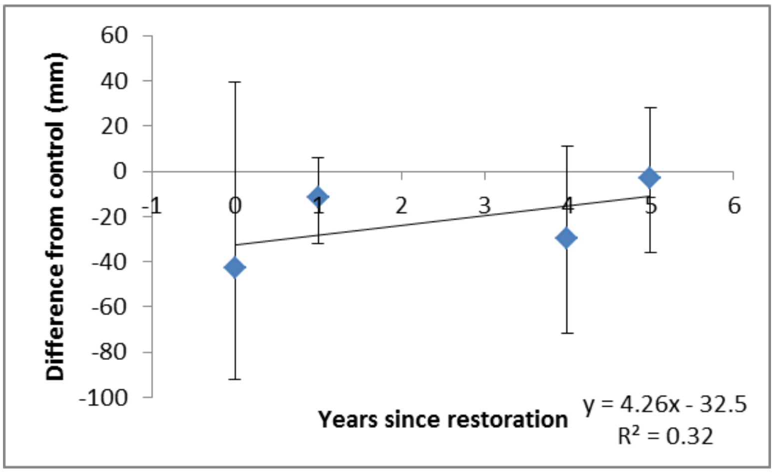
Site RC2



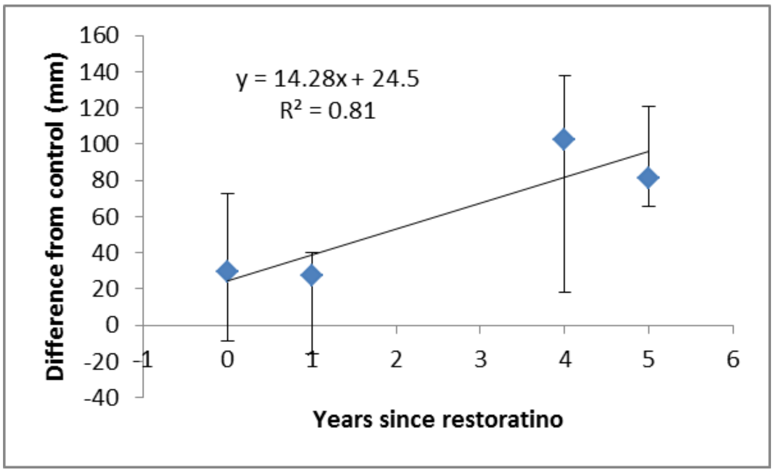
Site RC3

Figure A2.3 Difference from control for re-vegetated sites on at Rishworth Common (Re-vegetated April 2012). Rate of change is calculated using the fitted lines through the post restoration data. The control site for these calculations are the control at Turley Holes. 2011 data is omitted because there are not suitable control data. Points are median water table and error bars are the range of measured mean water tables for the site through the autumn sampling campaign.

Site N1



Site N2



Site O

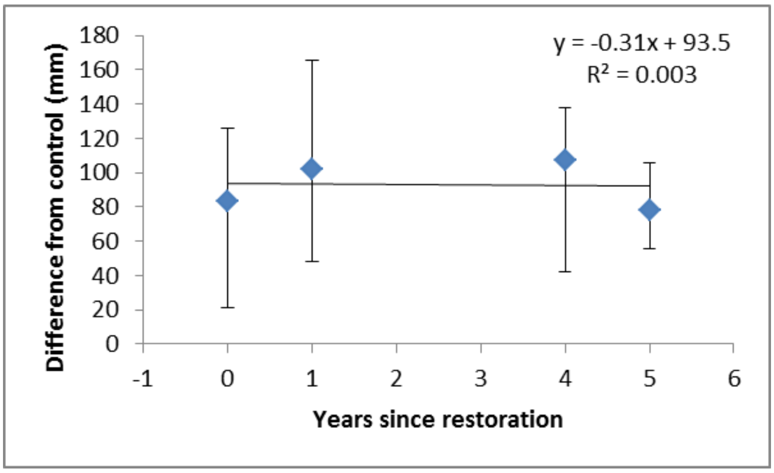
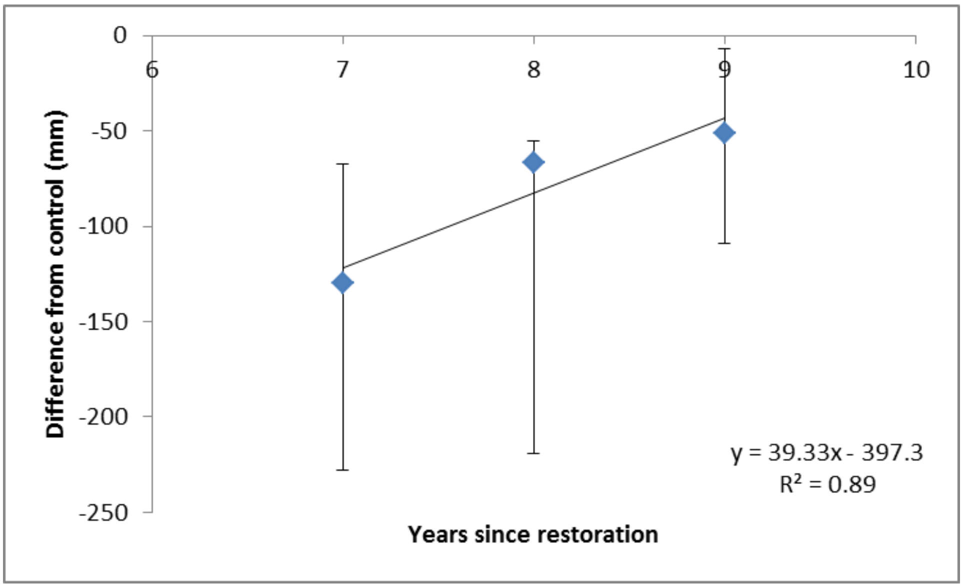
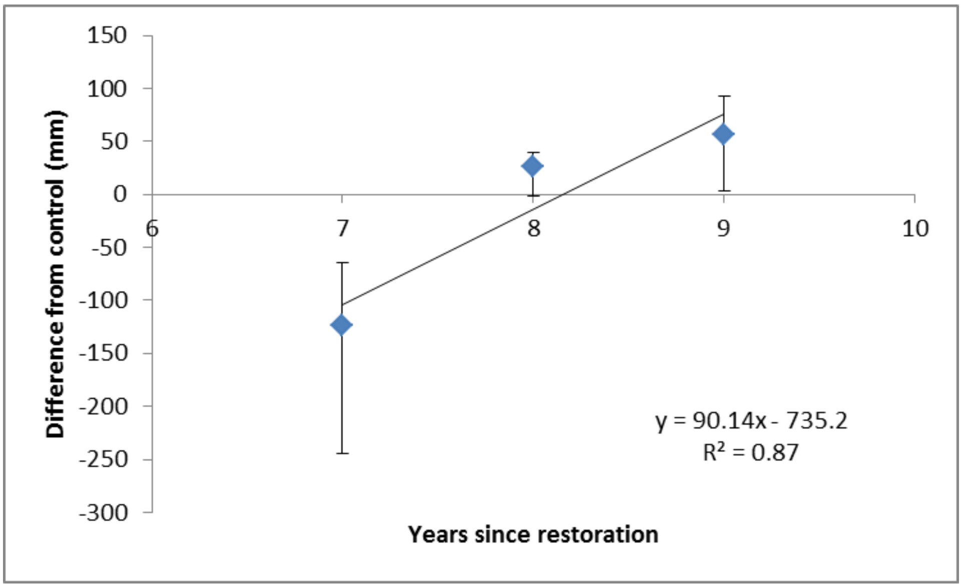


Figure A2.4 Difference from control for re-vegetated sites on at MS4W sites on Kinder Scout (Re-vegetated July 2011). Rate of change is calculated using the fitted lines through the post restoration data. Points are median water table and error bars are the range of measured mean water tables for the site through the autumn sampling campaign.

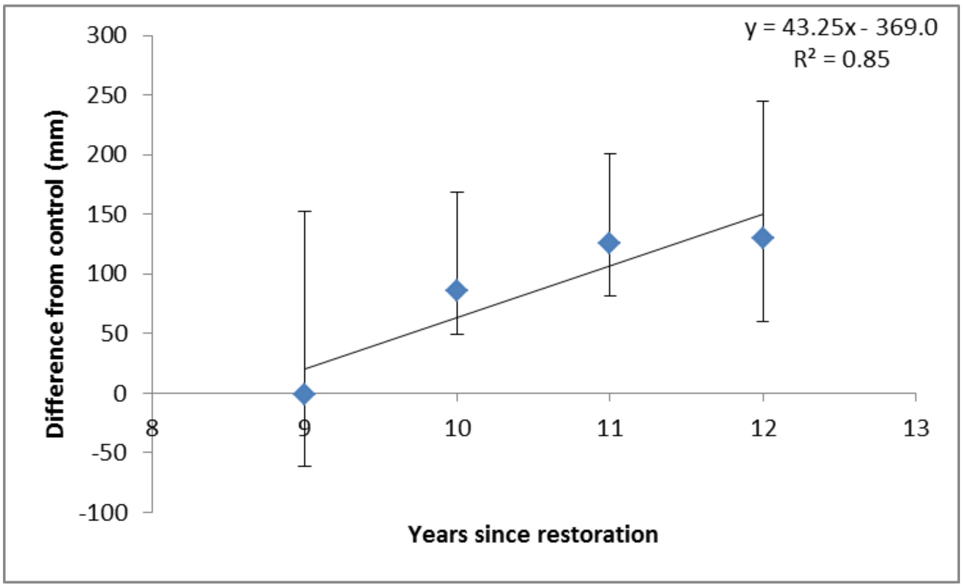


Site BH1

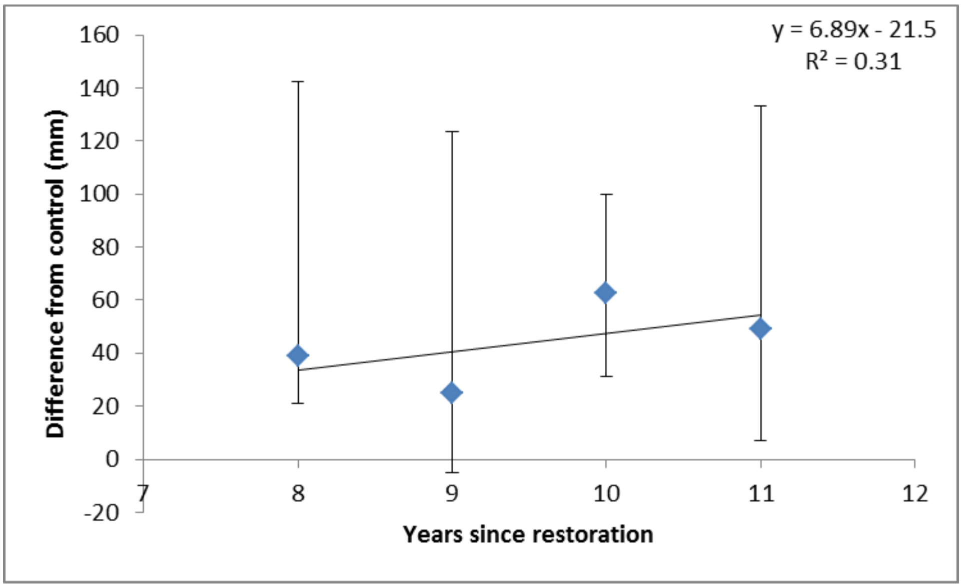


Site BH2

Figure A2.5 Difference from control for re-vegetated sites at Black Hill (Re-vegetated June 2006). The control site for these data was the bare peat site at Turley Holes. Rate of change is calculated using the fitted lines through the post restoration data. Points are median water table and error bars are the range of measured mean water tables for the site through the autumn sampling campaign.



Site Po



Site JP

Figure A2.6 Difference from control for older (late stage) re-vegetated sites at Bleaklow (Re-vegetated June 2003, JP ande June 2004 Po). Rate of change is calculated using the fitted lines through the post restoration data. Points are median water table and error bars are the range of measured mean water tables for the site through the autumn sampling campaign.

Appendix 3 Trends in continuous dipwell data

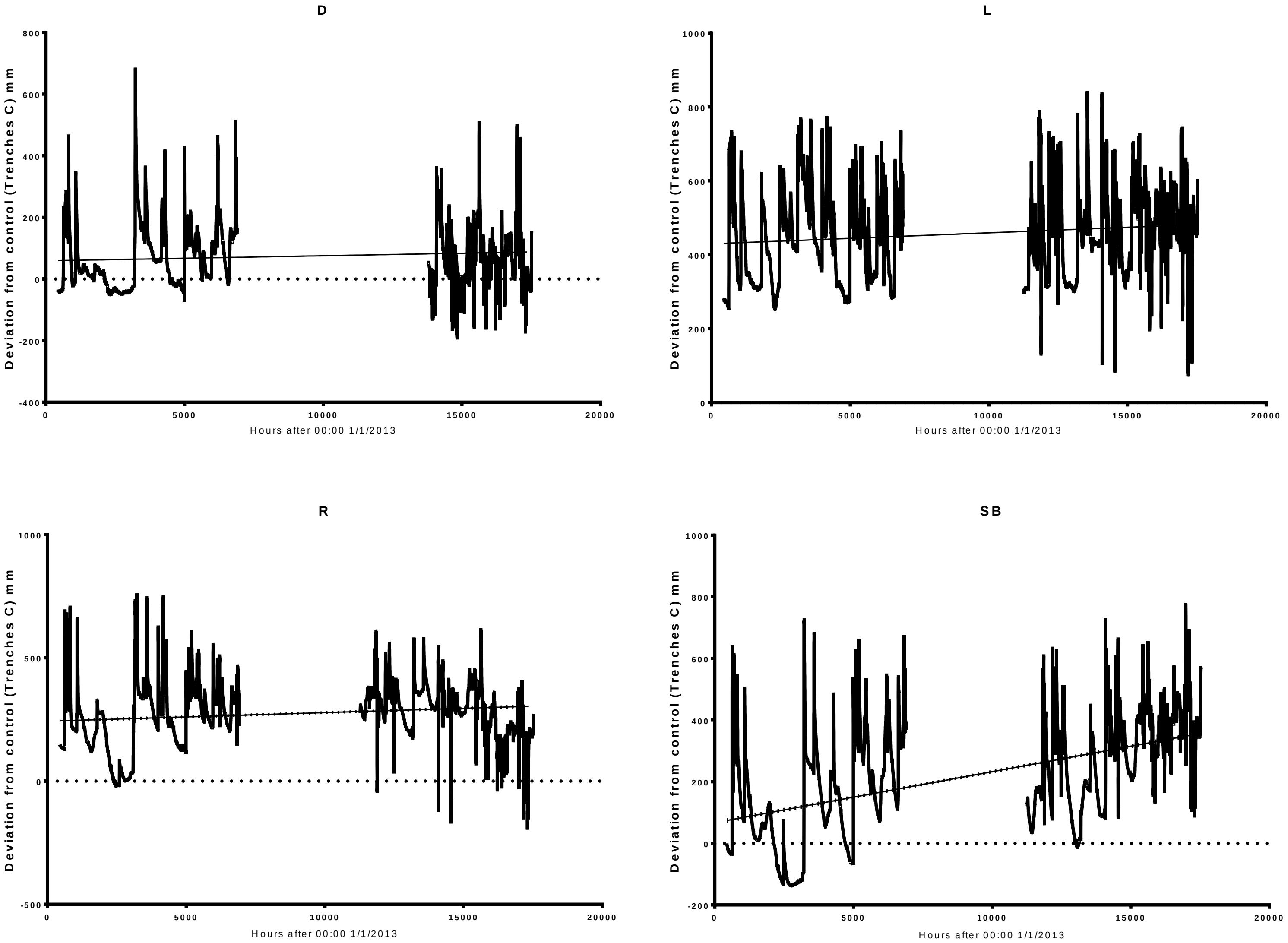


Figure A 3.1 Continuous dipwell data with best fit linear trend for early stage sites on Bleaklow

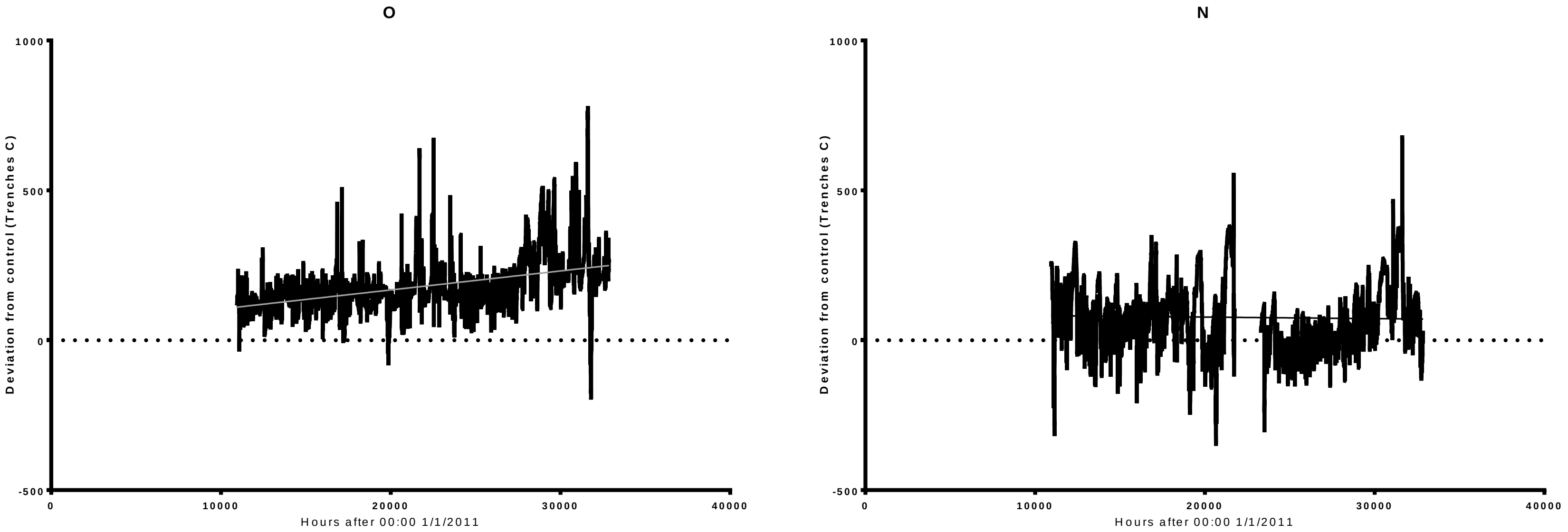


Figure A3.2 Continuous dipwell data with best fit linear trend for early stage MS4W sites on Kinder Scout

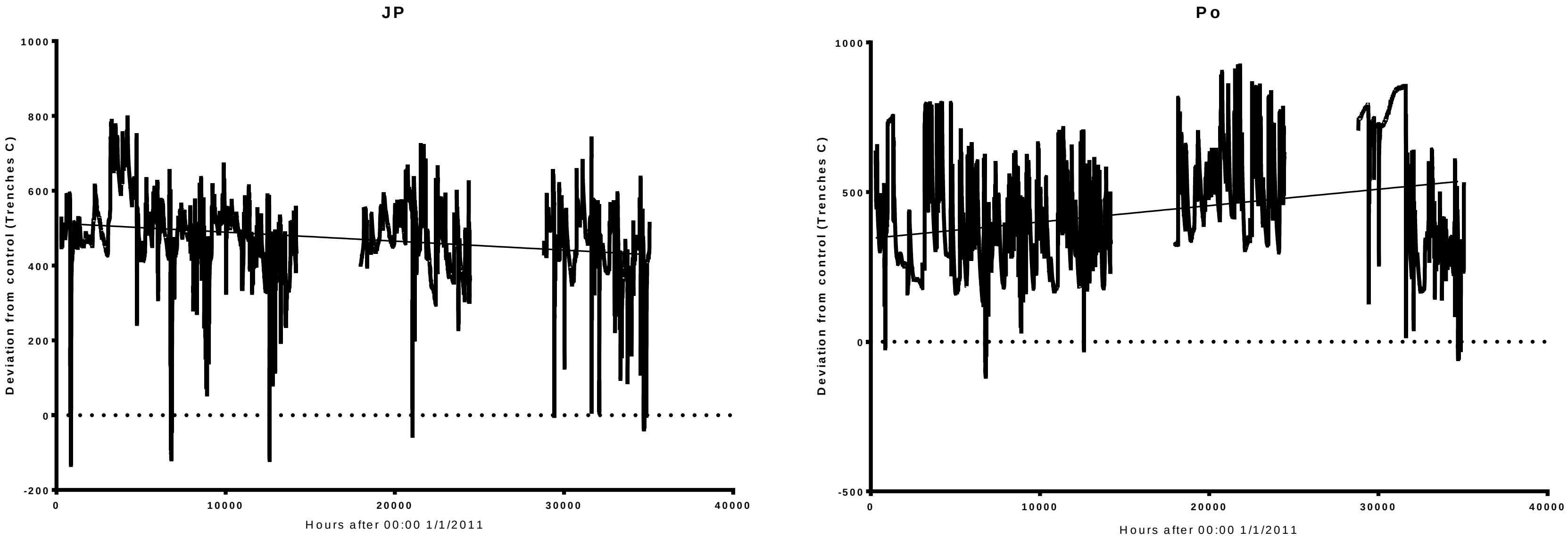


Figure A 3.3 Continuous dipwell data with best fit linear trend for late stage sites on Bleaklow