MONITORING THE BIODIVERSITY AND ECOSYSTEM SERVICE IMPACTS OF RESTORATION OF DEGRADED BLANKET BOG SITES

CHAPTER 4: WATER TABLE, SOIL MOISTURE & OVERLAND FLOW GENERATION

MoorLIFE 2020

MoorLIFE 2020 Final Report:
Action D2

Monitoring the biodiversity and ecosystem service impacts of restoration of degraded blanket bog sites

Chapter 4: Water Table, Soil Moisture & Overland Flow Generation

2022

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Suggested citation:

Allott, T.E.H., Blundell, A., Chandler, D., Evans, M.G, Margetts, J.J., Moody, C.S., Pilkington, M.G., Shuttleworth, E.L, Spencer T. (2022). *Chapter 4: Water Table, Soil Moisture & Overland Flow Generation* In Moors for the Future Partnership (2022) *Monitoring the biodiversity and ecosystem service impacts of restoration of degraded blanket bog sites.* Final report of the MoorLIFE 2020 project Action D2: Moors for the Future Partnership, Edale.

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1. Summary

Peatlands across the South Pennines have been heavily damaged by human activity, leading to extensive areas of bare peat, severe gullying and domination by single vegetation species. Erosion, and the subsequent development of extensive drainage networks, has lowered water tables and restricted the potential for key blanket bog species to recolonise naturally.

Monitoring of water tables at revegetated bare peat sites across the South Pennines using manual dipwells showed that water tables rose steadily but slowly by 6–8mm yr^{-1} for up to 17 years following treatment, although there is strong variability between sites, likely associated with severity of historic erosion. Continuous data from water table loggers at the same locations as the manual dipwells showed that water tables rose by 16 mm yr^{-1} for up to 10 years. The rate of water table recovery appears to be limited by severity of historic gully erosion.

Monitoring of water tables on sites dominated by single species showed varied results. Where *Sphagnum* was planted at high density (100 plugs m^{-2}) in *Eriophorum* a small but significant median water table rise of 14–18 mm was observed over the monitoring period. A smaller, but significant rise of ~4 mm was also seen where *Sphagnum* was introduced at high density into *Calluna* (although the result was not significant on the *Sphagnum* and gully blocked mini-catchment), so no clear trend was established. On these sites, no statistically significant changes have yet been observed where *Sphagnum* was introduced at a lower density of 4 plugs m^{-2}.

In contrast, on the *Molinia* dominated site, a small but significant rise in water table was seen where *Sphagnum* had been introduced at the lower 4 plugs m^{-2} density, despite *Sphagnum* cover increasing from 0 to only 3.5% – the least out of any dominant vegetation type monitored. However, the intensively planted plots where *Sphagnum* had established to ~11% cover showed a small fall in water table. The results on this site were likely to have been impacted by an internal difference between treatment and control areas in how water table was supported and/or supplied, possibly due to site morphology or differences in hydraulic conductivity.

Overland flow on a peatland surface is generated by a combination of infiltration-excess and saturation-excess. Infiltration-excess overland flow is generated by a surface of low permeability (or high hydrophobicity) retarding infiltration; saturation-excess is generated by high water tables and/or near-surface soil saturation. Increased *Sphagnum* cover may reduce surface hydrophobicity, reduce infiltration-excess and increase saturation-excess overland flow generation. *Sphagnum* has been shown to reduce overland flow velocities (Holden *et al.*, 2008), with important implications for stream discharge in heavy rain events.

Soil moisture was monitored at sites on Kinder Scout using newly-developed sensors. Initial data suggested that the top 12.5 cm of peat was wetter in revegetated areas than in bare peat areas, and that moisture was retained for longer following the cessation of precipitation. This supports the hypothesis that revegetation leads to an increase in saturation-excess overland flow generation (as opposed to infiltration-excess), with important implications for stormflow, as overland flow is attenuated by increased surface roughness resulting from a dense vegetation canopy. Further investigation of this monitoring technique could enhance current understanding of hydrological processes affected by revegetation work and, in particular, the re-introduction of extensive *Sphagnum* cover.

On the *Eriophorum* site, little change was seen in overland flow relative to control, but this lack of change was consistent with relatively stable water table from before to after treatment periods on this site. On the *Calluna* site, the treated catchments showed a greater increase in overland flow from the before to the after periods, compared to control. On the *Molinia* site a small relative increase in overland flow of 5% was seen in the lower planting density areas, whereas a small relative reduction in overland flow of ~18% was found in the high density planning areas. These observations

should be treated with caution when remarking on the effects of *Sphagnum* due to the short time period since planting. It is essential to continue monitoring to observe changes in both overland flow and water table over a much longer period firstly to allow *Sphagnum* to gain greater coverage and depth but also to observe reactions to various climate conditions.

2. Introduction

The long history of degradation of peatland landscapes within the areas now designated as the Peak District National Park and South Pennines Moors Special Area of Conservation is outlined in the introductory chapter of this report.

Exploitation for agriculture and forestry, together with deposition of atmospheric pollution and outbreaks of wildfire have been severely detrimental to the peatland habitats within this area. Such processes have led to the loss of *Sphagnum* mosses in almost all locations, a reduction in the diversity within remaining vegetation communities (leaving some peatlands dominated by a single species), and extensive areas without any vegetation cover, leaving an exposed and fragile bare peat surface.

This degradation has important implications for the ability of the landscape to provide ecosystem services. As such, water tables on sites with varying starting states have been monitored as restoration processes have been implemented. Recording changes in water table over time provides evidence of whether the ecosystem is recovering as a result of these restoration processes. It also provides context to other processes being monitored including surface water runoff, catchment discharge, water chemistry, and vegetation diversity.

Water table is a fundamental control on runoff production, which in turn influences storm hydrograph response. Previous investigations of blanket peat water tables have focussed on the effects of ditch blocking on water tables in areas of drained peat (e.g. Holden *et al*., 2004). While some parallels can be drawn between drainage ditch- and gully-blocking, gullied systems are more variable and dynamic landscapes than artificial ditch networks, and a more flexible approach to restoration must be taken, guided by geomorphic and hydrological process (Evans *et al*., 2005).

Allott *et al*. (2009) found substantial between-site variation in average water table conditions, which was strongly associated with erosion status. Intact sites with no erosion gullies at or proximate to the site have water tables consistently close to the peat surface, while sites with dense erosion gullies are associated with lower water table conditions. Allott *et al*., 2015 found that water tables at bare peat sites on Kinder Scout had risen by 35 mm, three years after revegetation. Alderson *et al*., 2019 found that water tables at bare peat restoration sites across the South Pennines rose by ~8 mm yr^{-1}.

This chapter builds on the work of Allott *et al*. (2015) and Alderson *et al*. (2019), using water table data from the same sites as in those studies, to further our understanding of the influence of re-vegetation on peatland water tables. Additionally, water tables were monitored at three sites which were dominated by single vegetation species (*Eriophorum vaginatum*, *Calluna vulgaris*, *Molinia caerulea*), where *Sphagnum* mosses were planted (all sites) and gully blocks were installed (*Calluna* only).

Overland flow is a key runoff pathway in blanket peat systems. In intact blanket peatlands, the majority of storm-flow is produced as saturation excess overland flow, particularly on more gentle slopes and on footslopes where overland flow occurs most frequently (Holden & Burt, 2003). Evans *et al*. (1999) show that the generation of near-surface and overland flow is influenced by the maintenance of high water tables close to the peat surface. In contrast, degraded peats with depressed water tables are likely to produce more bypassing rapid subsurface storm-flow through macropore and soil pipe networks, and therefore generate less overland flow (Holden & Burt 2003). Allott *et al.* (2015) found that overland flow production increased following the revegetation of bare peat surfaces, both on interfluves and on footslopes. This section builds on the work of Allott *et al.* (2015), monitoring overland flow generation at the same sites as in that study, and also at the three sites dominated by single species.

This chapter presents spatial and temporal data in order to evaluate the impact of re-vegetation and vegetation diversification on water table depth and overland flow generation. These variables were monitored at two sets of sites:

1. Those with a bare peat starting state (including field labs on Kinder Scout; and wider context sites in the South Pennines) which have undergone restoration
2. Those dominated by a single species (referred to as species dominated sites)

Table 1. Sites at which water table was monitored

Bare peat starting state		**Species dominated starting state**
Kinder Scout field labs	**Wider context sites**	
N	Joseph Patch (Bleaklow)	Heather (*Calluna*) – Derwent and Howden
O	Shelf Moor (Bleaklow)	Cotton-grass (*Eriophorum*) – Birchinlee
F (bare peat control)	Shining Clough (Bleaklow)	Purple moor-grass (*Molinia*) – Moss Moor
	Woodhead (Bleaklow)	
	Skyes Moor (Bleaklow)	
	T (Bleaklow bare peat control)	
	Black Hill	
	Rishworth	
	Seal Edge (Kinder Scout)	
	Turley Holes	

As discussed in Baird and Low (2022), water tables are often referred to in overly-simplistic terms while they are in fact complex in their spatial variability (vertically and laterally) and behaviours. The method of using dipwells to monitor water tables is acknowledged here to result in a simplification of this complexity. The use of untreated control sites mitigates some of the potential problems associated with this simplification, and it is still considered a useful measure of soil condition. The addition of new, experimental soil moisture sensors adds some nuance to these observations.

2.1. Treatment regimes

2.1.1. Bare peat sites

The bare peat restoration process carried out on the Kinder field lab sites is detailed the introductory chapter of this report.

Under the Making Space for Water project in 2011–2013, grazing was excluded from the Kinder plateau, peat was stabilized using heather brash and geo-jute and the bare peat areas were then revegetated with applications of lime, mixed grass seed and fertilizer. Moorland species were then added as plug plants, and in 2015–2018 *Sphagnum* mosses were reintroduced to some areas in the form of mixed species plug plants. In addition, erosion gullies were blocked with both stone and timber dams. The treatments applied, and dates of application for each of the main field lab sites are summarized in Table 2 below.

2.1.2. Species dominated sites

The species dominated sites were treated by introducing mixed species *Sphagnum* moss plug plants at a density of 1 plug m^{-2}, aside from several higher-density areas as follows:

A 30 x 30 metre area containing a cluster of dipwells had plugs introduced at a density of 4 plugs m^{-2} – planted at 50 cm spacing regardless of micro-topography or vegetation. Flow pathways were also planted at 4 plugs m^{-2}, while the intensively planted run-off plots were planted at the highest density of 100 plugs m^{-2}, in order to attempt to simulate the potential future condition of the wider catchment during a shorter time span. In addition, wooden gully blocks were also added to an extra treatment catchment on the *Calluna* dominated site.

Treatments applied and the dates of application are outlined in Table 2 below.

Table 2. Summary of treatments applied to main monitoring sites

Restoration process	**Bare Peat sites**				**Calluna site**			**Eriophorum site**		**Molinia site**	
	F	**P**	**O**	**N**	**Cal.con**	**Cal.spha**	**Cal.sphaGB**	**Eri.con**	**Eri.spha**	**Mol.con**	**Mol.spha**
Grazing exclusion	2013	-	2013	2013	-	-	-	-	-	-	-
Gully blocking	-	-	-	2011	-	-	2019	-	-	-	-
Heather brash	-	-	2011	2011	-	-	-	-	-	-	-
Geo-jute	-	-	2011	2011	-	-	-	-	-	-	-
Seeding: amenity grasses and moorland species	-	-	2011	2011	-	-	-	-	-	-	-
Lime + fertiliser	-	-	2011, 2012, 2013	2011, 2012, 2013	-	-	-	-	-	-	-
Sphagnum planting	-	-	-	2015, 2018	-	2019	2019	-	2019	-	2019

3. Methodology

3.1. Experimental design

Field labs based on mini-catchments were established to monitor changes in water table at sites with a bare peat starting state, and those dominated by a single species; as outlined in Table 1. The introductory chapter of this report contains details of the location and characteristics of these mini-catchments.

The sites were monitored using a BACI (Before-After-Control-Impact) design, using as similar a method as possible allowing for site-specific differences such as catchment shape/size, slope, aspect and drainage network density. Each of the species dominated sites, plus the bare peat sites on Kinder Scout were set up with a control catchment adjacent to treatment catchments. At the wider context sites, it was not always possible to retain a long-term untreated control site due to obligations placed on the landowner to restore areas of bare peat. A bare peat control site was preserved at Bleaklow (site T); this served as the control for all of the wider context sites except Seal Edge (Kinder Scout), where site F (Kinder Scout field lab) was used as it was closer. While the lack of a nearby control site limits the confidence in results of BACI analyses, the wider context sites were retained as they provide valuable replication, although with the caveat that the different sites could be affected by variation in local weather systems.

Water tables were monitored in the following ways:

- Manually – by taking readings from multiple dipwells on site visits

- Continuously – using automated water pressure loggers installed in dipwells

Overland flow generation was monitored using crest stage tubes. Towards the end of the monitoring period, experimental sensors were installed at the bare peat mini-catchments to monitor soil moisture.

3.2. Water table monitoring

3.2.1. Field setup

The water table depth at each site was determined using dipwells. Allott *et al.* (2009) showed that multiple randomly located dipwells are required for the reliable quantification of water table conditions at the site scale, and determined that 15 dipwells are required to obtain reliable estimates of site water table conditions at any given time. Accordingly, clusters of 15 dipwells were randomly located within a 30 x 30 m area at each site.

At the core bare peat sites, the following clusters were installed:

- **F** (untreated control): three clusters installed in 2010
- **O** and **N** (treatment): three clusters installed across the two sites in 2010; an additional two clusters installed in 2015 in areas of site N where *Sphagnum* was planted
- **P** (intact reference): three clusters installed in 2010

Within these, Trutrak WT-HR 1000 capacitance probe water height loggers were installed in 2010 in extra dipwells associated with:

- All three clusters at **F** (control)
- The weirs at **O** and **N** (treatment)
- All three clusters at **P** (intact reference)

These were set to take a reading every 10 minutes.

Details of the water table monitoring installed at the wider context bare peat sites are detailed in Table 3 below.

At the species dominated sites, one cluster of dipwells was installed at each mini-catchment in 2018. In addition, two dipwells were installed into each intensively treated plot (three plots; six dipwells per mini-catchment).

Dipwells on bare peat sites were constructed and installed to the same specifications outlined in Allott *et al.* (2009). In brief, each dipwell comprised a 1 m length of polypropylene waste pipe (internal diameter 30 mm) with perforation holes drilled at 100 mm intervals, to allow water levels to equilibrate inside the pipe. Dipwells were driven into pre-prepared boreholes of the same diameter, with approximately 100 mm of pipe protruding above the ground surface.

On the species dominated sites, dipwells were constructed using a similar but updated specification, with four 5 mm diameter holes being drilled at 35 mm intervals along the length of the tube. These dipwells were installed using the same method as those on the bare peat sites.

Measurements were taken to the nearest mm, using a blow-tube affixed to a ruler. Measurement of the pipe protruding above the ground surface was made with a ruler, at a mark on the north side of the pipe.

On the species dominated sites, a Solinst Levelogger Edge 3001 LT automated water pressure logger was installed within one dipwell in each mini-catchment, suspended using kevlar cord. This was set up to take a reading at five-minute intervals.

Measurements of water levels in the dipwells were made using the timing and duration summarised in Table 3.

Table 3. Summary of dipwell sampling regimes

Site	ID	Treatment/ control	Dipwells present on site: location (number)	Manual sampling interval (days)	Continuous measurement logger: location (number)	Continuous measurement period
Bare peat (Kinder)	F	Control	3 clusters (15 in each)	7 (autumn only)	Clusters (3)	2010–2021
	O	Treatment	2 clusters (15 in each)	7 (autumn only)	Clusters (2)	2010–2021
	N	Treatment	3 clusters (15 in each)	7 (autumn only)	Clusters (3)	2010–2021
Calluna	Cal.con	Control	Cluster (15) Intensive plots (6)	~21; (7 – autumn only)	Intensive plot (1)	2017–2021
	Cal.spha	Treatment	Cluster (15) Intensive plots (6)	~21; (7 – autumn only)	Intensive plot (1)	2017–2021
	Cal.sphaGB	Treatment	Cluster (15) Intensive plots (6)	~21; (7 – autumn only)	Intensive plot (1)	2017–2021
Eriophorum	Eri.con	Control	Cluster (15) Intensive plots (6)	~21; (7 – autumn only)	Intensive plot (1)	2017–2021
	Eri.spha	Treatment	Cluster (15) Intensive plots (6)	~21; (7 – autumn only)	Intensive plot (1)	2017–2021
Molinia	Mol.con	Control	Cluster (15) Intensive plots (6)	~21; (7 – autumn only)	Intensive plot (1)	2017–2021
	Mol.spha	Treatment	Cluster (15) Intensive plots (6)	~21; (7 – autumn only)	Intensive plot (1)	2017–2021
Wider context bare peat sites						
Bleaklow	T	Control	2 clusters (15 in each)	7 (autumn only)	Clusters (2)	2011–2020
	JP	Treatment	3 clusters (15 in each)	7 (autumn only)	Clusters (3)	2011–2020
	Po	Treatment	1 cluster (15)	7 (autumn only)	Cluster (1)	2011–2020
	R	Treatment	1 cluster (15)	7 (autumn only)	Cluster (1)	2011–2020
	L	Treatment	1 cluster (15)	7 (autumn only)	Cluster (1)	2011–2020
	D	Treatment	1 cluster (15)	7 (autumn only)	Cluster (1)	2011–2020
	S	Treatment	1 cluster (15)	7 (autumn only)	Cluster (1)	2011–2020
	SB	Treatment	1 cluster (15)	7 (autumn only)	Cluster (1)	2011–2020
	P	Intact reference	3 clusters (15 in each)	7 (autumn only)	Clusters (3)	2011–2020 2011–2020
Black Hill	BH	Treatment	4 clusters (15 in each)	7 (autumn only)	Clusters (4)	2011–2020
Rishworth	RC	Treatment	4 clusters (15 in each)	7 (autumn only)	Clusters (4)	2011–2020
Turley Holes	TH	Treatment	4 clusters (15 in each)	7 (autumn only)	Clusters (4)	2011–2020

3.2.2. Water table data analysis

3.2.2.1. Bare Peat

3.2.2.1.1. Manual WT data

For each sampling visit, an average water table depth value was calculated for each cluster of dipwells. These were converted into relative values using the formula: control-treatment. These relative values were converted into a single median value per year. These annual median values were normalised by conversion into change-since-baseline. In this way, the effects of treatment were isolated from external factors such as weather/climatic changes over the years.

3.2.2.1.2. Continuous WT data

Extensive datasets were compiled from sites across the South Pennines using sensors logging water-table-depth-below-surface values every 10-minutes from 2010–2020. An initial data audit showed that various complications had arisen during the monitoring period:

- Control sites for some treatment sites were treated during the monitoring period, due to pressure to rehabilitate degraded peatland
- Sensor failures led to gaps in some datasets
- Disturbance of some dipwell tubes led to uncertainty over continuity of calibration values and therefore data quality
- Water table dropped below the bottom of the sensor at some sites during prolonged dry periods

Following this audit, the sites with no remaining controls (Black Hill, Rishworth, Turley Holes) were disregarded, as they were all at significant distance from the nearest remaining control sites. The control sites at Bleaklow (loggers TA and TC) and Kinder Scout (loggers F1, F2, F3) were maintained so these sites were included in analyses. Both Bleaklow control loggers had complications (the TA logger failed intermittently; the water table dropped below the bottom of TC during dry periods). Of the three loggers at the Kinder control mini-catchment (F), F1 had the best quality dataset. To assess the suitability of F1 as a control for all treatment sites, baseline data from treatment sites on Kinder Scout and Bleaklow were plotted against corresponding data from F1. This showed strong linear relationships in all cases (see Table 4). Data from F1 were therefore used as the control dataset for data from Kinder Scout and Bleaklow treatment sites.

At the treatment sites on Bleaklow, several loggers had failed intermittently or been disturbed; three datasets were consistently good quality so these were retained for analysis (Po, SB and JP). On Kinder Scout, the dipwell at N was dysfunctional and so the data were disregarded; data from O were retained for analysis.

Table 4: Comparison of pre-treatment continuous water table data from subsequently revegetated sites to corresponding data from bare peat control data

Monitoring site	Relationship of daily mean WTd (mm) to F (Kinder Control) daily mean WTd (mm)	R^2
O (Kinder)	O = 1.10*F – 149	0.99 (p<0.001)
Po (Bleaklow)	Po = 0.76*F + 117	0.79 (p<0.001)
SB (Bleaklow)	SB = 0.96*F + 144	0.73 (p<0.001)
JP (Bleaklow)	JP = 0.25*F + 210	0.89 (p<0.001)

As with the manual water table data, treatment sites were compared to control sites to isolate the effects of treatment. Due to the highly responsive nature of water tables in peatlands, comparison of 10-minute data across spatially diverse sites created a noisy dataset. To minimise this, all data were converted to daily mean values. The relationship between control and treatment in the baseline year (see Table 4) was used to model how the water table would have behaved at treatment sites in the following years had no treatment been applied, based on observed values from F in those years.

Observed values from the treatment sites were then compared to these modelled values; variation from the modelled values indicated effects of treatment. Changes in this variation from modelled values through the monitoring period (grouped into years) were tested for statistical significance using the Kruskal-Wallis test for difference between multiple samples.

Where paired rainfall and water table data were available (Kinder), additional analyses were carried out to assess water table response to storm events. The following metrics were calculated for any rainfall events where more than 1mm of rain fell in a single event:

- Peak water table depth, mm (water table depth below surface at the closest-to-surface level recorded during the water table response to rainfall)
- Peak water table lag, h (time from peak rainfall intensity to peak water table depth)
- Water table recession 6 hours, mm h^{-1} (rate of water table recession in the first 6 hours after peak water table depth)
- Water table recession 12 hours, mm h^{-1} (rate of water table recession in the first 12 hours after peak water table depth)

3.2.2.1.3. Peat surface height change at bare peat control sites

Significant lowering of the peat surface was observed at the bare peat control sites (F on Kinder Scout; T on Bleaklow) since the start of monitoring. Surface height change was monitored at the sites using two methods:

1. All dipwell tube heights were measured at each visit. For each year the median value for each tube was calculated; these medians were used to calculate a mean tube height for each cluster of dipwells. The change in this yearly mean was used to quantify the rate of surface height change at each cluster through the years.

2. Four peat anchors (12mm threaded steel bar) were installed at mini-catchment F in 2014; an additional six anchors were installed at each of F and N in 2019. These were installed by pushing them down through the peat and hammering them into the mineral substrate, leaving a short length of the bar protruding above the peat surface. They were securely anchored in the mineral substrate and unable to move up or down with freeze/thaw or bog breathing movements within the peat. The length of each anchor protruding above the peat surface was measured at regular intervals; any change in this length over time was assumed to represent a change in the peat surface height above the mineral substrate.

Results from these two methods, when presented as trends of peat surface height change over time showed a strong degree of agreement (see Figure 1). It was therefore concluded that using tube height data alone was an appropriate measure of peat surface height change at all sites, regardless of whether peat anchor data were also available (they were not available for most sites).

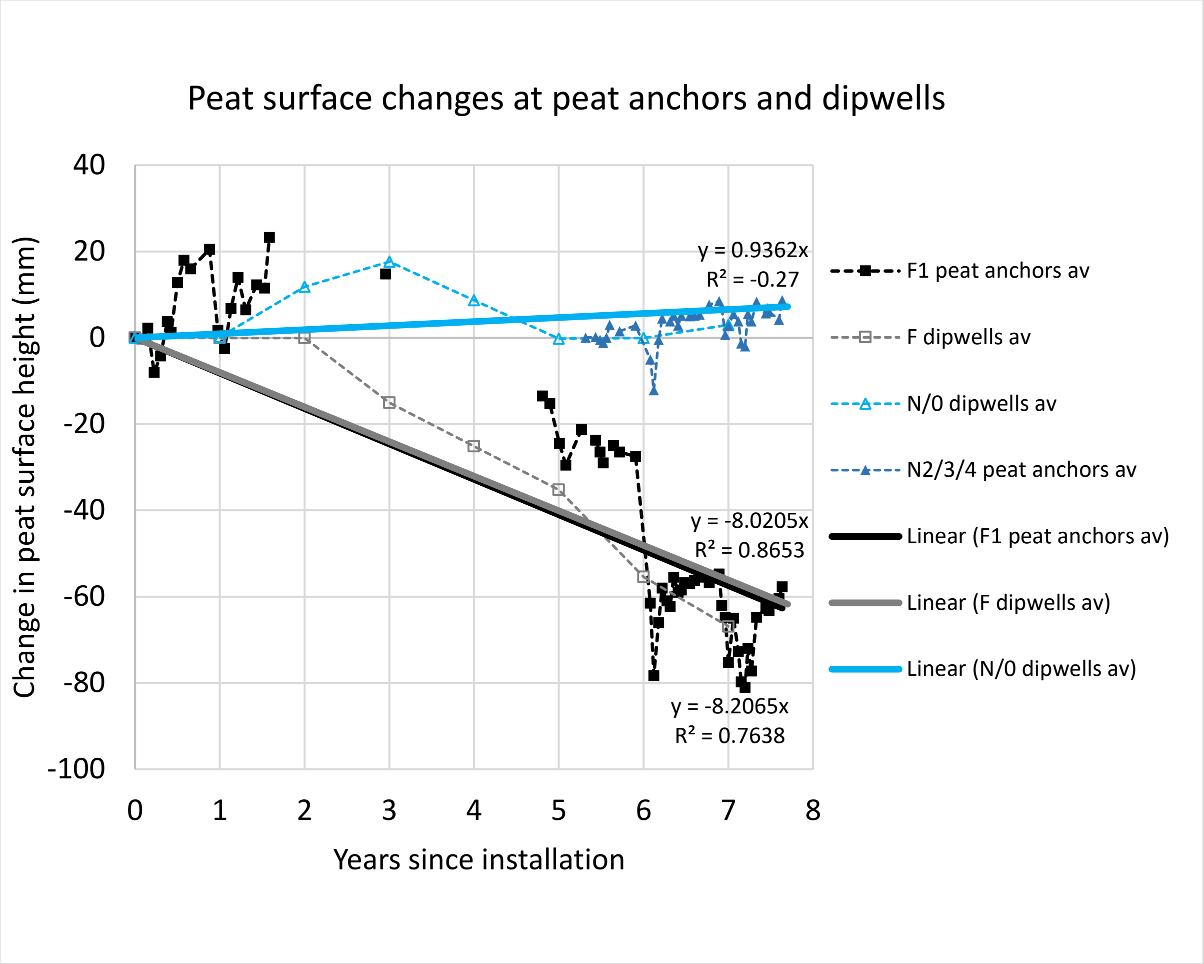


Figure 1: Rate of peat surface height change at bare peat control (F) and treatment (N/O) sites on Kinder Scout, as monitored by changes in dipwell tube heights and peat anchors since 2014

It is hypothesised that this lowering of the peat surface reduced the depth of the water table below the peat surface, as the water table level did not react to changes in the level of the peat surface, leading to an apparent rise of the water table towards the surface (see Figure 2), as observed in the water table data (see Figure 3) and described in Lindsay (2010). This lowering of the peat surface may be caused by proximity to drainage gullies and lack of protective vegetation leading to exposure to drying effects and subsequent compression of the peat mass, oxidative wastage and surface erosion (Lindsay, 2010; onsite observations). Lowering of the peat surface was not observed on the same scale at the treated sites, as the revegetation work protected and stabilised the peat surface and almost entirely stopped erosion within the catchments.

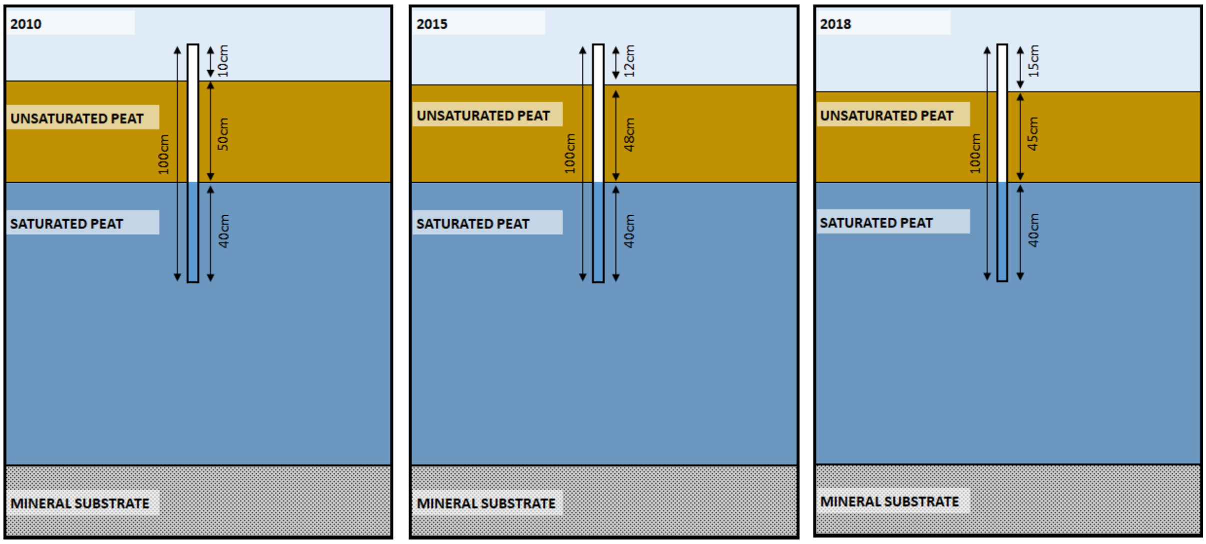


Figure 2: Conceptual diagram showing the hypothesized effects of lowering of the peat surface on proximity of water table to the peat surface at bare peat control sites.
As the peat surface lowers, the water table does not respond by lowering towards the mineral substrate. As a result, the water table is observed to become closer to the peat surface.

The combination of lowering of the peat surface at the bare peat control and no change in peat surface height at the treatment sites confounded results from the raw data, as the apparent rise towards the surface of the water table at the bare peat control led to an apparent lowering of the relative water table (control-treatment) at the treatment sites (or at least a reduction in the rise of the relative water table).

It was therefore considered inappropriate to use depth-below-peat-surface as the primary measure for change in relative water table depth. Instead of the peat surface, the top of the dipwell tube was used as the height datum for each dipwell (at control and treatment sites, for both manual and continuous datasets) when presenting results as change at treatment sites since baseline, relative to control. In presentation of results, these data are labelled as ‘corrected for peat surface height change’. For reference, the raw depth-below-surface data are also presented; these are labelled as ‘not corrected for peat surface height change’. As shown in Figure 3, when raw water table depth data at F were corrected for changes to peat surface height, the apparent rise in water table observed in the raw data reverted to a trend of no change (as would be expected). This supports the hypothesis that lowering of the peat surface at the bare peat control was confounding results, and correcting for peat surface height change at all sites was a more accurate method for assessing the effects of treatment on water table depth.

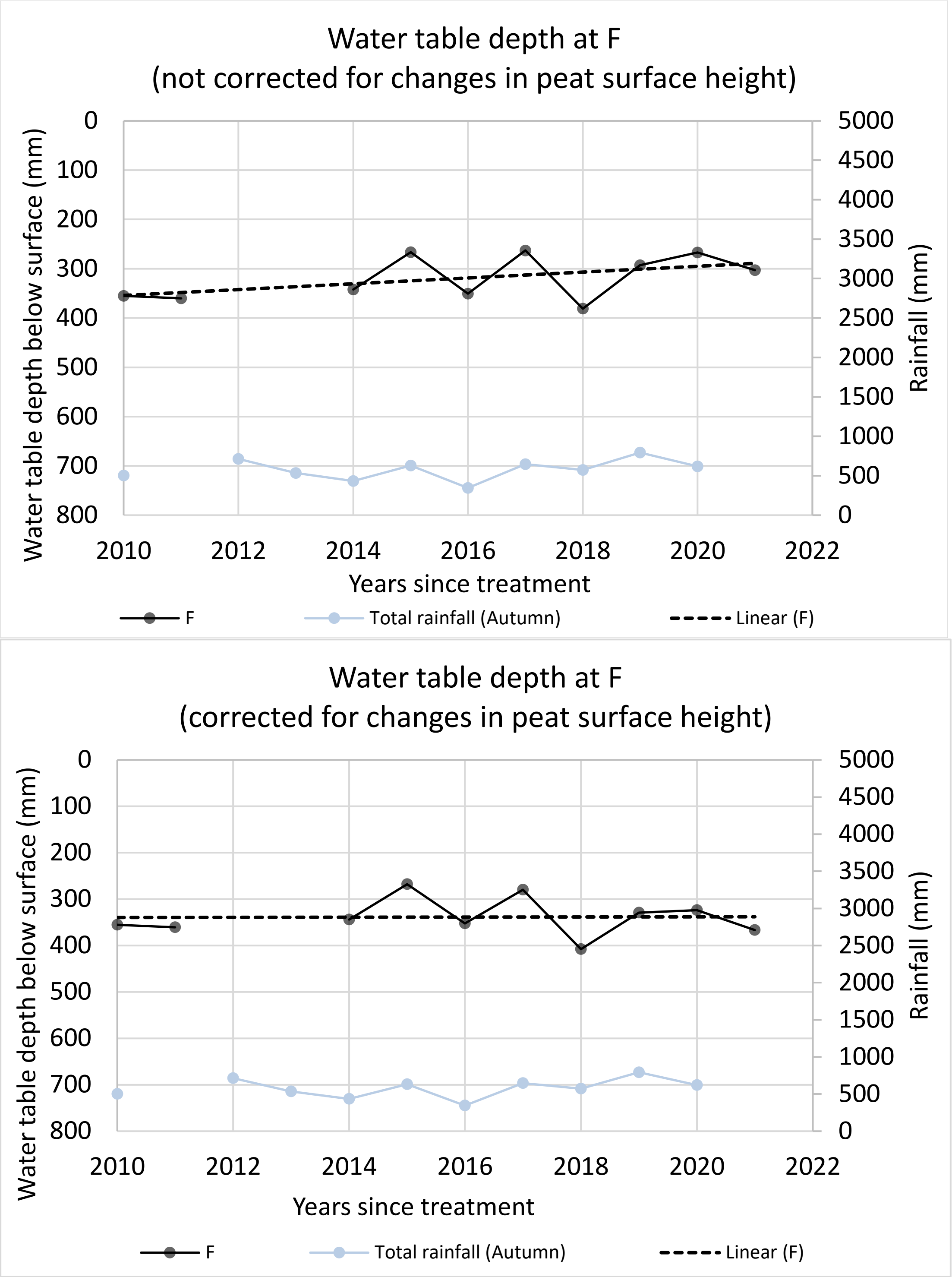


Figure 3: Water table depth at F (bare peat control), showing an apparent rise of the water table towards the surface when not corrected for peat surface height change.
When corrected for peat surface height change, the water table trajectory has no positive or negative trend.

While the hypothesis is that lowering of the peat surface at the bare peat control sites has not led to a corresponding lowering of the water table (Lindsay, 2010), it is possible that it has had some effect. It is therefore likely that the 'true' effect of treatment lies somewhere between the 'corrected' and 'not corrected' methods.

The rates of peat surface height change at the bare peat control sites, as monitored by measuring dipwell tube heights were ~-6mm yr^{-1} at F and ~-16mm yr^{-1} at T. At the treatment sites, peat surface height change rates varied between ~-4mm yr^{-1} and ~+2mm yr^{-1} (surface rise, possibly accumulation).

3.2.2.2. Species Dominated

3.2.2.2.1. Manual water table data

Manual water table measurements at both cluster and intensively planted plots provide a low temporal resolution record of water table depth across the hydrological year. Although low temporal resolution, their low cost means many can be deployed providing good spatial coverage.

If results are combined to a summary metric it can be considered a more robust measure than a single dipwell. Manual water table measures are specific to the conditions at the exact time measured and therefore it should be noted that in the days before and after without a measure, extremes in water tables may be experienced. This is clearly illustrated in the Figure 27 (Results section) when the continuous and manual records are compared.

It is important to be informed about the benefits and limitations of data to permit correct usage. Mean manual dipwell values for the relevant mini catchment were derived from the 15 dipwells measured. Internal bias should be examined to make sure the summary value is a robust representation of the mini-catchment. This is examined in the results section, where every dipwell in the cluster is ranked monthly so that can be seen if the relationship between dipwells remains consistent or if there is a substantial internal reorganisation.

There were a number of sample points missing from the datasets during periods when site visits could not be made, e.g. during Covid-19 restrictions in spring 2020.

Results derived from the single auto water table logger in each mini-catchment were used to model values for those data gaps. The proportion of modelled datapoints used is shown in Table 5. Modelling was based on the relationship between the continuous water table value and the mean manual dipwell value for the relevant mini catchment. There was a strong linear relationship between the continuous and manual water table values on most catchments. In the *Calluna* control catchment the relationship was weaker.

Table 5. Details of modelled dipwell results on species dominated sites

	Calluna			***Eriophorum***		***Molinia***	
	Con	**Spha**	**SphaGB**	**Con**	**Spha**	**Con**	**Spha**
Proportion of modelled values for clusters	N = 8/54			N = 9/52		N = 8/52	
R^2 value for relationship between continuous WT and cluster	0.583	0.622	0.877	0.933	0.781	0.887	0.896
Proportion of modelled values for intensive plots	N = 10/36			N = 11/36		N = 10/35	
R^2 value for relationship between continuous WT and intensive plots	0.528	0.836	0.898	0.914	0.938	0.877	0.882

Once datasets were as complete as possible, mean water table values for each catchment (both cluster and intensive plot) were plotted to examine the spread of those data.

Treatment catchment values were then subtracted from control values (control minus treatment) for the periods before treatment (year 0) and after treatment (years 1 + 2 cluster; year 1 intensive). Differences were plotted, with the before period median value baselined to zero. Differences were tested for significance using a Mann-Whitney U non-parametric test for independent samples.

3.2.2.2.2. Continuous water table data

Contrary to manual water table measurements the continuous record supplies high-resolution (5 minute) water table data that can not only be employed to determine general changes in water table depth or trajectory over time but can permit reactions to storm events to be analysed.

Cost of equipment prevents deployment across a site, so sensors have been deployed in locations where the greatest benefit can be gained. Here that applies to where treatment applied is most concentrated (in intensive *Sphagnum* plug planted plots (3 × 1 m)) and more likely to result in changes in water table activity, especially over the project lifespan.

Continuous water table measures here do not provide a robust spatial overview like that provided by the manual derived data. However, when confined to the 3 m^2 intensively planted plot the record can be considered representative.

Continuous water tables were calibrated against manual measures to ensure any sensor drift or movement in the dipwell could be corrected for. Measures were analysed in raw and median normalised form for treatment years, and a series of storm related metrics derived.

Low amplitude daily cycles are evident in the data especially in dry periods and are a result of deficiencies in the logger equipment. These were not removed by smoothing as resultant output decreased the temporal resolution attainable for looking at storm events. These were left in the dataset as they do not affect annual measures and are not evident upon reaction to a storm event.

Datasets were reduced to daily median values reducing any possible effects of systematic noise for analyses looking at seasonal and annual change. It is evident that for these summaries over long time-periods, use of 5 minute or median daily values makes little difference. Relative changes in water tables between control and treatment are derived by subtracting treatment from control ('control minus treatment').

For storm response analysis, the rainfall data was divided into storm events. Separate event were defined as those with at least a one-hour gap with zero rainfall, between preceding and new events. Metrics including timing of event start/peak/end and total rainfall were then derived.

The water table record was analysed for storm response to these events by detecting substantial changes in slope defining the initial response to a storm rainfall event and the subsequent peaks attained. The numerous events found were filtered to ensure that only reactions to substantial rainfall events were examined. Depth to water table was required to reduce by at least 20 mm in the event, with the majority reducing by a much greater amount.

Periods of possible snow and ice formation were avoided. Every figure (for example Figure 4) for water table response and corresponding rainfall event chosen was further examined so that any containing clear sensor derived issues were removed and emphasis was placed on 'simple' events with relatively concentrated rainfall.

Figure 4. Example of a water table response event at the *Eriophorum*-species dominated site plot. Green – control plot, red Sphagnum treated plot. The rainfall event is concentrated between the vertical blue lines with control reacting quickly compared to Sphagnum treated plot here

For each chosen storm, numerous rainfall and water table metrics were derived. For the species dominated sites, the following are reported:

- ***Start lag*** – time lag from start of rainfall event to start of water table response (minutes)
- ***Peak lag*** – time lag from peak of rainfall intensity to peak of water table response (minutes)
- ***Water table change*** – change from initial response to shallowest attained (mm)
- ***Water table minimum*** – water table at start of response (mm)
- ***Water table maximum*** – shallowest water table as result of event (mm)
- ***Six-hour recession rate*** – rate at which water table declines after peak over subsequent 6 hours (mm hr^{-1})
- ***Twelve-hour recession rate*** – rate at which water table declines after peak over subsequent 12 hours (mm hr^{-1})

The number of events examined for the recession rates are often lower than for the other metrics as not all storm events exhibit 6 or 12-hour periods post peak without further minor periods of rainfall.

3.3. Overland flow generation

Flow on a peatland surface is generated either by, or as a combination of, a surface of low permeability retarding infiltration or by high water tables effectively providing the former. Overland flow on blanket bog locations may occur as both a rapid flow above the surface or as a much slower within the upmost litter layers (Holden *et al*., 2008). The shallow nature of flows observed mean that surface vegetation, litter, and constituents of the acrotelm may exert a substantial effect on flow generation.

Crest stage tubes used to collect evidence of overland flow, depending on the consistency of the depth of water collecting holes history through deployment, are likely to have derived evidence of both the more rapid and the slower flow within the upmost litter layer.

Evidence here is confined to presence or absence of water. Crest-stage runoff traps were used to monitor surface ponding at both the bare peat and species dominated sites, with the intention of evidencing the potential for the generation of overland flow, as detailed below.

3.3.1. Bare peat sites

At the bare peat sites these traps comprised a 50 ml plastic Universal Tube, sealed with a screw cap with four 5 mm holes drilled in the side of the tube. The traps were installed in clusters of nine tubes; each tube was sunk into the peat such that the hole was flush with the peat surface, allowing any water ponding on the surface around the tube to enter the trap. The traps were monitored at weekly intervals during each monitoring campaign (11–12 visits per campaign): the presence/absence of water was recorded and all tubes were emptied using a syringe to minimise disturbance. The proportion of tubes within a cluster was used to calculate a runoff quotient (RQ) to allow runoff behaviour at each mini-catchment to be compared. An RQ of 0 would indicate that no traps contained water; an RQ of 1 would indicate that all traps contained water.

In 2010 (pre-treatment), three clusters of crest-stage runoff traps were installed and monitored at untreated control mini-catchment F and three across treatment mini-catchments O and N. These were all installed on interfluve surfaces. In 2014, three additional clusters were installed on footslope surfaces at F and three at O/N, to assess any effects of topography on surface ponding and overland flow generation. All 12 clusters were monitored in 2014, 2018, 2019 and 2020.

3.3.2. Species dominated sites

Crest stage tubes were constructed out of 32 mm diameter PVC tubing, cut to individual lengths of 200 mm and capped at one end. Six 5 mm diameter holes were drilled through the tubing at 100 mm (halfway along the tube) allowing for a sample volume of approximately 50 ml to be collected within the tubing when installed. Using a soil corer, the crest stage tubes were inserted into the peat to a depth of 100 mm. This allowed the line of water entry holes to be level with the ground surface and collect overland flow.

A crest stage tube was installed approximately 30 cm from each dipwell on the species dominated sites. This includes the 15 random locations within the dipwell cluster and two locations within each intensively planted plot. The crest stage tubes were visited at the same frequency as the dipwells (see Table 3) and manually checked to see whether they contained water. After they had been checked, each crest stage tube containing water was emptied using a syringe and length of pipe to reset it for the next period whilst minimising disturbance.

Presence/absence data were converted into percentage recovery for the 15 tubes in the cluster and for the 6 tubes in the intensive plots (2 tubes in 3 intensive plots). This is simply the count of occurrences when water was evident in the tubes divided by the count of visits to that tube for the specific period being examined e.g. project year or season. If on a single visit 14 of the 15 tubes for that cluster contained water the percentage recovery for that day would be 93%, however over a project year the total sum of tubes with water in divided by the number of overall site visits would provide the project year cluster percentage recovery. Heatmaps have been used to provide a simple but effective way to examine the performance of each individual tube for the clusters allowing internal variation to be examined and detection of any substantial changes in behaviour in particular tubes that could be traced to a geographical factor.

3.4. Soil moisture

In 2021, a set of experimental capacitance probes were installed to monitor soil moisture at the bare peat mini-catchments: three at F, one at O and two in areas dominated by *Sphagnum* at N. These sensors measure regular linear capacitance, which is then converted to Volumetric Water Content (%VWC) in four depth zones (0–125 mm, 126–250 mm, 251–375 mm, 376–500 mm) below the peat surface. These sensors allowed a space-for-time comparison of soil saturation in the near-surface zone in bare and restored conditions and a second source of information for assessing the likelihood of surface ponding and overland flow generation. In 2022 additional sensors were installed at the three experimental sites to improve replication and increase confidence in results.

The sensors were calibrated by the manufacturers using a laboratory method as follows:

1. A gravimetric recording rig was used to capture data. This consisted of
   a) A sample of peat (initially from Ilkley Moor; then repeated in 2022 using a sample from Kinder Scout) freely suspended off a load cell to record the sample mass change over time.
   b) A sensor probe inserted into the sample and connected to a data recorder to record sample capacitance change over time.
   c) Mass and capacitance readings taken simultaneously at intervals.
2. The sensor was inserted into a suspended mass of peat soil and allowed to dry in free air.
3. Capacitance data and mass data were read from the sensor and accompanying load cell. Recording continued until the sample mass had stabilised or the mass range of interest had been passed.
4. At the start of the data collection run the sample was soaked to ensure it was fully saturated and measured so the sample volume was known.
5. At the end the sample was oven dried and reweighed to ensure the final measurement was dry mass.
6. An example of data collected is shown in Figure 5. Multiple runs were conducted to achieve a consistent set of results representative of the sensor.
7. The collected data were then processed to identify a suitable conversion that was used to convert the raw data to %VWC values for the soil type the sensors on Kinder Scout were reporting on (peat).

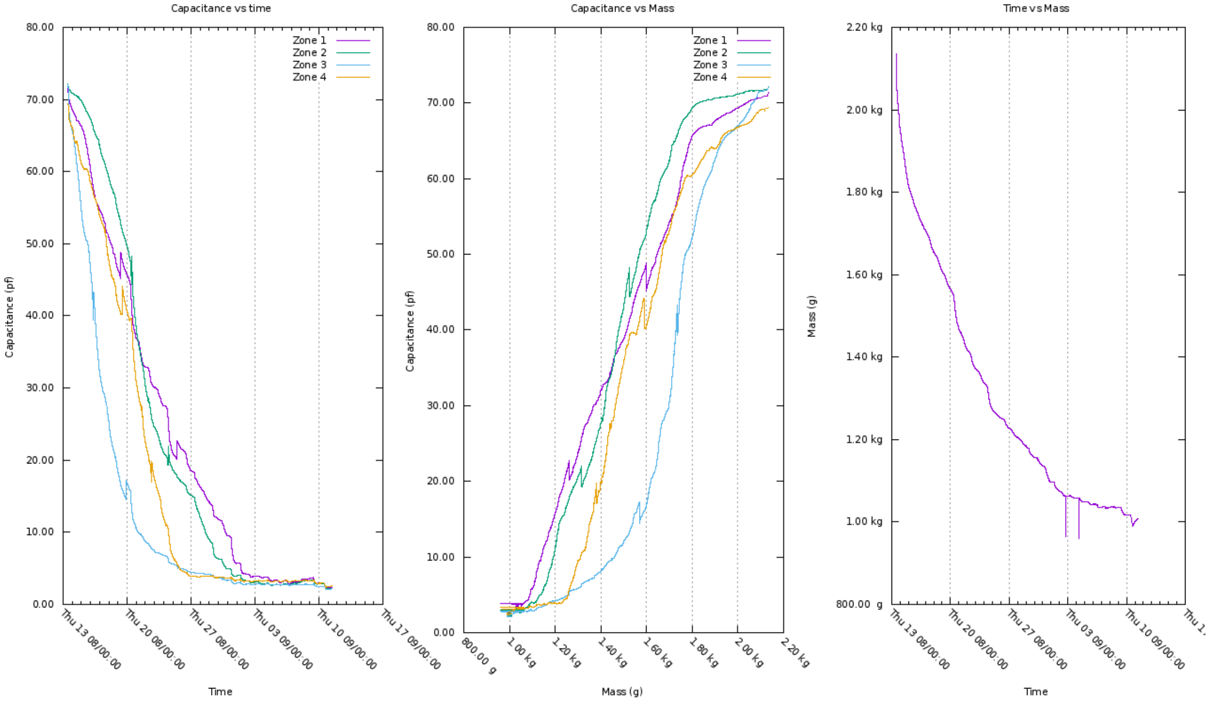


Figure 5: Gravimetric calibration of a peat sample from Ilkley moor. Figure produced by Dales Land Net Ltd

Additionally, the accuracy of the sensors was assessed by measuring soil moisture directly using peat samples extracted from the mini-catchments as follows:

1. 3 peat cores (20 mm diameter, 500 mm depth) were extracted from ~800 mm away from each sensor
2. Each core was immediately divided into the four depth zones (0–125 mm, 126–250 mm, 251–375 mm, 376–500 mm); each subsample was transferred into a sealed plastic bag

3. All samples were stored in a fridge and then processed at a laboratory the following day
4. At the laboratory, each sample was weighed, dried (24 hours at 105C) and then weighed again
5. The change in weight was assumed to equal the Gravimetric Water Content of the sample at the time that it was extracted on site
6. %GWC values from the peat core samples were compared to %VWC values from the sensors at the time that the samples were collected in the field
7. Regression analysis showed a positive (but noisy) relationship ($R^2 = 0.58$, $p<0.01$) between %VWC values from the sensors and %GWC values from manually-analysed soil samples (see Figure 6).

It should be noted that the relationship was weak, in part due to a small number of paired values (n=11), resulting from not all sensors being operational at the time when the manual samples were collected. Therefore, while the laboratory analyses showed general agreement with the sensor data, the data from the sensors should still be treated with caution, in particular when comparing absolute values (as opposed to behavioural patterns). Further testing of the sensors using peat samples from the locations of the sensors is ongoing at the time of writing, this will add confidence in these datasets in any future analyses.

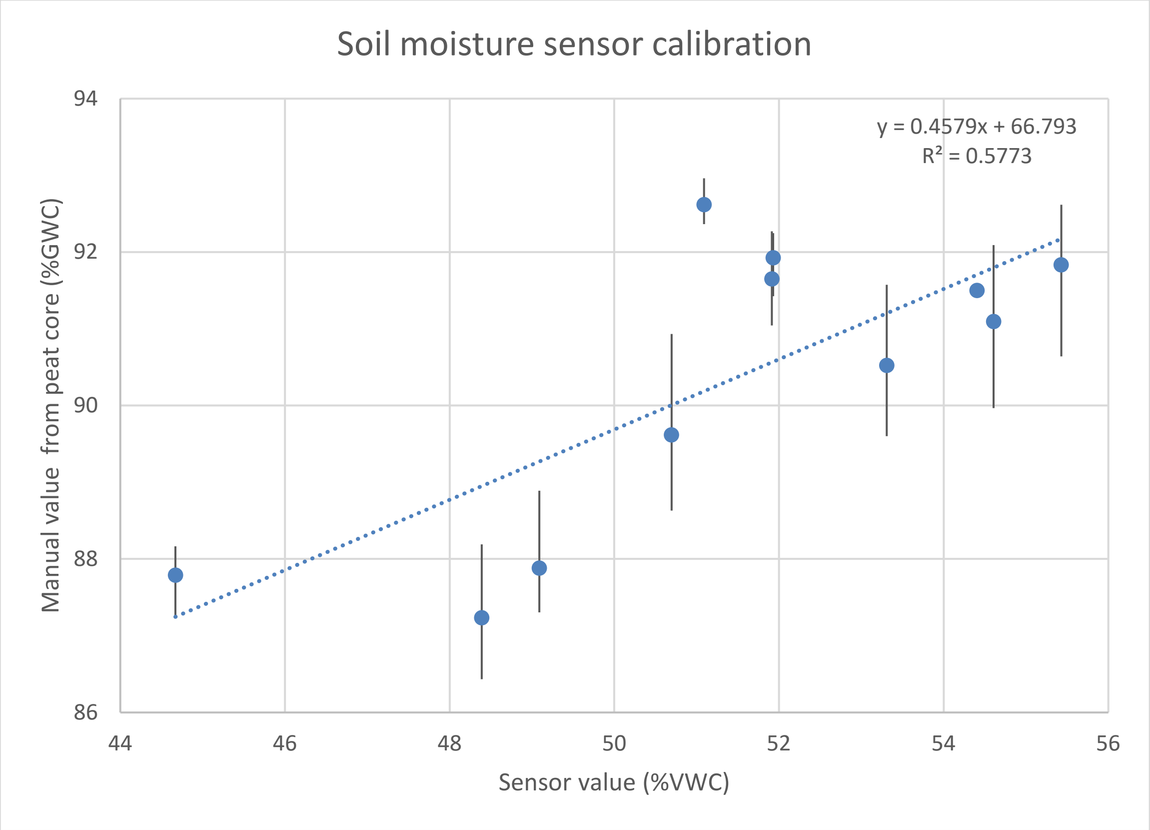


Figure 6: Relationship between %VWC as recorded by soil moisture sensors and %GWC as measured by drying peat core samples in the laboratory.
Error bars = max and min values (3 manual samples per sensor value)

4. Results

4.1. Bare peat sites

4.1.1. Manual water table

Water table depth was monitored at clusters of dipwells at the bare peat mini-catchments F, N and O on Kinder Scout. Three clusters (N1, N2, O1) were installed across the treated mini-catchments N and O in the year before treatment. These clusters were installed sufficiently far away from any gully blocks installed in mini-catchment N that the gully blocks should have had negligible impact on water tables.

Raw data (water table depth below surface) showed no significant trends of change over time, with variation across years driven by variation in the amount of rainfall during the monitoring season (Autumn). During the monitoring period (2010–2021), yearly median water table depth at F (control) ranged from 260 mm – 380 mm; yearly median water table depth at O/N (treatment) ranged from 225 mm – 340 mm. The trendlines in Figure 7 are for illustrative purposes only.

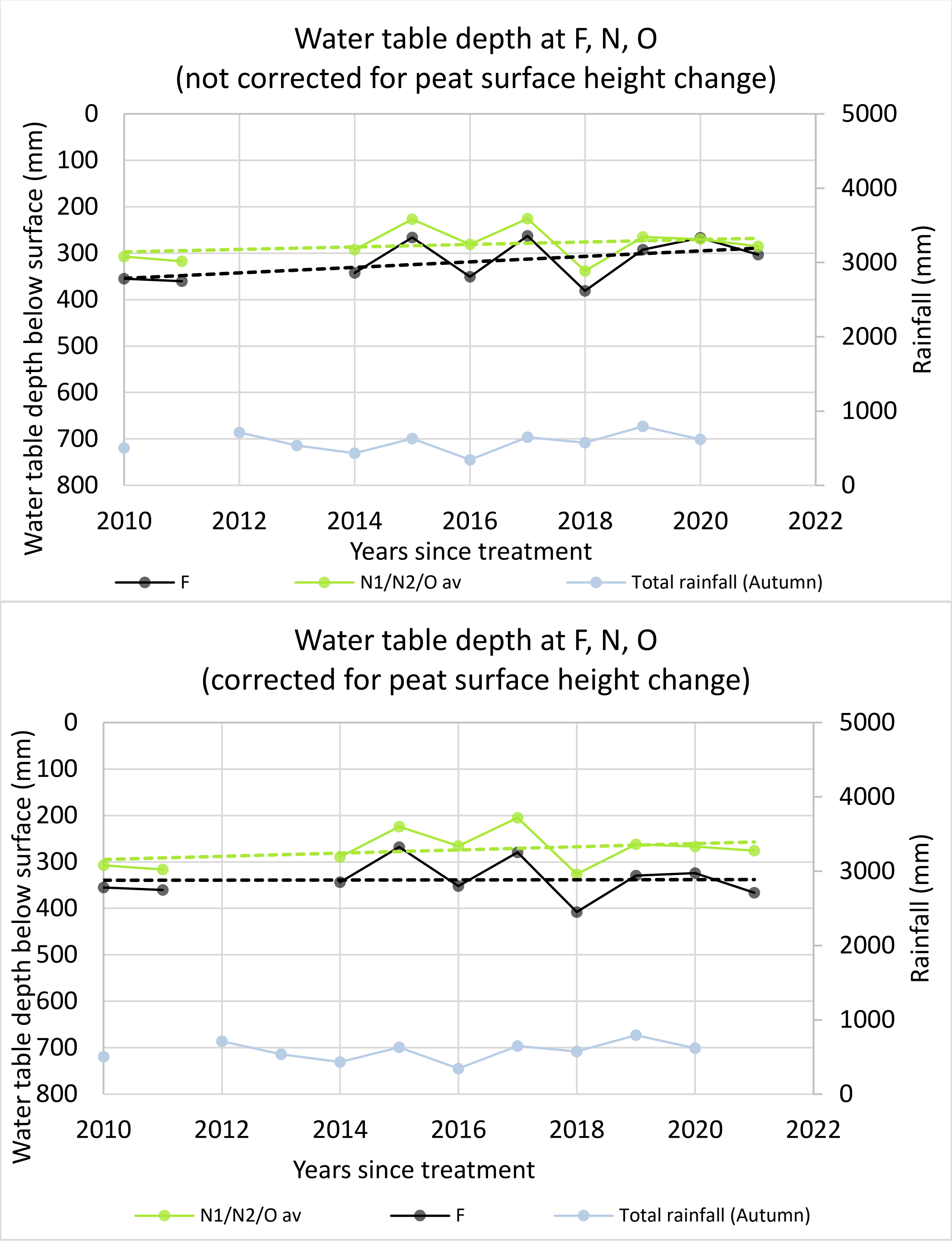


Figure 7: Water table depth below surface at bare peat control (F) and revegetated (N/O) sites in the 11 years following initial treatment on Kinder Scout
Treatment at N/O: revegetated only; negligible proximity to gully-blocking or *Sphagnum*-planting. Top graph = raw (not corrected for peat surface height change); bottom graph = corrected (changes in tube heights used to correct the raw data for rates of peat surface height change). Trendlines are for illustrative purposes only.

Data from these clusters of manual dipwells, when expressed as relative to untreated control (control-treatment), change since baseline and corrected for changes in peat surface height, showed a slow and steady rise in water tables towards the peat surface of ~6mm yr^{-1}, best characterised as a linear trajectory (R^2=0.86, p<0.01); see Figure 8.

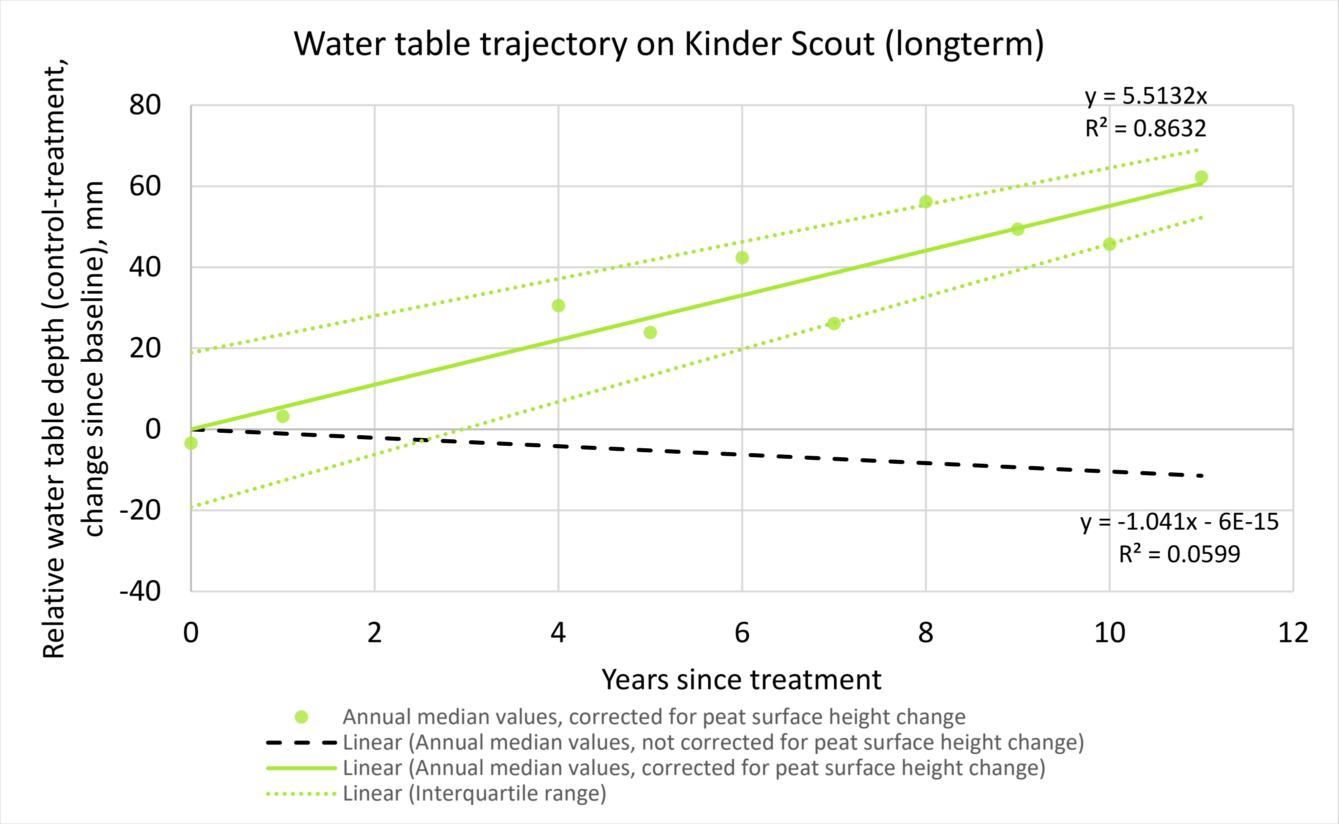


Figure 8: Water table trajectory at treated sites (revegetated only; negligible proximity to gully-blocking or *Sphagnum*-planting) on Kinder Scout in the 11 years following initial treatment

In 2015, *Sphagnum* mosses were planted throughout mini-catchment N. In order to assess the impacts of this new intervention, two additional clusters of dipwells were installed in areas where *Sphagnum* was anticipated to thrive. Data from these dipwells showed no significant change in water table depth over time (2015–2021), with variability driven by variation in the amount of rainfall during the monitoring season (Autumn). During the monitoring period (2015–2021), yearly median water table depth at F (control) ranged from 260 mm – 380 mm; yearly median water table depth at N (*Sphagnum* treatment) ranged from 60 mm – 150 mm. The trendlines in Figure 9 are for illustrative purposes only.

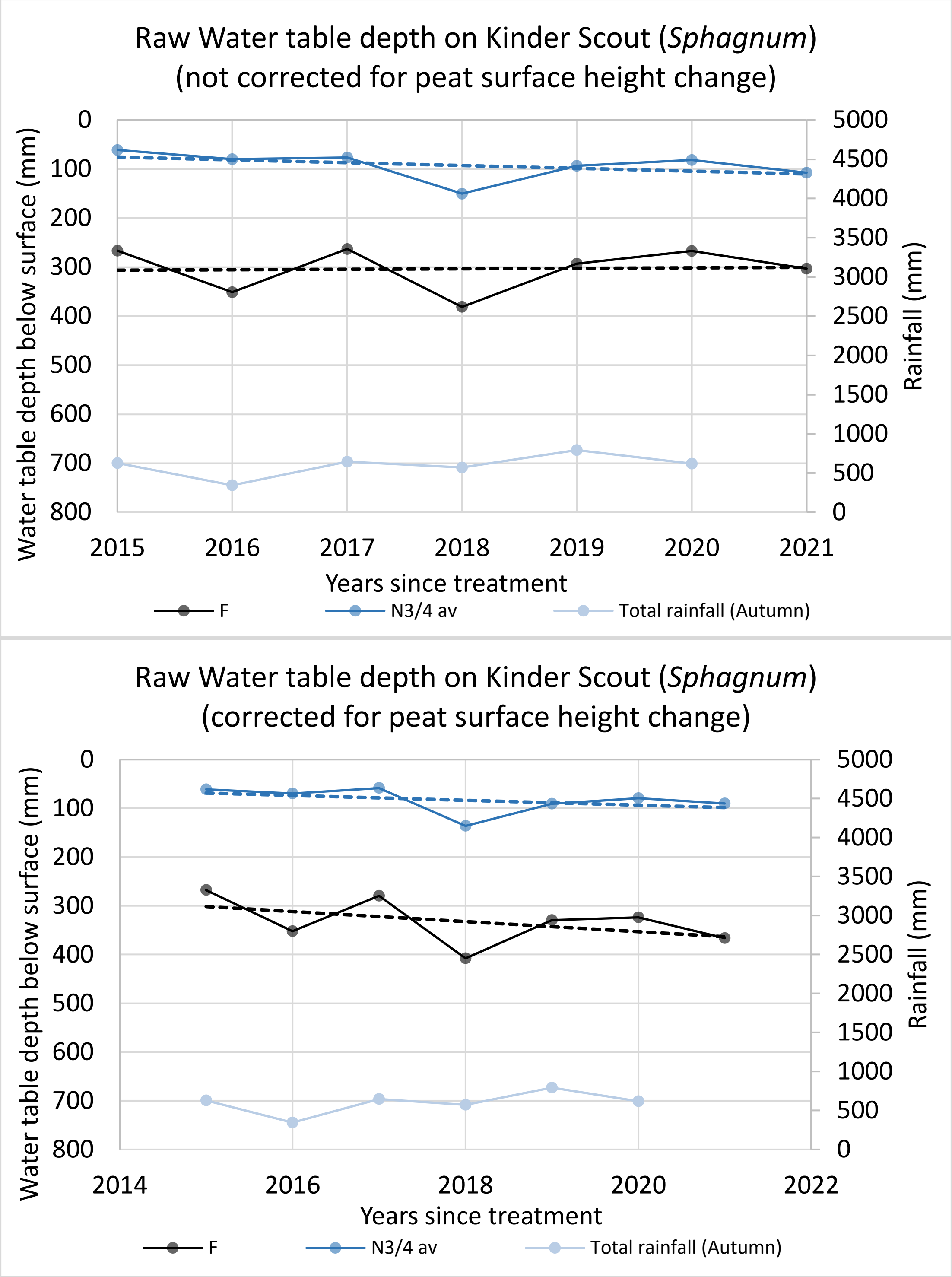


Figure 9: Water table depth below surface at bare peat control (F) and treated (N3/N4) sites on Kinder Scout in the six years following *Sphagnum* planting.
Treatment at N3/N4: revegetated and gully-blocked (2011); *Sphagnum*-planted (2015), gully-blocks within 30 metres of dipwell clusters. Top graph = raw data (not corrected for peat surface height change); bottom graph = corrected (changes in tube heights used to correct the raw data for rates of peat surface height change). Trendlines are for illustrative purposes only.

Data from these dipwell clusters, when expressed as relative to untreated control (control-treatment), change since baseline and corrected for peat surface height change, showed an overall rise in water tables towards the peat surface of ~7 mm yr^{-1}, although there was strong variability between years and the relationship between years since treatment and water table rise was not significant ($R^2=0.32$, $p<0.2$); see Figure 10. While this rate of water table rise was marginally faster than the 6mm yr^{-1} observed at the non-*Sphagnum* clusters (N1, N2, O1), it should be noted that the trend at the *Sphagnum* clusters was insignificant, and the difference in rates was within the error of both datasets.

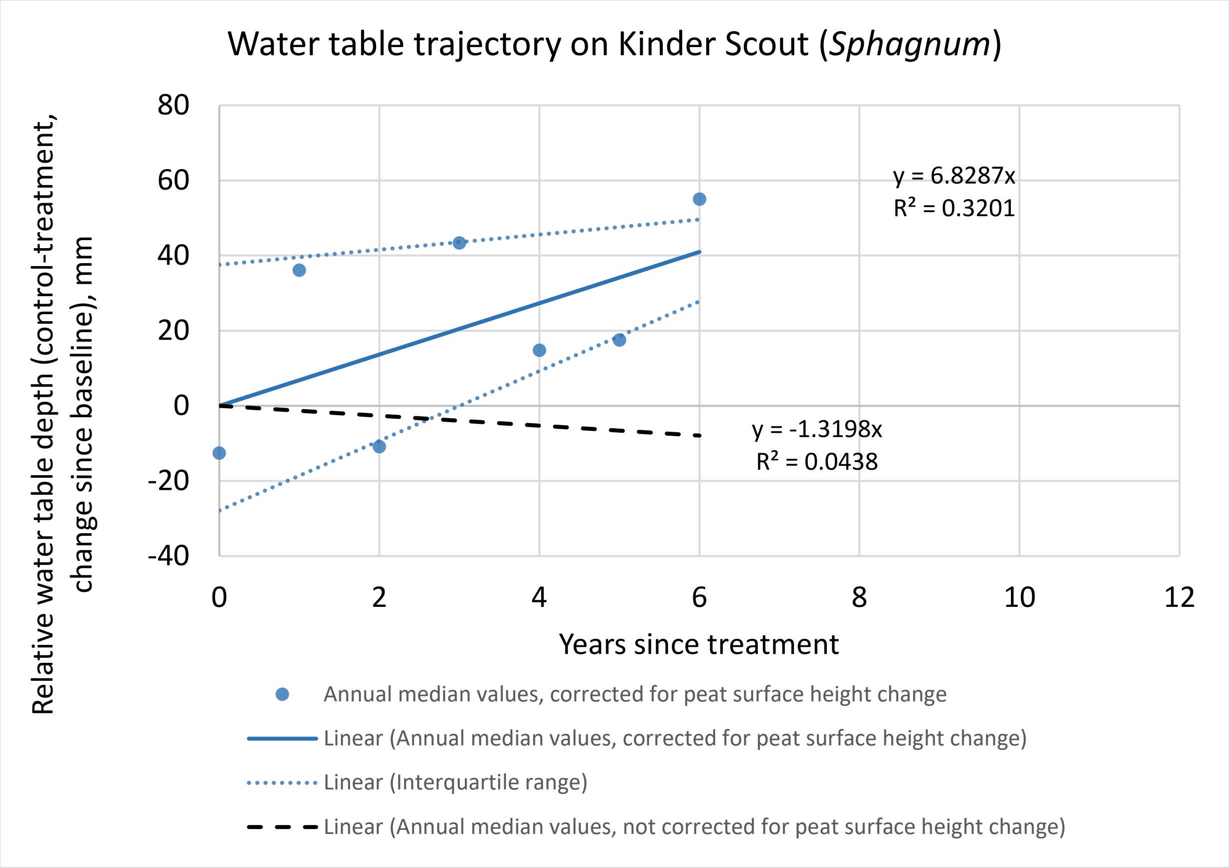


Figure 10: Water table trajectory at treated sites (revegetated and *Sphagnum*-planted, gully-blocks within 30 metres) on Kinder Scout in the six years following *Sphagnum* planting.

Water table depth was monitored using clusters of manual dipwells at a range of sites around the South Pennines to provide replication and a wider context for the data from the more intensively monitored sites on Kinder Scout. These sites included some which had been treated in 2003, although the water tables were only monitored from 2011. Estimated water table depth data were extrapolated for years 2003–2010 based on the available observed data from 2011–2020. 20 clusters were monitored for up to 11 years after treatment; five clusters were monitored at the sites treated in 2003, extending the dataset to 17 years post-treatment, but with less replication in these additional years. Overall, yearly median data from all the wider context site clusters, when expressed as relative to untreated control (control-treatment), change since baseline and corrected for changes in peat surface height, showed a steady rise in water tables towards the peat surface of ~7 mm yr^{-1}, best characterised as a linear trajectory (R^2=0.91, p<0.01); see Figure 11.

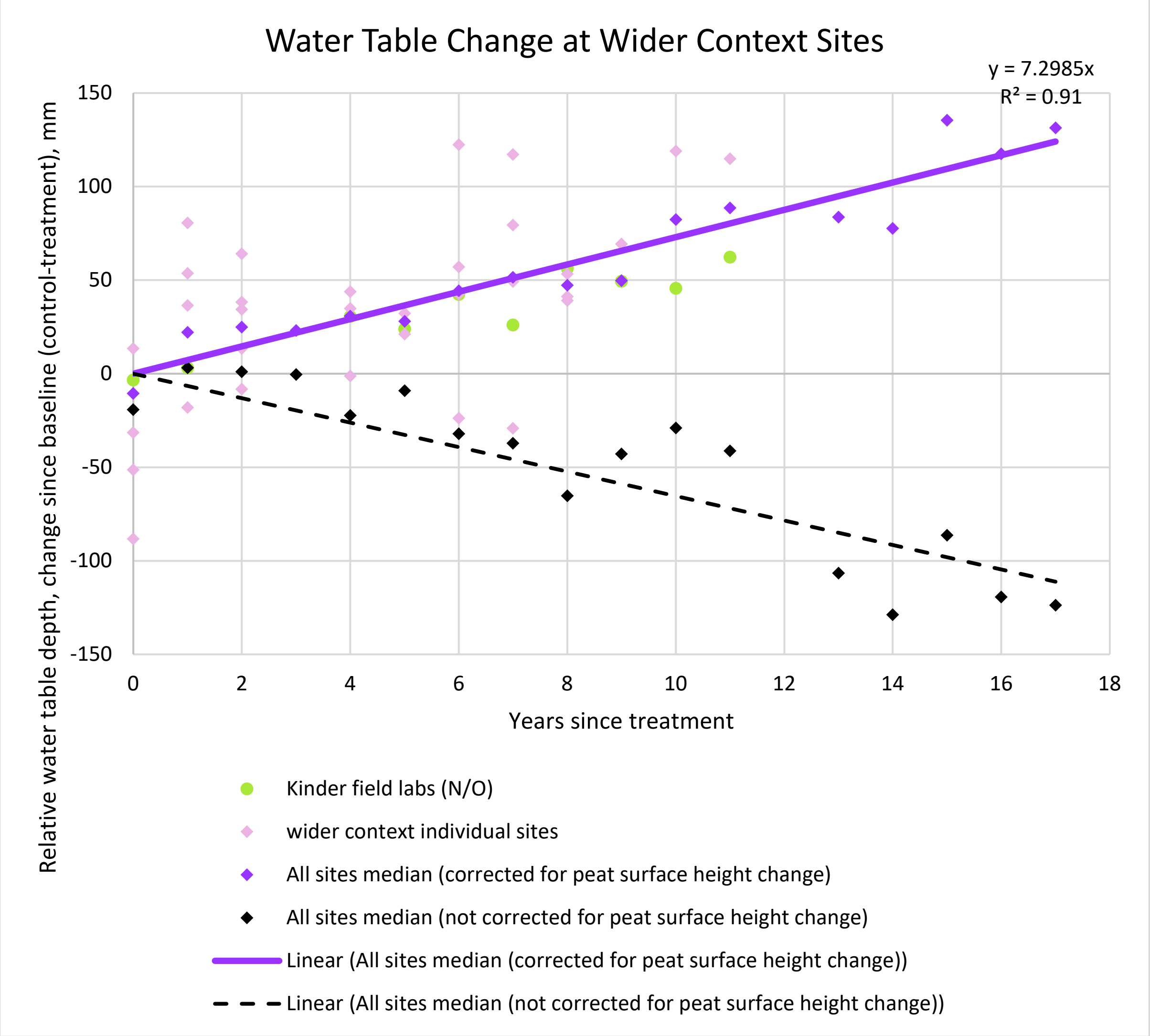


Figure 11: Water table trajectory at wider context treated sites (revegetated only; negligible proximity to gully-blocking or *Sphagnum*-planting) up to 17 years following initial treatment

4.1.2. Continuous water table

Continuous water table data were available from loggers on Kinder Scout (2010–2020, n=2) and Bleaklow (2012–2020, n=4). When viewed as a single continuous series, the behaviour of the water table was observed to be highly responsive to precipitation; in prolonged periods without precipitation the water table drew down at all locations (see Figure 12 and Figure 13) – this occurred most notably in the dry periods in 2018 and 2020. Water tables appeared to recover following these extended dry periods, although levels may not have returned to levels as close to the surface as before the dry periods at all locations.

Water table response to precipitation remained flashy at restored sites, up to nine years following treatment.

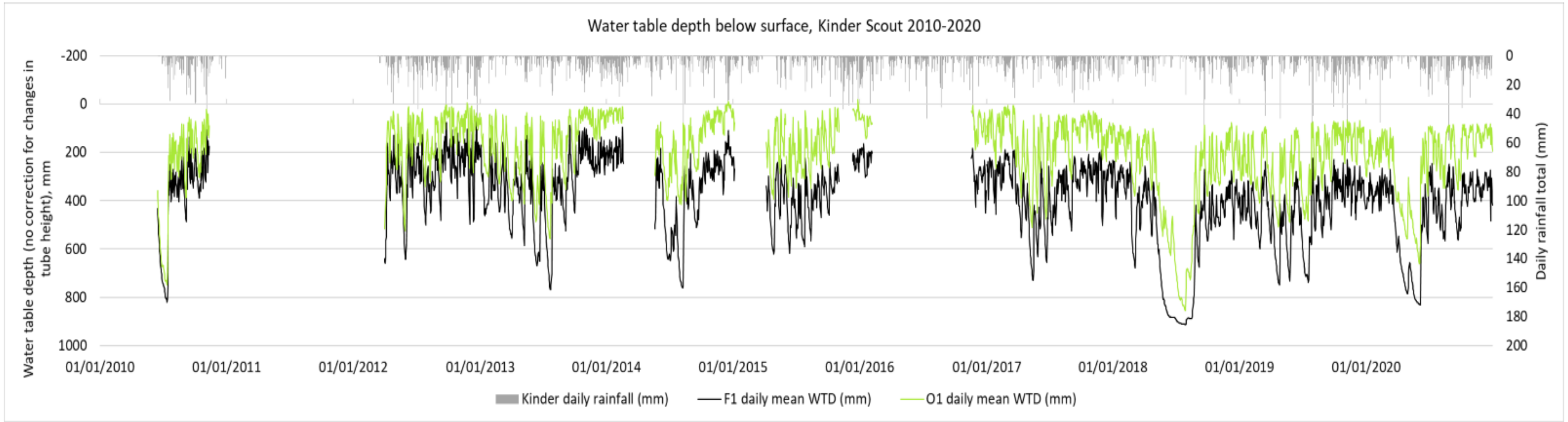


Figure 12: Continuous water table depth at F (bare peat control) and O (revegetated site) on Kinder Scout, 2010–2020.

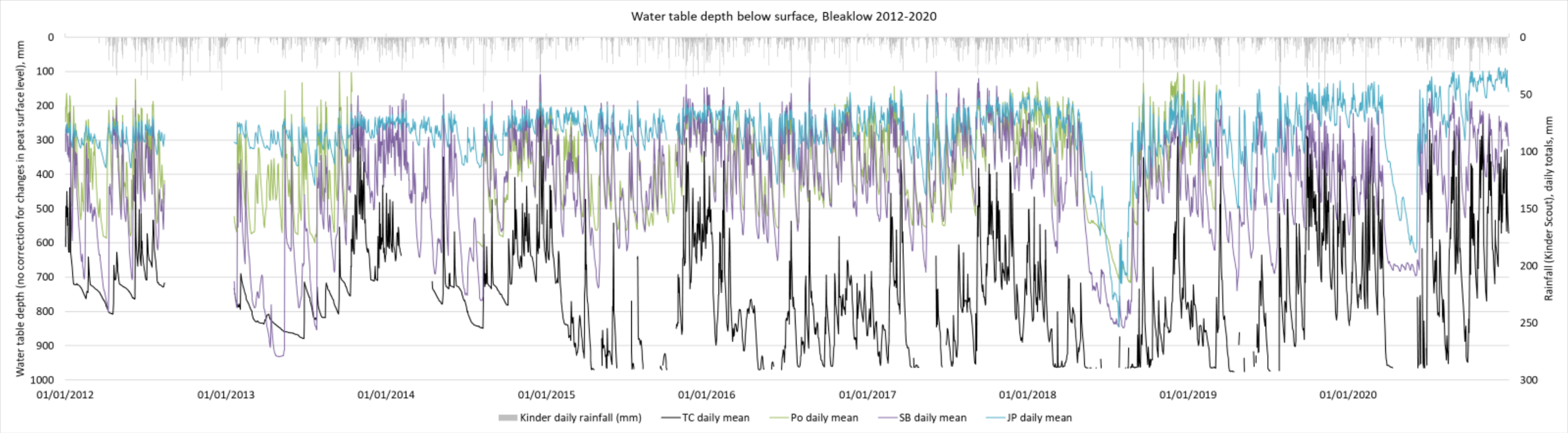


Figure 13: Continuous water table depth at TC (bare peat control) and Po, SB, JP (revegetated sites) on Bleaklow, 2012–2020.

As described in the Methods section of this chapter, continuous water table data (daily mean values) were converted to show variation from expected values based on their observed relationship to control data in the baseline year. These modelled-observed values were compiled into yearly sets; differences between years were then assessed. This process showed that water tables rose towards the surface at all four treated locations in the years following treatment (see Figure 14, Figure 15, Figure 16, Figure 17). By the end of monitoring (nine years after treatment), water tables had risen by 100–200mm as a result of treatment (median modelled-observed WTd; see Table 6, Table 7, Table 8, Table 9). Median rate of water table rise from these four sites was 16mm yr^{-1}. The change between baseline and post-treatment years was significant from three years post-treatment at all sites (except Po, where difference became significant six years post-treatment), when tested using the Kruskall-Wallis test for difference between samples (see Table 10).

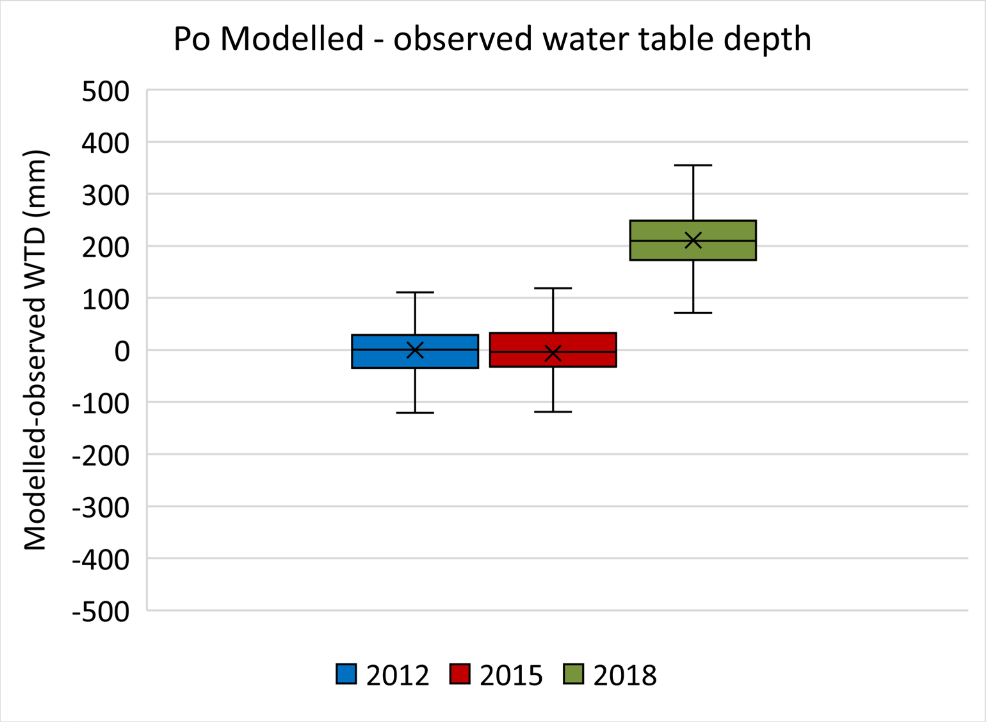


Figure 14: Modelled-observed water table depth from continuous data at revegetated site Po (Bleaklow, treated in 2012).
Positive values indicate that the water table is rising towards the surface following treatment.

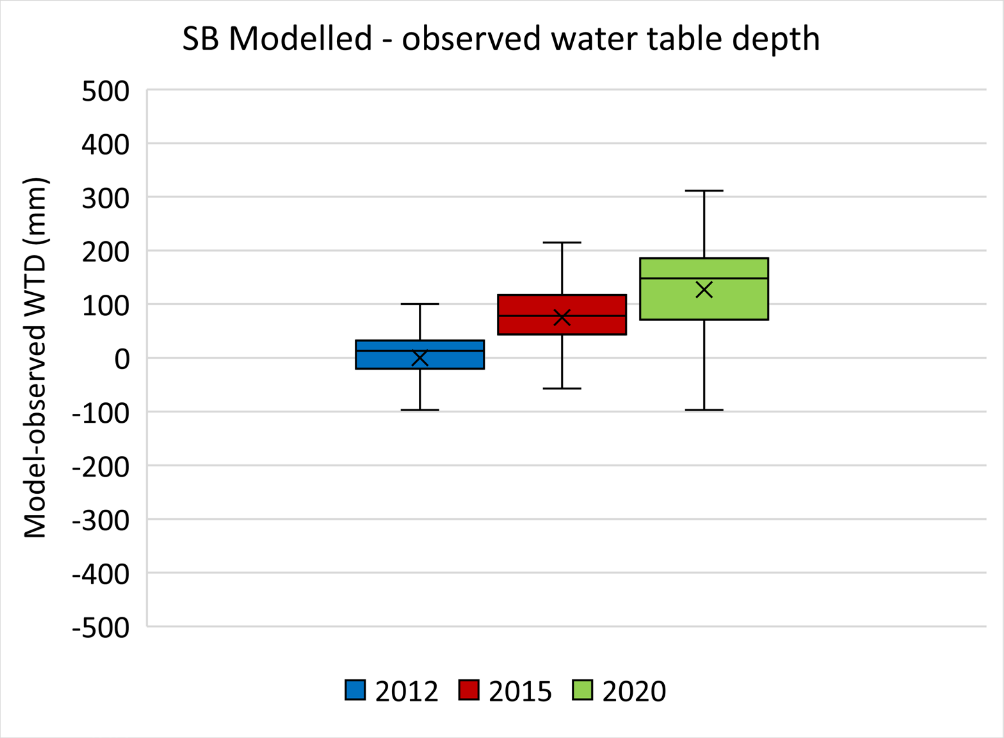


Figure 15: Modelled-observed water table depth from continuous data at revegetated site SB (Bleaklow, treated in 2012).
Positive values indicate that the water table is rising towards the surface following treatment.

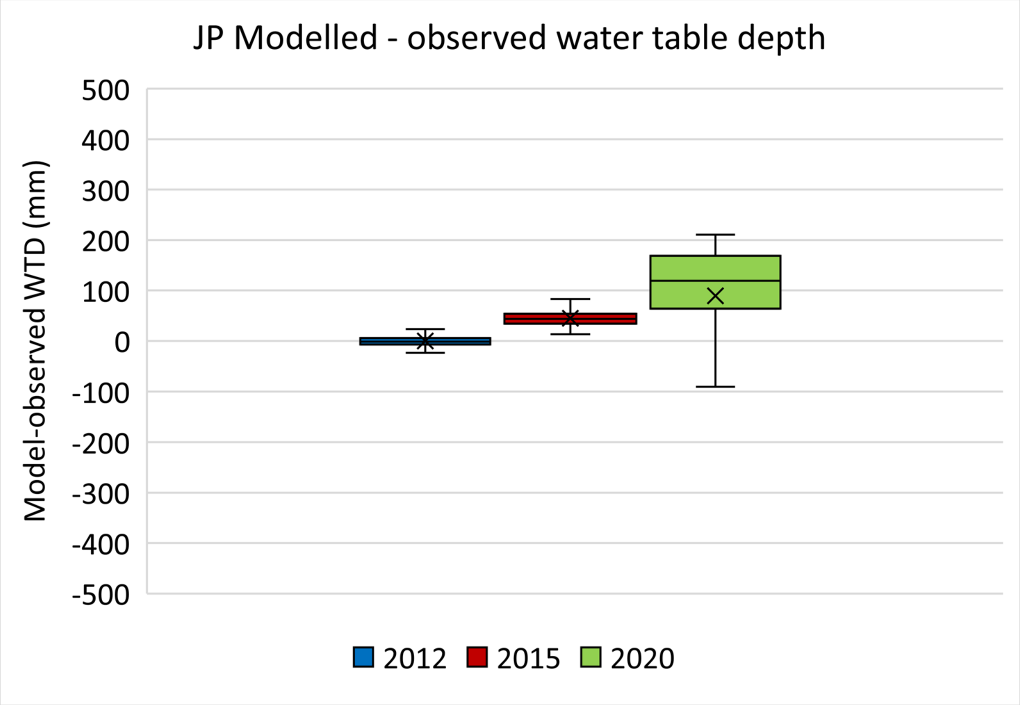


Figure 16: Modelled-observed water table depth from continuous data at revegetated site JP (Bleaklow, treated in 2003).
Positive values indicate that the water table is rising towards the surface following treatment.

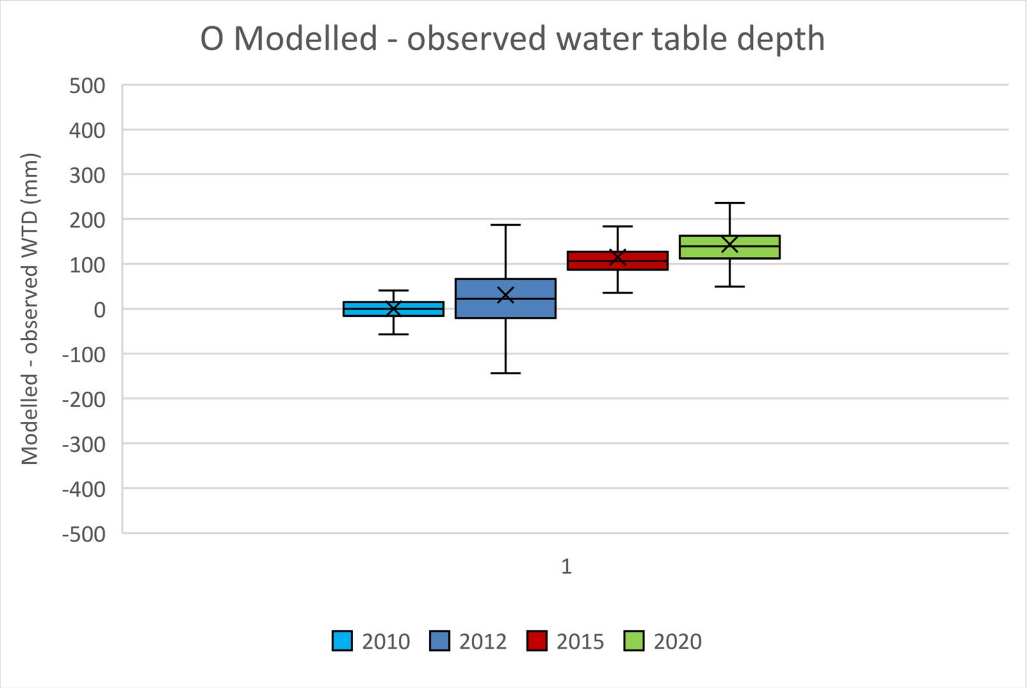


Figure 17: Modelled-observed water table depth from continuous data at revegetated site O (Kinder Scout, treated in 2011).
Positive values indicate that the water table is rising towards the surface following treatment.

Table 6: Descriptive statistics for relative water tables based on daily mean values, modelled-observed at site Po (Bleaklow), using continuous water table data.
Some years had data gaps in water table and/or rainfall data, as shown by Count data.

Po	**Relative water tables based on daily mean values, modelled-observed (mm)**										**Rainfall**	
Year	Years since treatment	Count	Mean	Std dev	Min	LQ	Median	UQ	Max	Change since baseline (median)	Rainfall total, Kinder Scout (mm)	Count (days)
2012	0	137	0	51	-121	-34	1	28	243	0	1521	259
2013	1	270	11	79	-303	-32	11	53	320	11	1334	363
2014	2	157	17	68	-157	-28	22	56	328	21	1468	343
2015	3	236	-6	53	-163	-32	-4	32	119	-4	1187	345
2016	4	75	*11*	*54*	*-110*	*-24*	*19*	*51*	*102*	*19*	1324	359
2017	5	365	49	56	-149	15	56	94	189	55	1405	349
2018	6	271	211	61	-45	173	210	249	387	209	1143	360
2019	7	67	206	65	46	145	222	259	305	221	1706	363
2020	8	0										

Table 7: Descriptive statistics for relative water tables based on daily mean values, modelled-observed at site SB (Bleaklow), using continuous water table data.
Some years had data gaps in water table and/or rainfall data, as shown by Count data.

SB	**Relative water tables based on daily mean values, modelled-observed (mm)**										**Rainfall**	
Year	Years since treatment	Count	Mean	Std dev	Min	LQ	Median	UQ	Max	Change since baseline (median)	Rainfall total, Kinder Scout (mm)	Count (days)
2012	0	137	0	75	-430	-20	13	32	136	0	1521	259
2013	1	347	-119	152	-663	-177	-54	-8	54	-68	1334	363
2014	2	276	30	56	-85	-5	29	64	392	16	1468	343
2015	3	216	75	63	-149	44	78	116	246	65	1187	345
2016	4	79	48	56	-55	11	48	86	175	35	1324	359
2017	5	365	126	91	-142	66	143	198	522	129	1405	349
2018	6	365	160	63	-118	127	173	203	308	160	1143	360
2019	7	365	98	55	-66	61	107	142	223	93	1706	363
2020	8	296	127	77	-97	72	148	186	311	134	1593	350

Table 8: Descriptive statistics for relative water tables based on daily mean values, modelled-observed at site JP (Bleaklow), using continuous water table data.
Some years had data gaps in water table and/or rainfall data, as shown by Count data.

JP	**Relative water tables based on daily mean values, modelled-observed (mm)**										**Rainfall**	
Year	Years since treatment	Count	Mean	Std dev	Min	LQ	Median	UQ	Max	Change since baseline	Rainfall total, Kinder Scout (mm)	Count (days)
2012	0	137	0	11	-27	-7	-2	6	58	0	1521	259
2013	1	347	18	18	-52	8	18	27	122	20	1334	363
2014	2	276	19	17	-29	9	18	27	115	20	1468	343
2015	3	216	45	17	0	34	43	54	115	45	1187	345
2016	4	79	36	21	-2	23	36	50	98	37	1324	359
2017	5	365	41	37	-70	21	46	68	177	47	1405	349
2018	6	365	-4	118	-402	-46	37	80	140	39	1143	360
2019	7	363	54	57	-104	18	63	100	155	65	1706	363
2020	8	365	90	105	-203	65	119	168	210	121	1593	350

Table 9: Descriptive statistics for relative water tables based on daily mean values, modelled-observed at site O (Kinder Scout), using continuous water table data.
Some years had data gaps in water table and/or rainfall data, as shown by Count data.

O		Relative water tables based on daily mean values, modelled-observed (mm)									**Rainfall**	
Year	Years since treatment	Count (days)	Mean	Std dev	Min	LQ	Median	UQ	Max	Change since baseline	Rainfall total, Kinder Scout (mm)	Count (days)
2010	0	151	0	24	-57	-15	0	15	155	0	744	225
2012	1	275	31	75	-144	-20	22	65	364	22	1521	259
2013	2	365	44	53	-126	19	41	67	309	41	1334	363
2014	3	276	92	91	-180	42	77	108	600	77	1468	343
2015	4	236	115	52	-46	88	107	127	378	106	1187	345
2016	5	79	58	42	-25	29	60	87	182	60	1324	359
2017	6	365	90	55	-14	58	82	103	488	82	1405	349
2018	7	365	115	70	-4	71	100	142	357	99	1143	360
2019	8	365	102	48	0	75	95	114	373	95	1706	363
2020	9	365	144	49	-6	113	140	163	462	140	1593	350

Table 10: Results of Kruskall-Wallis test for difference in relative (modelled-observed) water tables between baseline and post-treatment years at sites Po, SB, JP and O, using continuous water table data.

Relative water tables based on daily mean values, modelled-observed (mm)												
	Po			SB			JP			O		
	Change since baseline	Diff vs baseline		Change since baseline	Diff vs baseline		Change since baseline	Diff vs baseline		Change since baseline	Diff vs baseline	
Year		Test stat	P value		Test stat	P value		Test stat	P value		Test stat	P value
2010										0		
2012	0			0			0			22	-3.9	0.001
2015	-4	0.2	1.0	65	-8.1	<0.001	45	-8.3	<0.001	106	-13.7	<0.001
2018	209	-16.1	<0.001									
2020				134	-14.8	<0.001	121	-15.6	<0.001	140	-19.7	<0.001

4.1.2.1. Water table response to precipitation

Continuous water table data from Kinder (sites O and F) were analysed to assess any changes in behaviour during/following rainfall events. During/following rainfall events, peak water table depth rose towards the peat surface following restoration at ~10mm yr^{-1} (Figure 18). There was a significant difference between relative peak WTD in 2010 (baseline year) and all years from 2017 onwards ($p<0.001$). This is consistent with the rate of rise observed in mean daily water table depth reported above.

Table 11: results of analyses of water table response to rainfall events. All data are relative to control, change since baseline.
Peak WTD = control-treatment (positive values indicate peak WTD rising towards the peat surface); all other metrics are treatment-control (positive values indicate increasing lag time/recession rate). Note that, due to gaps in the data, only 10 rainfall events were available for analysis in 2016.

Water table response to rainfall, Kinder Scout (O/F): relative data, change since baseline						
Year	Years since treatment	n (storms)	Peak WTD (mm)	Peak rain-WTD lag (min)	6hr recession rate (mm hr^{-1})	12hr recession rate (mm hr^{-1})
2010	0	29	0	0	0	0
2012	1	19	-15	170	-1.3	0.3
2013	2	66	16	-30	-0.1	0.4
2014	3	49	45	-70	1.0	1.0
2015	4	34	125	-190	3.8	3.7
2016	5	10	35	-190	0.6	0.8
2017	6	65	90	-70	1.7	1.8
2018	7	59	89	-10	2.3	2.4
2019	8	65	85	-20	1.0	1.5
2020	9	72	82.5	-30	1.5	1.3

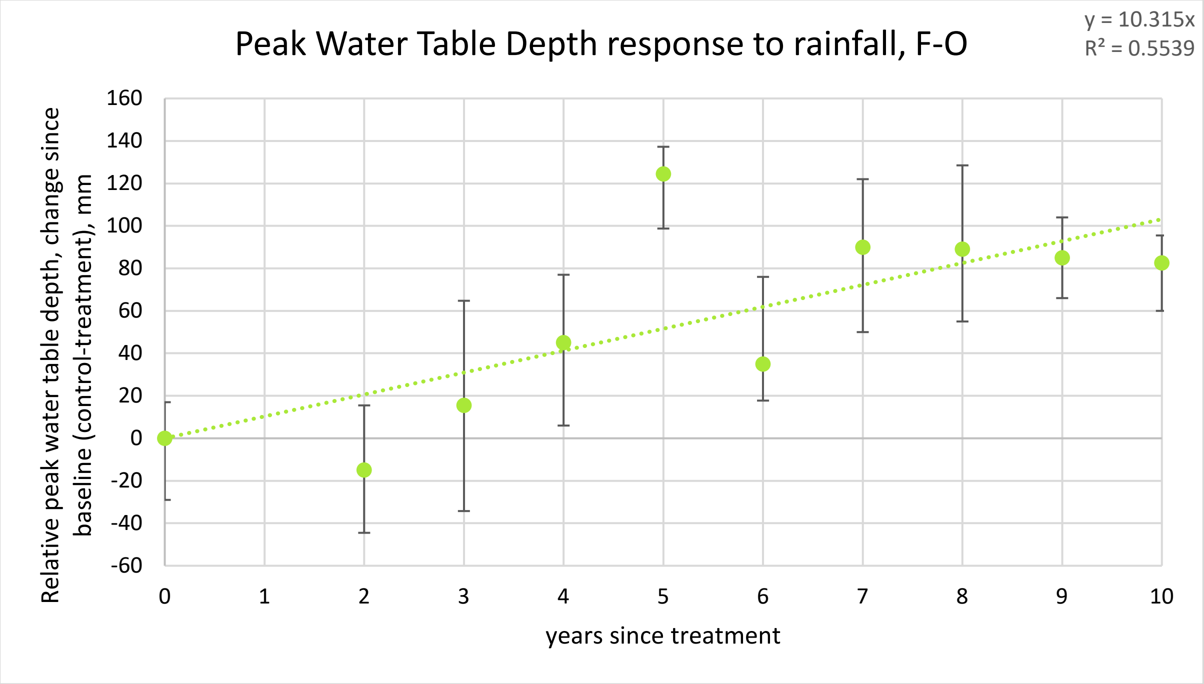


Figure 18: Peak water table depth response to rainfall at O, Kinder Scout (control-treatment, change since baseline). Positive values on the y axis indicate peak water table depth was closer to the surface than in the baseline year. Error bars represent the interquartile range.

No significant changes were observed in lag time from peak rainfall intensity to peak water table depth (Figure 19); no significant changes were observed in water table recession rates during the 6 or 12 hour periods following peak water table depth (Figure 20, Figure 21).

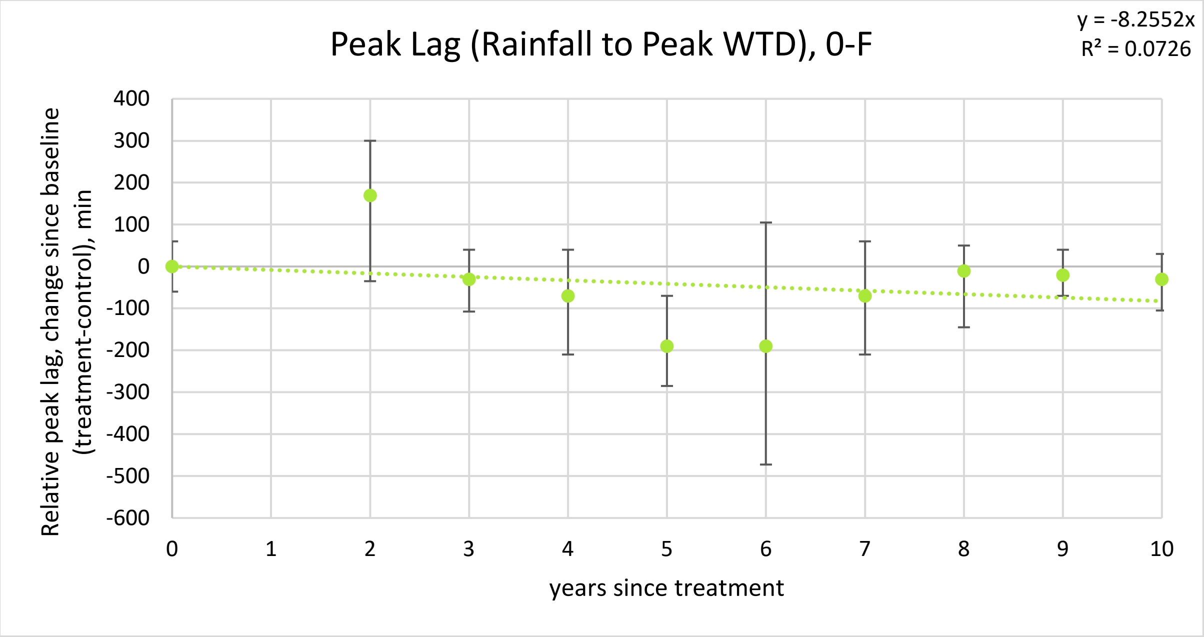


Figure 19: Relative lag time from peak rainfall intensity to peak water table depth at O, Kinder Scout (treatment minus control, change since baseline).
Positive values on the y axis indicate longer lag times than in the baseline year. Error bars represent the interquartile range

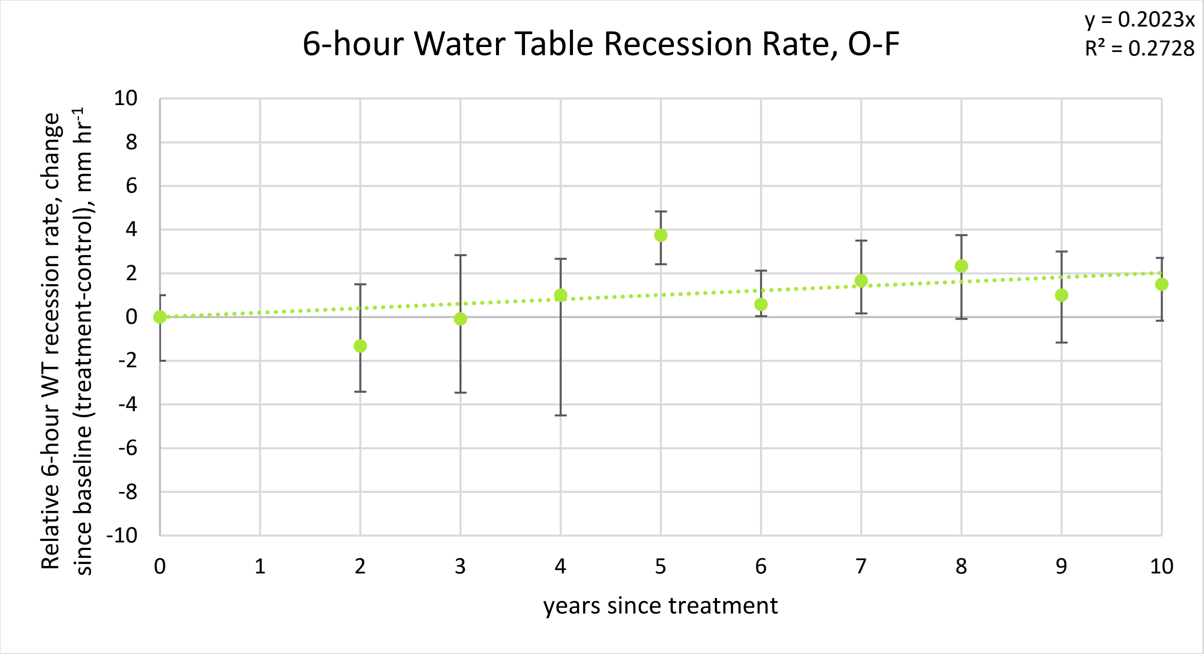


Figure 20: Relative rate of water table recession during the first 6 hours after peak water table depth during/following rain events at O, Kinder Scout (treatment minus control, change since baseline). Positive values on the y axis indicate faster recession rates than in the baseline year. Error bars represent the interquartile range.

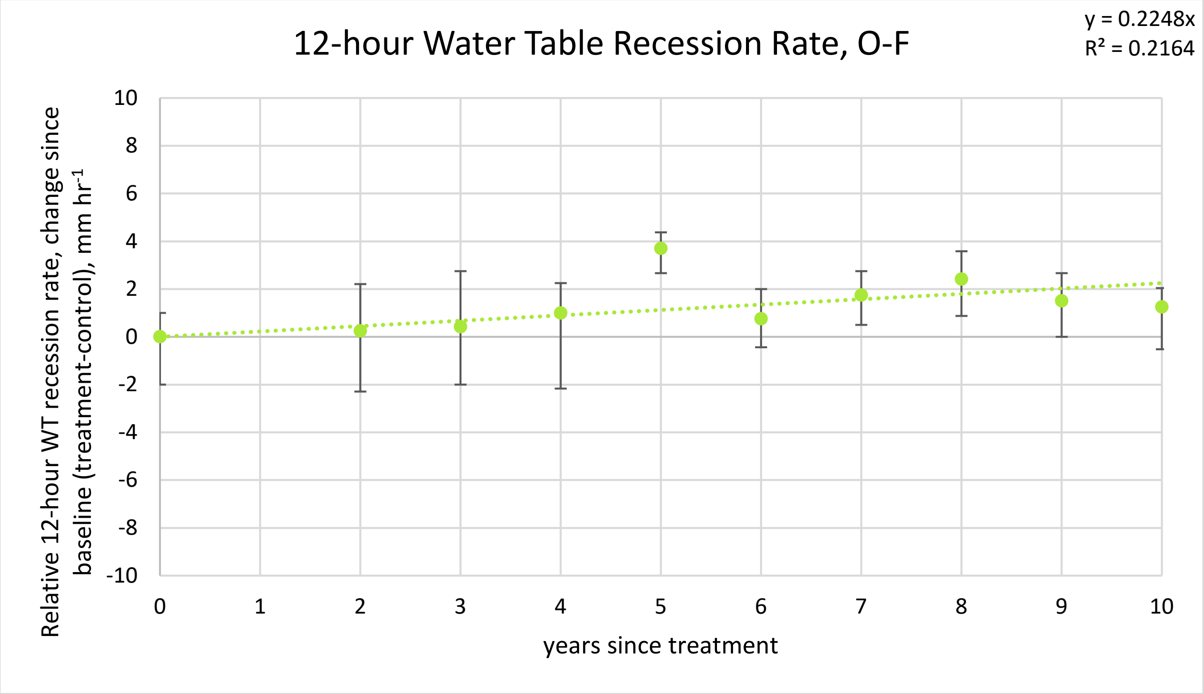


Figure 21: Relative rate of water table recession during the first 12 hours after peak water table depth during/following rain events at O, Kinder Scout (treatment minus control, change since baseline). Positive values on the y axis indicate faster recession rates than in the baseline year. Error bars represent the interquartile range.

4.1.3. Overland flow generation

Allott *et al.* (2015) found that surface ponding and therefore overland flow generation increased on interfluve surfaces following revegetation. Results from the crest-stage runoff traps in 2018, 2019 and 2020 appear to show a reduction in surface ponding at treated sites, with relative values (treatment-control) comparable to the pre-treatment year. As described in the Discussion section below, it appears that the crest-stage runoff traps are not an effective method for monitoring surface ponding or overland flow generation when installed in mature vegetation. These results are therefore considered to be void.

Data from the soil moisture probes installed in 2021 appear to demonstrate an increase in near-surface soil moisture at revegetated sites, with the peat retaining moisture for significantly longer than at the bare peat control site during periods without precipitation. This would be consistent with an increase in surface ponding as a result of treatment, in contrast to the results of the crest-stage runoff traps.

4.1.4. Soil Moisture

Soil moisture was monitored from March to October 2021 using capacitance probes supplied as part of a trial by Dales Land Net. The sensors are still in the process of being optimised for use in peat soils, so results should be treated with caution – in particular when comparing absolute values. However, the data appear to highlight some important differences in soil moisture behaviour, in particular in the top 12.5 cm of the peat, depending on the nature of the peat surface. Time series and cumulative frequency graphs are presented in Figure 18 and Figure 19.

At F (bare peat control), volumetric water content (%VWC) in the top 12.5 cm of the peat fluctuated between ~10% and ~45%, with rapid increases and decreases similar in form to those observed in continuous water table data from dipwells. %VWC tended towards stabilising at the lower end of the range. By contrast, data from both O (standard vegetation) and N (*Sphagnum*) suggest a less flashy response to precipitation. During dry periods, %VWC was lowered to comparable levels to F (~10%) but in general %VWC appeared to stabilise towards the top of the range (~50% at O; 65% at N), only lowering during prolonged dry periods. The data suggest that N was generally wetter and less flashy than O, which was generally wetter and less flashy than F.

In the lower depth zones (12.5–25 cm, 25–37.5 cm, 37.5–50 cm), there was generally less fluctuation in %VWC at all sensors. Soil moisture in the 12.5–25 cm depth zone appeared to reduce at O and N more than at F during extended periods of no precipitation (possibly in part because it was generally higher at O and N than at F before these dry periods and therefore had more potential to dry out). In general, however, across all three lower zones, N was wetter than O, which was wetter than F.

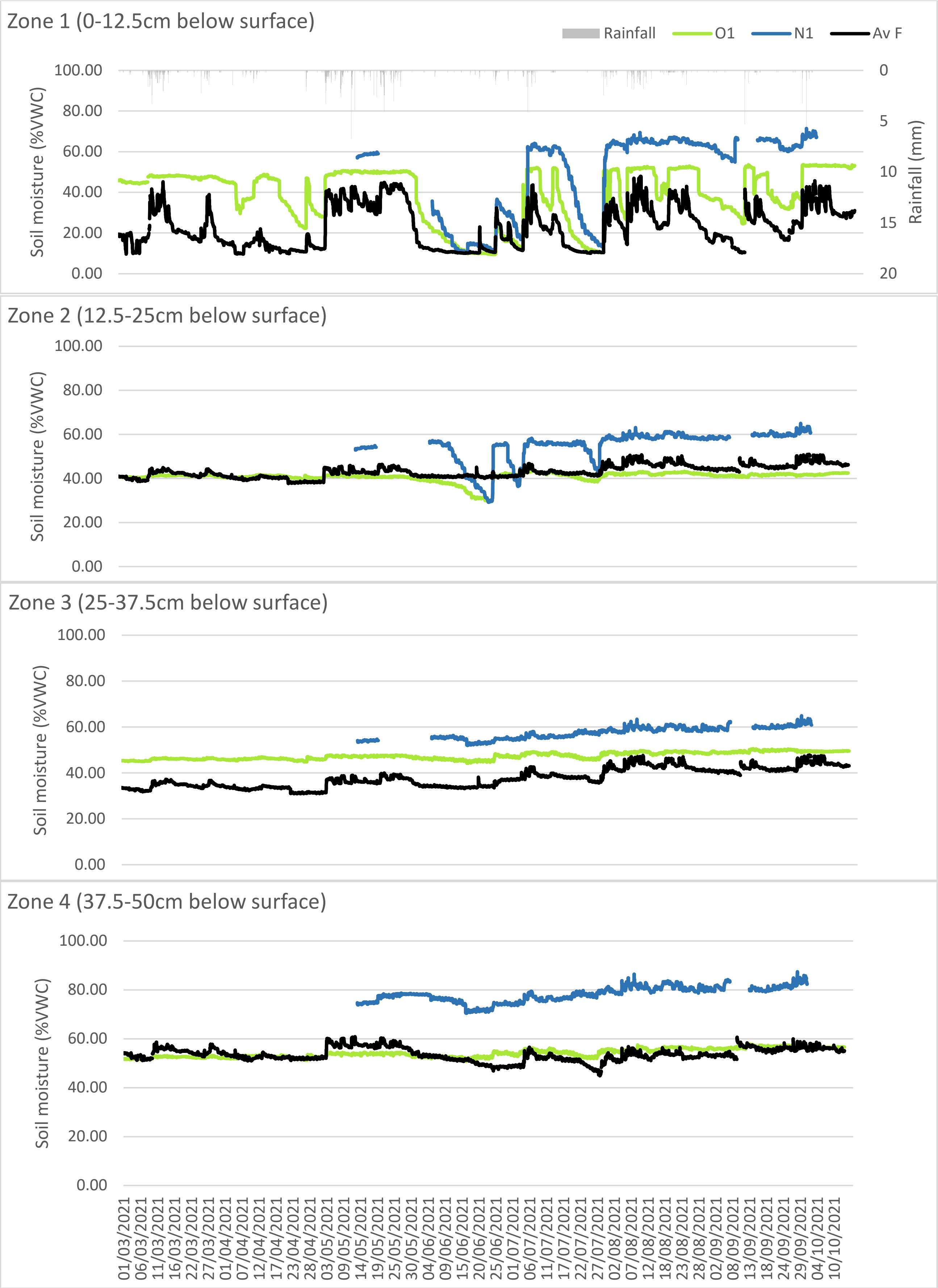


Figure 22: %VWC of peat in four depth zones to 50cm below surface at F (bare peat), O (mixed graminoids and bryophytes) and N (dense *Sphagnum*) as measured by 1–3 soil moisture probes at each site, 2021

The cumulative frequency graph in Figure 23 shows the percentage of all values recorded at each depth at each sensor, where soil moisture was below (drier) than a given moisture content (%VMC). A near-vertical line on the graph suggests little variation in soil moisture (eg at N, 37.5–50 cm, VMC was never drier than ~70%, and never wetter than 85%). A near–horizontal line suggests that soil moisture varied more widely and was less frequently at any given %VMC. For example at F, 0–12.5 cm, VMC varied between ~10% and ~40% with a slight tendency towards the drier end of that window; at N, 0–12.5 cm, soil moisture was less than 60% for 40% of the time (and therefore more than 60 %VMC for ~60% of the time) – within this drier window soil moisture varied more widely than at F or O indicating that it did sometimes dry out, but not often.

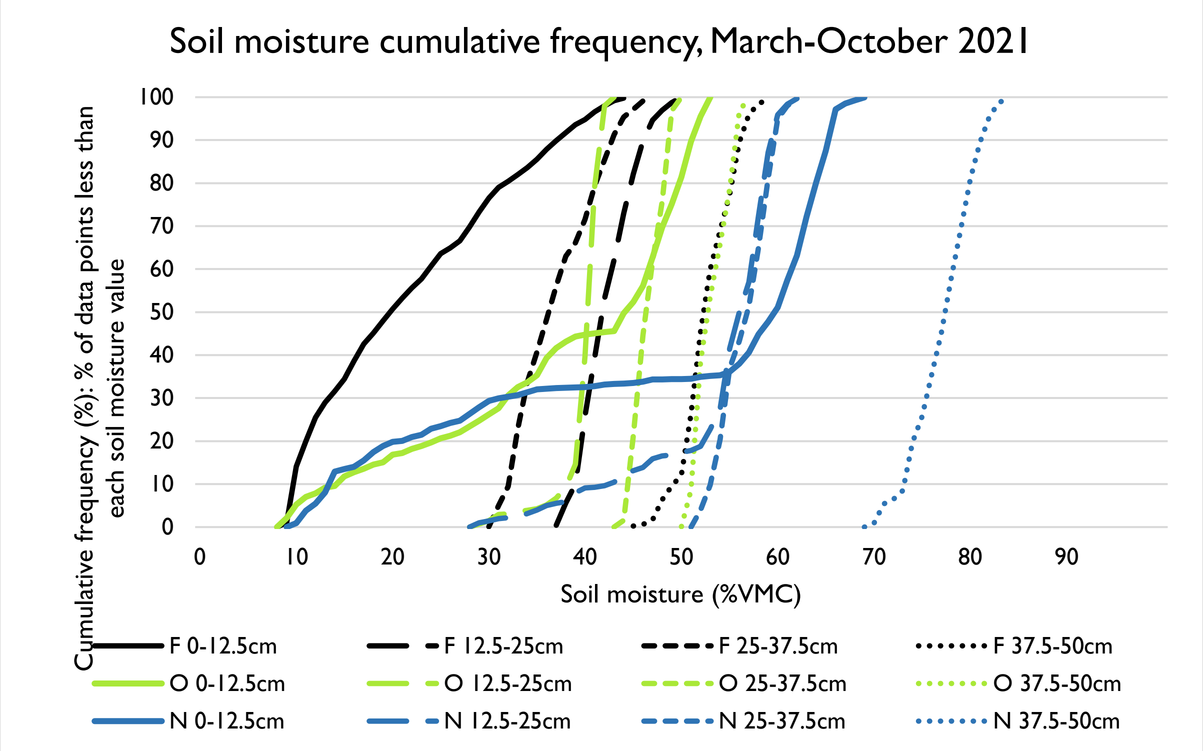


Figure 23: Cumlative frequencies of soil moisture (%VWC) at four depth zones to 50cm at F (bare peat), O (mixed graminoids and bryophytes) and N (dense *Sphagnum*)

Additional sensors were installed in July 2022 to increase replication of these results, in combination with a signal repeater to improve connectivity and reduce data gaps. Soil samples were taken from each of the three sites to enable a site-specific calibration process (previous data were calibrated using a soil sample from Ilkley Moor). Data from four sensors at each site were available for analysis from 28/07/2022 to 21/09/2022 (see Figure 24, Figure 25). These data supported the initial findings of the pilot studied presented above:

- N was wetter than O (in the 0–12.5 cm zone; then similar lower down); N and O were wetter than F (in the 0–25 cm zones; then similar lower down)
- The top 12.5 cm of peat remained wetter for longer in prolonged dry periods at N than at O, and wetter for longer at O than F

In general, data from all three sites in the lower depth zones suggested the peat was wetter (and that soil moisture varied less in the lower depth zones) than in the pilot study. This could be due to the new site-specific soil moisture calibration, or due to an actual change in soil moisture conditions from 2021 to 2022.

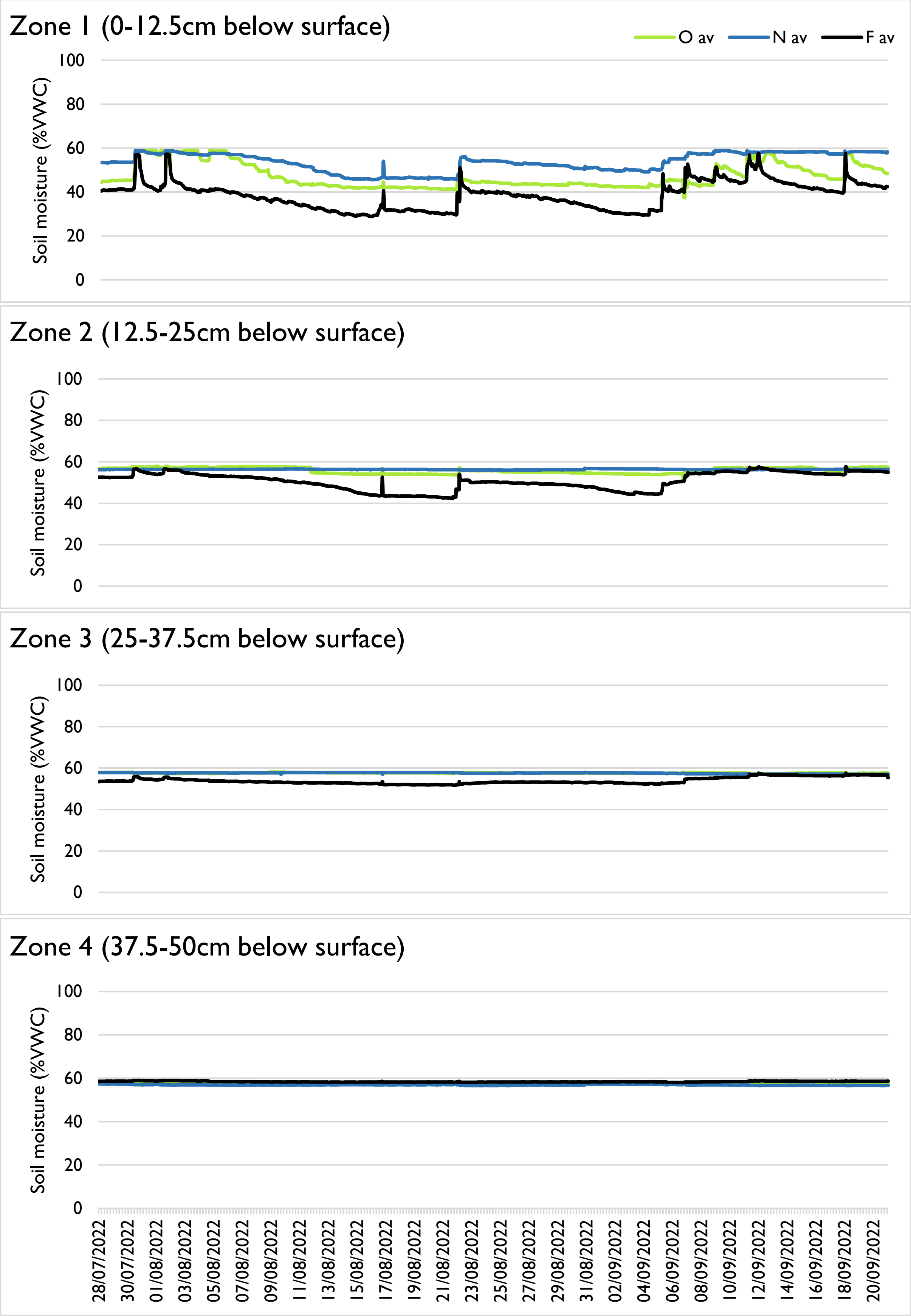


Figure 24: %VWC of peat in four depth zones to 50cm below surface at F (bare peat), O (mixed graminoids and bryophytes) and N (dense *Sphagnum*) as measured by 4 soil moisture probes at each site, 2022

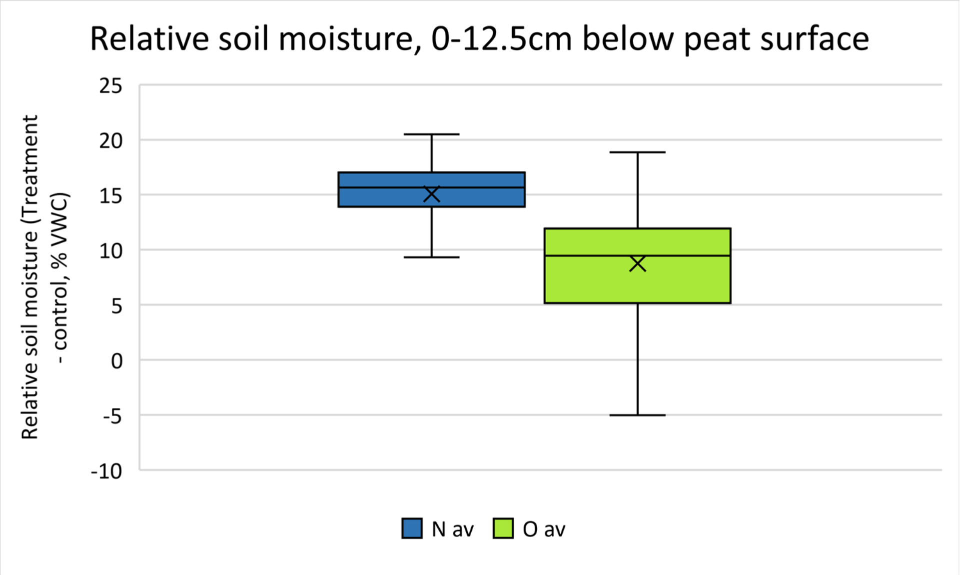


Figure 25: Relative soil moisture in Zone 1 (0–12.5cm below peat surface), 2022 (4 sensors at each site). Treatment minus control: positive values indicate wetter peat at treatment than at control

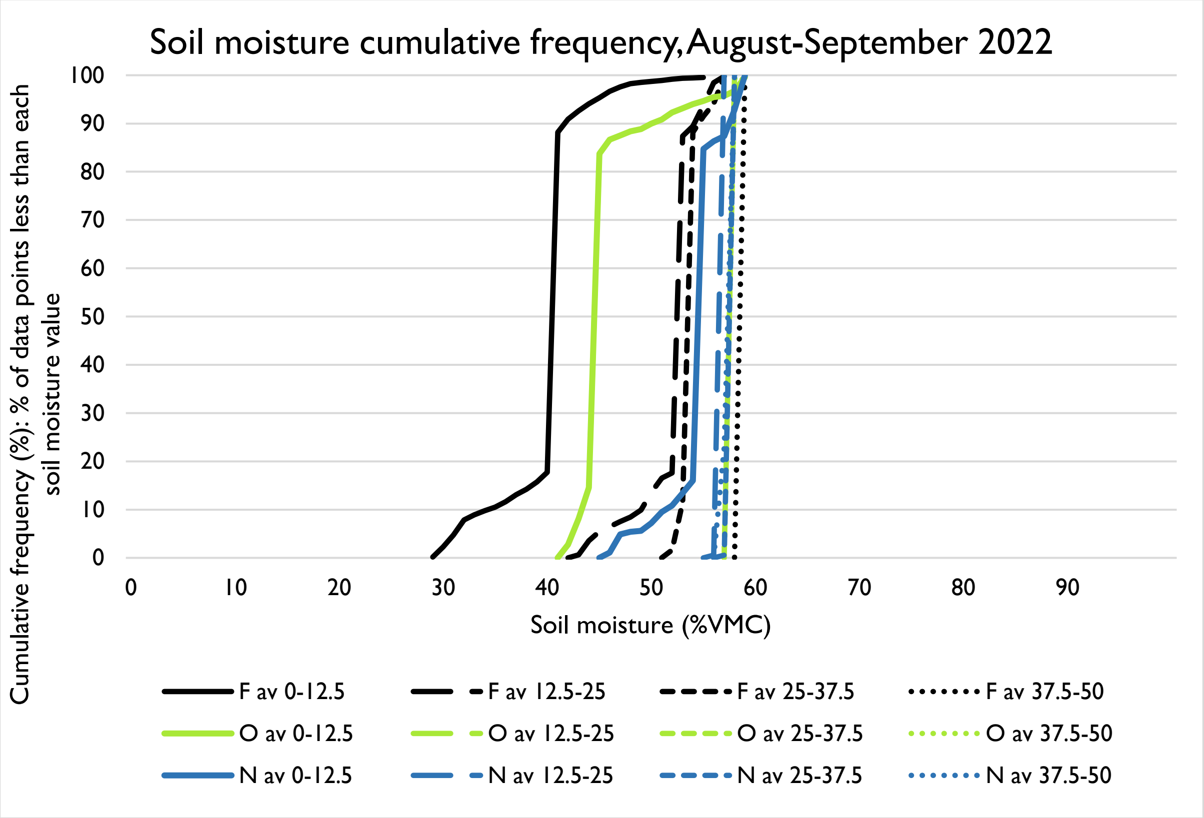
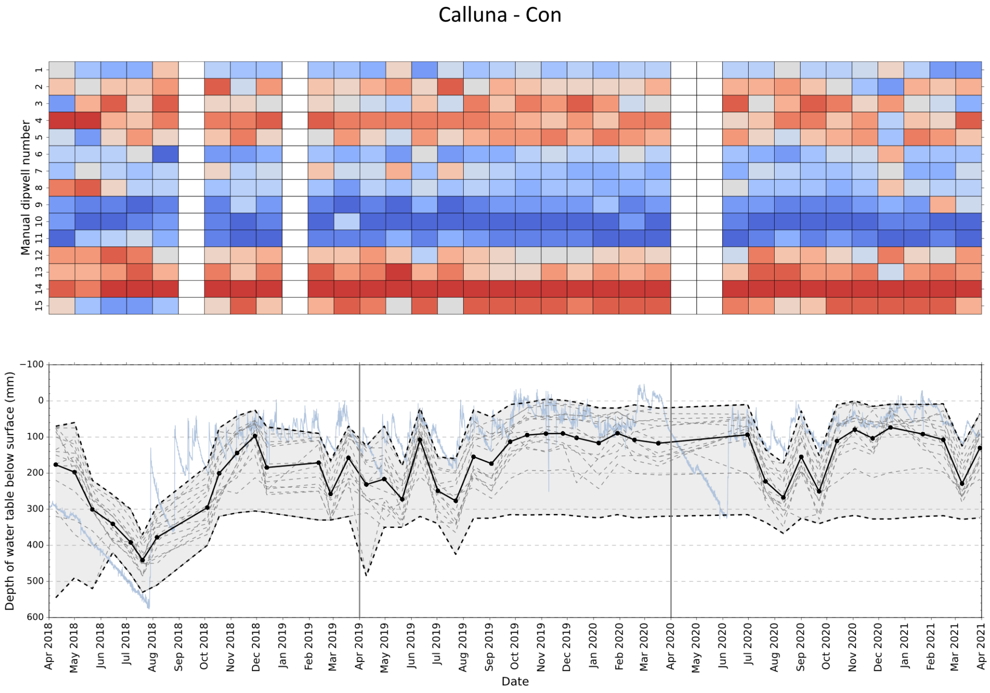


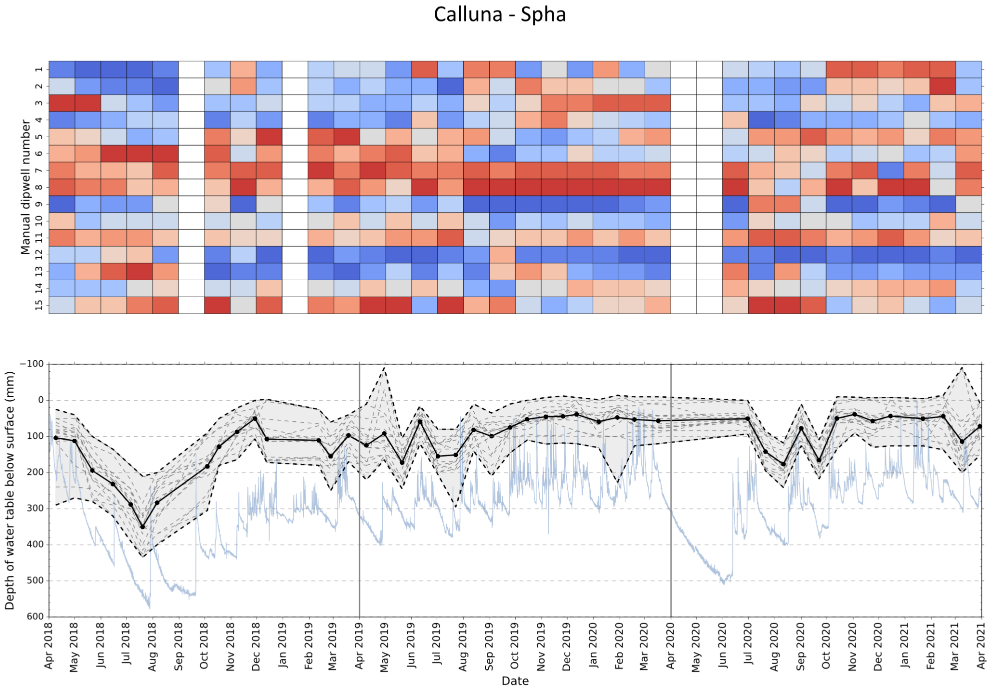
Figure 26: Cumlative frequencies of soil moisture (% VWC) at four depth zones to 50cm at F (bare peat), O (mixed graminoids and bryophytes) and N (dense *Sphagnum*)

4.2. *Calluna* dominated site

4.2.1. Manual water table



a)



b)

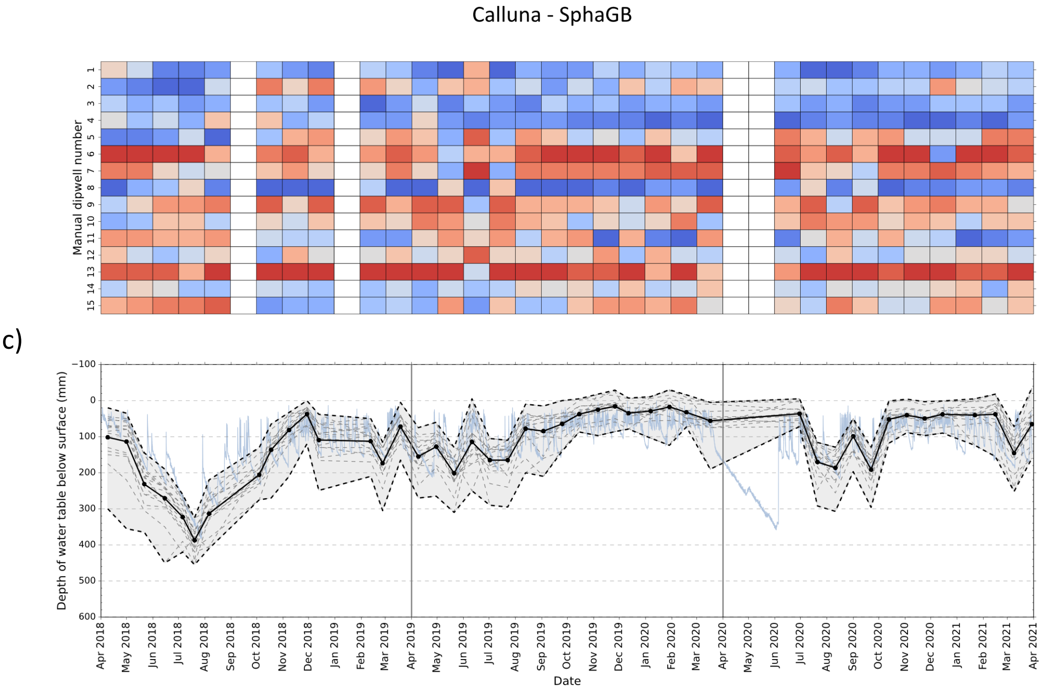


Figure 27. Time series and heat maps of manual water tables in *Calluna* catchments.

Figure 27 displays time series of manual water tables from all dipwells clusters in *Calluna* a) control, b) *Sphagnum* and c) *Sphagnum* and gully blocked treatment catchments (dashed grey lines). Mean dipwell depth from all 15 individual dipwells is displayed (black solid line) together with maximum and minimum depths (black dashed lines). Grey shading highlights the range of depths for each time step. Black vertical lines delimit the years (before treatment April 2018–19; and after treatment April 2019–21) of the study. Continuous water table records from the intensive plot sites are also displayed (blue line). Heatmaps above represent the monthly ranking of each dipwell to display inter-dipwell variation through time. Colours are from blue, shallowest water table, to red, deepest water table, for that time step.

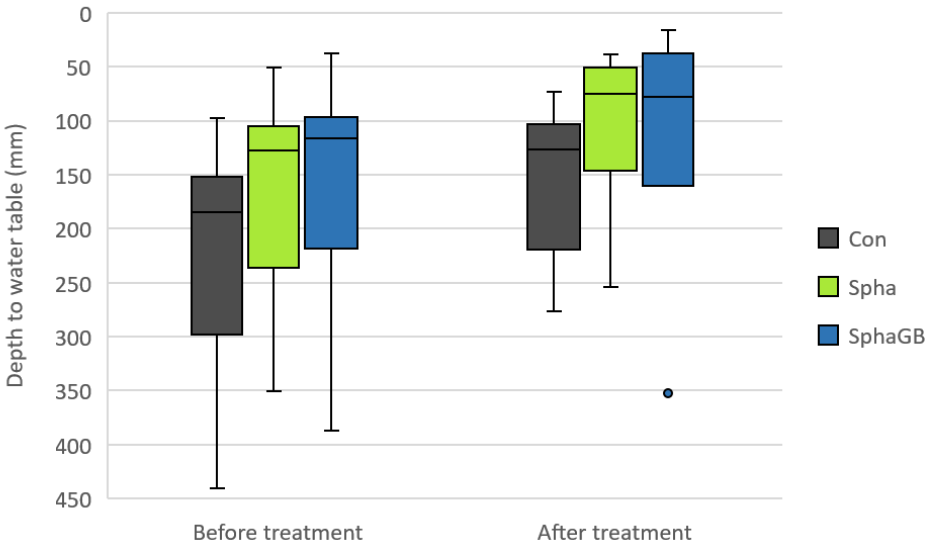


Figure 28. Boxplots of mean manually measured water table depth below surface (mm) for control and treatment catchment dipwell clusters on the *Calluna* site, before and after treatment.

Figure 28 displays boxplots of mean manually measured water table depth in the cluster dipwells (n = 15) before (year 0) and after (year 1 + 2) treatment in the three mini-catchments on the *Calluna* site allowing for a comparison of the overall changes seen in each catchment.

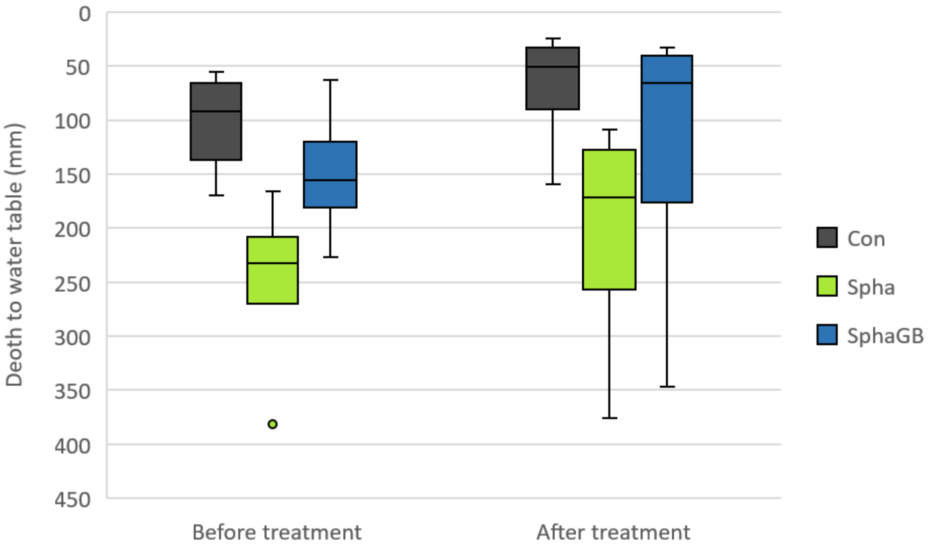


Figure 29. Boxplots of mean manually measured water table depth below surface (mm) for control and treatment intensive plot dipwells on the *Calluna* site, before and after treatment.

Figure 29 shows the equivalent data from the intensive plot dipwells (n = 6) before (year 0) and after (year 1) treatment. It can be seen that water table measured in the dipwell clusters is generally further from the surface in the control catchment both before and after-treatment. This contrasts with the results observed in the intensive plots, where the *Sphagnum* (Spha) catchment was furthest from the surface. This may be partly explained by the situation of the Spha intensive plots near to a deep gully edge further down the catchment slope than the dipwell cluster.

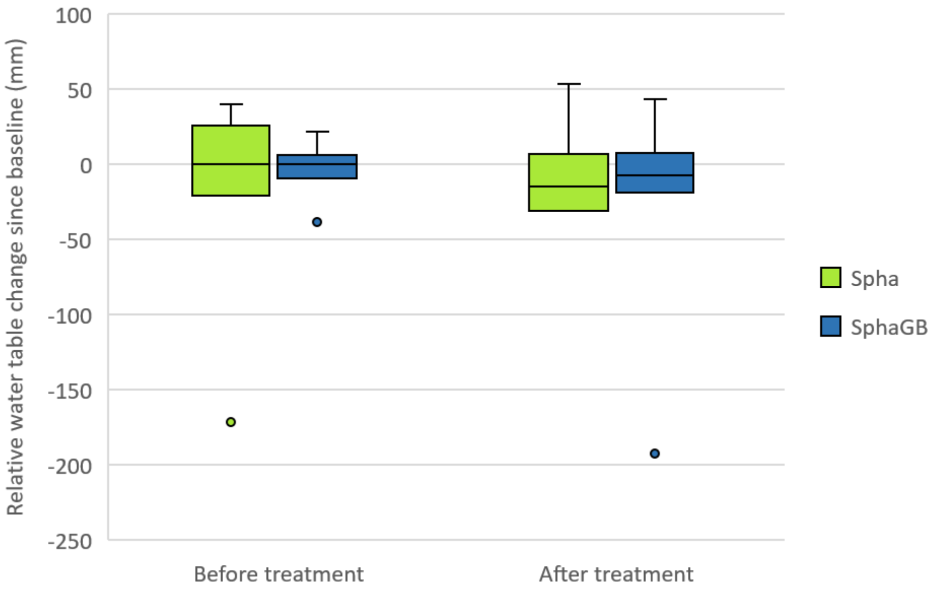


Figure 30. Boxplots of mean manually measured water table depth (mm) in treatment catchment clusters on *Calluna* site, relative to control (control – treatment), before and after treatment. Before median values have been normalised to zero to show change since treatment.

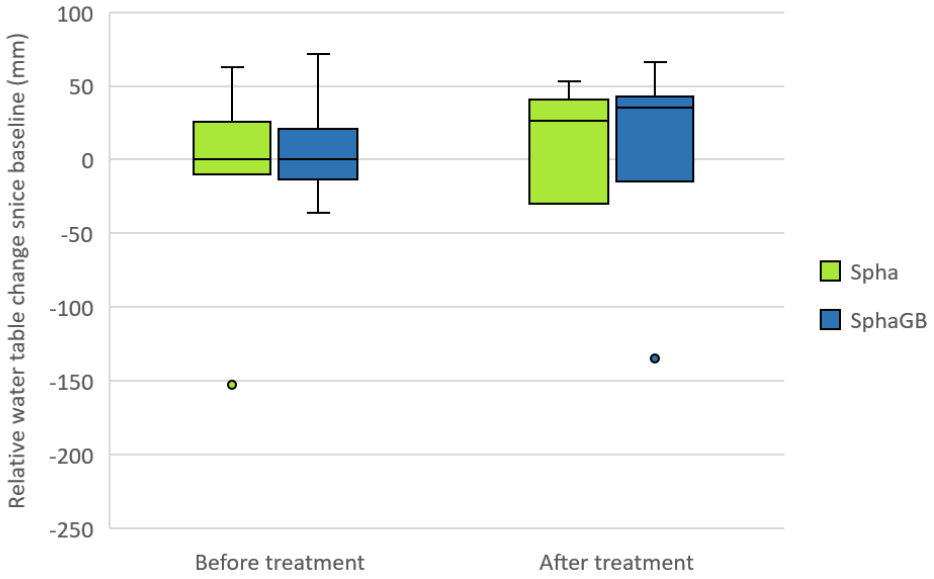


Figure 31. Boxplots of mean manually measured water table depth (mm) in treatment catchment intensive plot dipwells on *Calluna* site, relative to control (control – treatment), before and after treatment. Before median values have been normalised to zero to show change since treatment.

Figure 30 and Figure 31 show boxplots of the mean manually measured water table depth relative to the control catchment on the *Sphagnum* (Spha) and *Sphagnum* & gully blocked (SphaGB) treatment catchments. Relative figures were derived by subtracting treatment from control (control –

treatment), to produce positive figures if the water table depth from surface decreases relative to control. Boxplots for the 'before' period are displayed with the median normalised to zero to allow for a simple visualisation of change over time.

Little change is evident in the treatment site cluster or intensive measurements. A small drop in median relative water table (15 mm Spha; 8 mm SphaGB) was seen on both treatment site clusters, while a slight rise in median relative water table (27 mm Spha; 35 mm SphaGB) was observed in the intensive plots. However, neither of these changes are statistically significant, and there is a great deal of overlap between the spread of before and after data.

Table 12 and Table 13 display descriptive statistics for the cluster and intensive plots respectively.

Table 12. Descriptive statistics for water table depths at cluster before and after treatment on *Callluna* site

		Control	Treatment (Spha)	Treatment (SphaGB)	Difference (Spha)	Difference (SphaGB)
Before	Max	441	350	387	113	90
	Q3	298	236	219	98	75
	Median	185	128	116	73	69
	Q1	152	105	96	52	59
	Min	97	50	37	-98	30
After	Max	277	254	353	126	112
	Q3	220	147	160	79	76
	Median	126	75	78	58	61
	Q1	103	51	38	42	50
	Min	74	39	16	-94	-123

Table 13. Descriptive statistics for water table depths in intensive plots before and after treatment on *Calluna* site

		Control	Treatment (Spha)	Treatment (SphaGB)	Difference (Spha)	Difference (SphaGB)
Before	Max	170	382	227	-74	18
	Q3	137	270	181	-111	-32
	Median	92	233	156	-137	-53
	Q1	66	208	120	-147	-67
	Min	56	166	63	-289	-89
After	Max	159	367	347	-84	13
	Q3	90	257	176	-96	-11
	Median	51	172	66	-110	-18
	Q1	33	128	40	-167	-68
	Min	25	109	33	-289	-188

Table 14 displays the results of Mann-Whitney U tests to compare relative water table depths before and after-treatment. There were no significant differences (at $p < 0.05$) found as a result of treatment.

Table 14. Results of Mann-Whitney U test employed to compare manual water table depths on *Calluna* site before and after treatment.

	Spha cluster	SphaGB cluster	Spha INTS	SphaGB INTS
Mann-Whitney U	262.0	275.0	141.0	138.0
P – value	0.202	0.302	0.531	0.471

4.2.2. Continuous water table

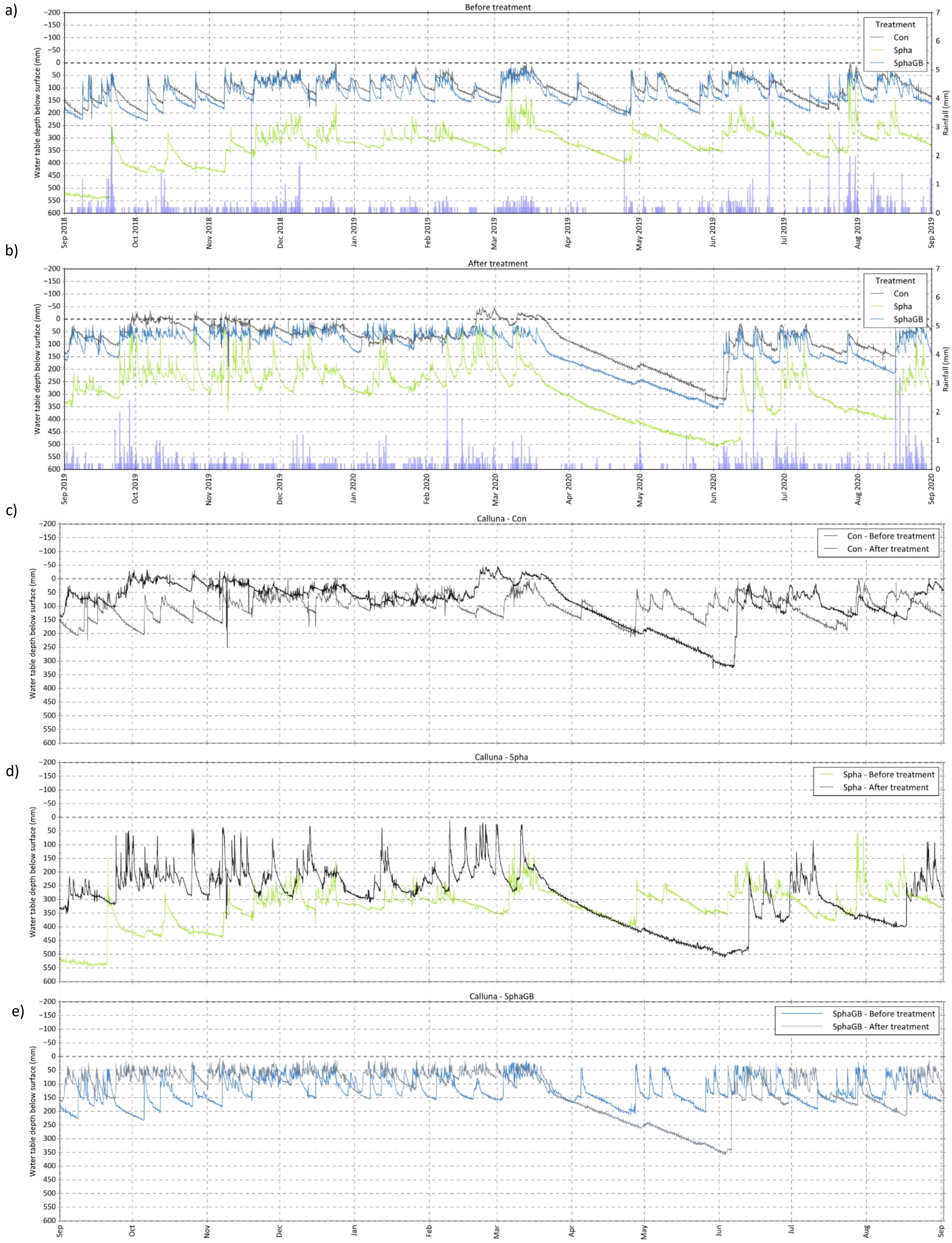


Figure 32. Full automated water table time series for *Calluna* species-dominated sites.
Figures a–b display automated water table for each treatment for years 0 (before treatment) and 1 (after treatment) together with rainfall at 5-minute intervals. Figures c to e allow comparison of the same treatment with year 0 and 1.

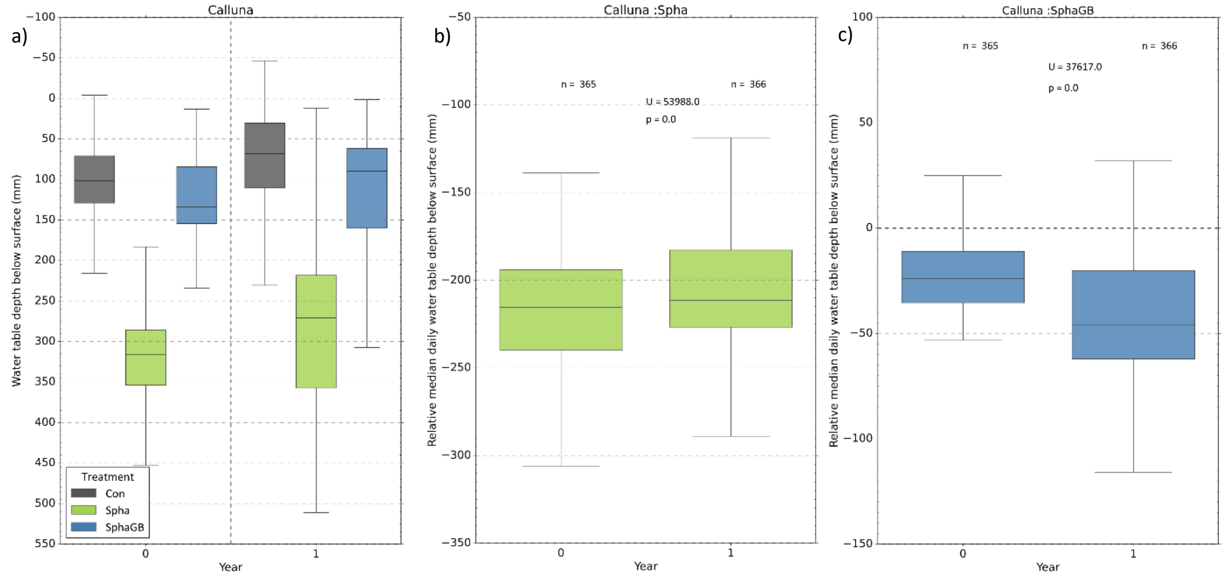


Figure 33. Boxplots of continuous water table depths before and after treatment, *Calluna* site. a) median daily water table depth below surface (mm) for each treatment and year (using 5 minutes interval data) and b–c) the water table depth relative to control for median daily water table depth for each year (control minus treatment for every day in year 0 and year 1) together with Mann-Whitney U statistical tests to determine significant differences. A change towards less negative values from year 0 to 1 in b and c indicates a reduced difference between control and treatment and vice versa.

From times series plots (Figure 32 a–c) and boxplots (Figure 33 a) it is evident that the intensive plots within both control (Con) and *Sphagnum* planted/gully blocked (SphaGB) mini-catchments operate at similar ranges of water table depths. Although the intensive plot at the *Sphagnum* (Spha) mini catchment reacted synchronously to rainfall events, it existed at much deeper levels throughout the two project years and operated over a greater range.

Project year median water table depths are at least 180 mm deeper at the Spha site irrespective of project year. As for all species-dominated intensive plots, water tables have increased from year 0 to 1 at all treatments due to increased rainfall totals.

Table 15. Descriptive statistics of continuous water table at *Calluna* site.
a) water table depth below surface at 5-minute intervals, b) median daily water tables for each treatment and year and c) relative water tables (control minus treatment of median daily water tables). Differences between medians statistics at control and treatment for each year are displayed in a–b and Year 1 minus Year 0 medians are displayed in c.

a)

			Water table depth below surface (mm)							
Year	Treatment	Count	Mean	Stdev	Min	LQ	Median	UQ	Max	Median difference	Rainfall sum (mm)
0	Con	105120	103.4	41.5	-3.8	70.9	101.6	129.2	223.0		1249.0
0	Spha	105120	329.0	71.8	44.9	285.6	316.3	353.9	551.6	-214.8	1249.0
0	SphaGB	105120	124.2	45.7	13.4	84.3	133.8	154.5	234.3	-32.2	1249.0
1	Con	105408	81.9	74.7	-46.4	30.7	68.2	110.6	327.5		1628.8
1	Spha	105408	284.8	98.0	12.3	218.3	270.9	357.5	510.9	-202.8	1628.8
1	SphaGB	105408	121.4	79.6	1.4	61.9	89.7	160.2	358.6	-21.5	1628.8

b)

			Water table depth below surface (mm)								
Year	Treatment	Count	Mean	Stdev	Min	LQ	Median	UQ	Max	Median difference	Rainfall sum (mm)
0	Con	365	103.9	41.1	21.4	71.5	102.2	129.2	204.7		1249.0
0	Spha	365	330.2	70.8	171.5	286.9	315.7	354.4	539.2	-213.5	1249.0
0	SphaGB	365	125.4	44.4	37.4	86.6	134.5	154.3	230.5	-32.3	1249.0
1	Con	366	82.0	74.7	-36.1	30.4	68.1	110.7	319.2		1628.8
1	Spha	366	286.3	95.5	47.5	219.4	271.9	357.8	504.1	-203.8	1628.8
1	SphaGB	366	122.2	78.7	29.2	62.6	87.5	159.9	351.9	-19.4	1628.8

c)

			Relative water tables based on daily median values (mm)								
Treatment	Year	Count	Mean	Stdev	Min	LQ	Median	UQ	Max	Year 1 - Year 0 (median)	Rainfall sum (mm)
Spha	0	365	-226.3	48.9	-441.6	-240.0	-215.5	-194.0	-138.7		1249.0
Spha	1	366	-204.3	47.7	-436.5	-226.7	-211.4	-182.8	-43.9	4.1	1628.8
SphaGB	0	365	-21.5	19.2	-53.2	-35.4	-23.9	-11.1	89.9		1249.0
SphaGB	1	366	-40.3	33.4	-115.9	-62.1	-46.1	-20.3	182.6	-22.2	1628.8

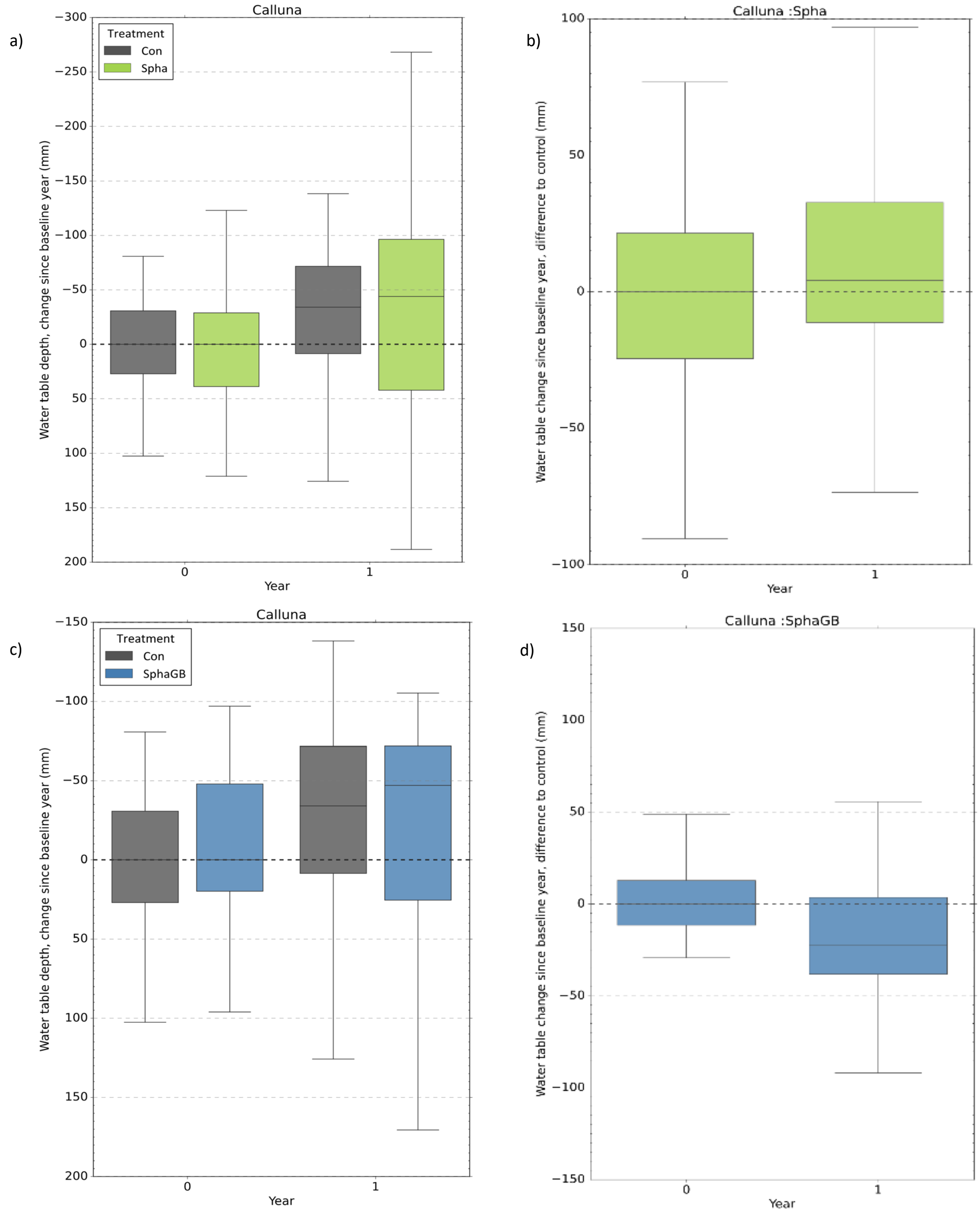


Figure 34. Boxplots of continuous water table depths standardised to zero before and after treatment, *Calluna* site.
Daily median water table depths standardised to year 0 median of each treatment (a and c) and relative water table from daily median water table data also standardised to year 0 median (b and d) for each treatment. Change to above 0 from year 0 to 1 (more negative values) indicates a change to more elevated water tables in a and c. In b and d change to more positive values indicates the relative water table depth (control minus treatment every day) from year 0 to 1 has decreased.

Relative (control minus treatment) water table depth at the *Sphagnum* treated plot, employing daily median water table depths, has remained stable with project year median values reducing only marginally from year 0 to 1, however distributions are significantly different (Table 15 a–b; Figure 33 b). When these relative changes are calculated by normalising the before (year 0) period median to zero (Table 15c; Figure 34 b) a small positive relative value of 4.1 mm is derived, indicating a small relative shallowing of water table at the treated plot. The opposite is observed at the *Sphagnum* and gully blocked plot as relative water table becomes more negative in from year 0 to year 1 (Table 15 a–b), with a project year median changing from -23.9 to -46.1, suggesting a greater difference between control and treatment with treatment being relatively deeper. When these relative changes are calculated by normalising the before (year 0) period median to zero (Table 15 c; Figure 34c) a relative negative value of -22.1 mm is derived indicating a relative deepening of water table at the treated plot.

This appears contrary to evidence in Figure 33 a that employs all data points (every 5 minutes) as opposed to the daily median values used in Figure 33 b–c. However, despite both the control and *Sphagnum* gully block plots having shallower overall median water tables moving from year 0 to 1, the differences between them have increased (Figure 34 c–d) suggesting that the treatment water table here has not risen proportionately to that of the control.

The latter point is well illustrated in the water table residence curves (Table 16; Figure 35). The control and *Sphagnum* gully block curves are more inflected in the mid-range of depths to the upper right indicating more time above these levels but the gap between the lines has increased largely because of shallower water tables at the control, so relative differences have become more negative (control minus treatment). The *Sphagnum* treated plot displays a similar curve shape in before and after-treatment years albeit shifted up the figure to higher water tables reflecting the elevated rainfall input.

Table 16. Water table residence time descriptive statistics for *Calluna* site.
Percentage of time water table above and below 0 (surface), 50- and 100-mm depths for each year and treatment. Differences between treatments for each year are also displayed.

		Percent of time above water table level					Percent of time below water table level				
					Relative					Relative	
Water table depth (mm)	Year	Con	Spha	SphaGB	Spha	SphaGB	Con	Spha	SphaGB	Spha	SphaGB
0	0	0.017	0.000	0.000	0.017	0.017	99.983	100.000	100.000	-0.017	-0.017
	1	9.832	0.000	0.000	9.832	9.832	90.168	100.000	100.000	-9.832	-9.832
50	0	8.966	0.001	4.877	8.965	4.089	91.034	99.999	95.123	-8.965	-4.089
	1	36.785	0.747	11.771	36.038	25.013	63.215	99.253	88.229	-36.038	-25.013
100	0	48.286	0.058	33.166	48.228	15.120	51.714	99.942	66.834	-48.228	-15.120
	1	70.057	2.537	55.232	67.520	14.825	29.943	97.463	44.768	-67.520	-14.825

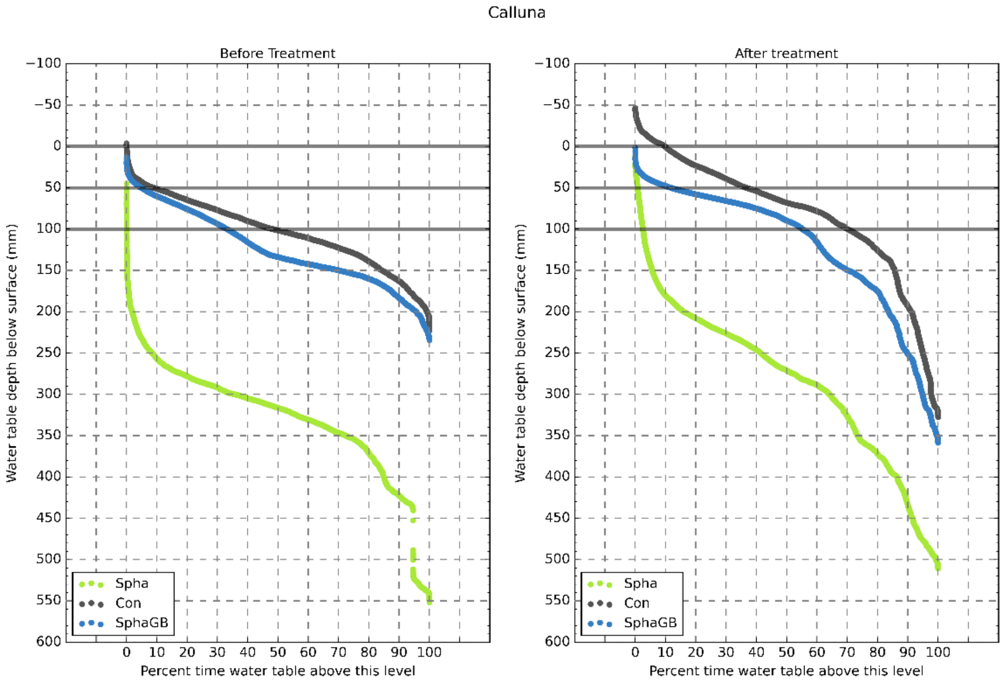


Figure 35. Water table residence time curves for *Calluna* site.
Residence time curves for each dipwell based on 5-minute sampling intervals. Curves display the percentage of time a water table exists above a certain water table level.

Time series plots (Figure 32) reveal a subtle change in the responsiveness of the dipwell at the control plot from year 0 to 1. The first half of year 2 (not displayed here) confirms the reduction of responsiveness as the record is less peaky especially when compared to the other two treated plots. This is due to the effective hydrological functioning of the dipwell that through time has deteriorated as most likely the holes in the dipwell have become blocked. Therefore, the data from the control plot is not suitable for analyses examining high temporal resolution changes such as response to storms but is still effective for determining longer-term trends.

4.2.3. Overland flow generation

4.2.3.1. Cluster area

Overland flow from mini catchments has increased from before-treatment to after-treatment years (0–1) for both control, *Sphagnum* and *Sphagnum* and gully blocked treatment clusters. This is a reaction to elevated rainfall resulting in higher water tables (Table 17; Figure 36 a–b; Figure 37 a–b; Figure 38). The before-treatment year was a period of prolonged deep-water tables due to drought conditions in late spring and early summer 2018.

Table 17. Cluster crest stage tube percentage recovery at each treatment for *Calluna* dominated sites. Values are displayed for each treatment and each year of project as well as before and after treatment (after being a consolidation of years 1 and 2). Differences between percentage recovery from treatment and control are also displayed. Recovery values here are based on presence or absence from all 15 crest stage tubes in each catchment from each year's / period's data. Counts are total number of crest stage data points and sums are the number of those data points with water being present.

		Treatment	Year	Sum	Count	% Recovery	Treatment - control
Calluna	All years	Con	0	67	180	37.2	
		Con	1	143	240	59.6	
		Con	2	118	195	60.5	
		Spha	0	83	180	46.1	8.9
		Spha	1	195	240	81.3	21.7
		Spha	2	154	195	79.0	18.5
		SphaGB	0	83	180	46.1	8.9
		SphaGB	1	182	240	75.8	16.3
		SphaGB	2	149	195	76.4	15.9
	Before / after	Con	Before	67	180	37.2	
		Con	After	261	435	60.0	
		Spha	Before	83	180	46.1	8.9
		Spha	After	349	435	80.2	20.2
		SphaGB	Before	83	180	46.1	8.9
		SphaGB	After	331	435	76.1	16.1

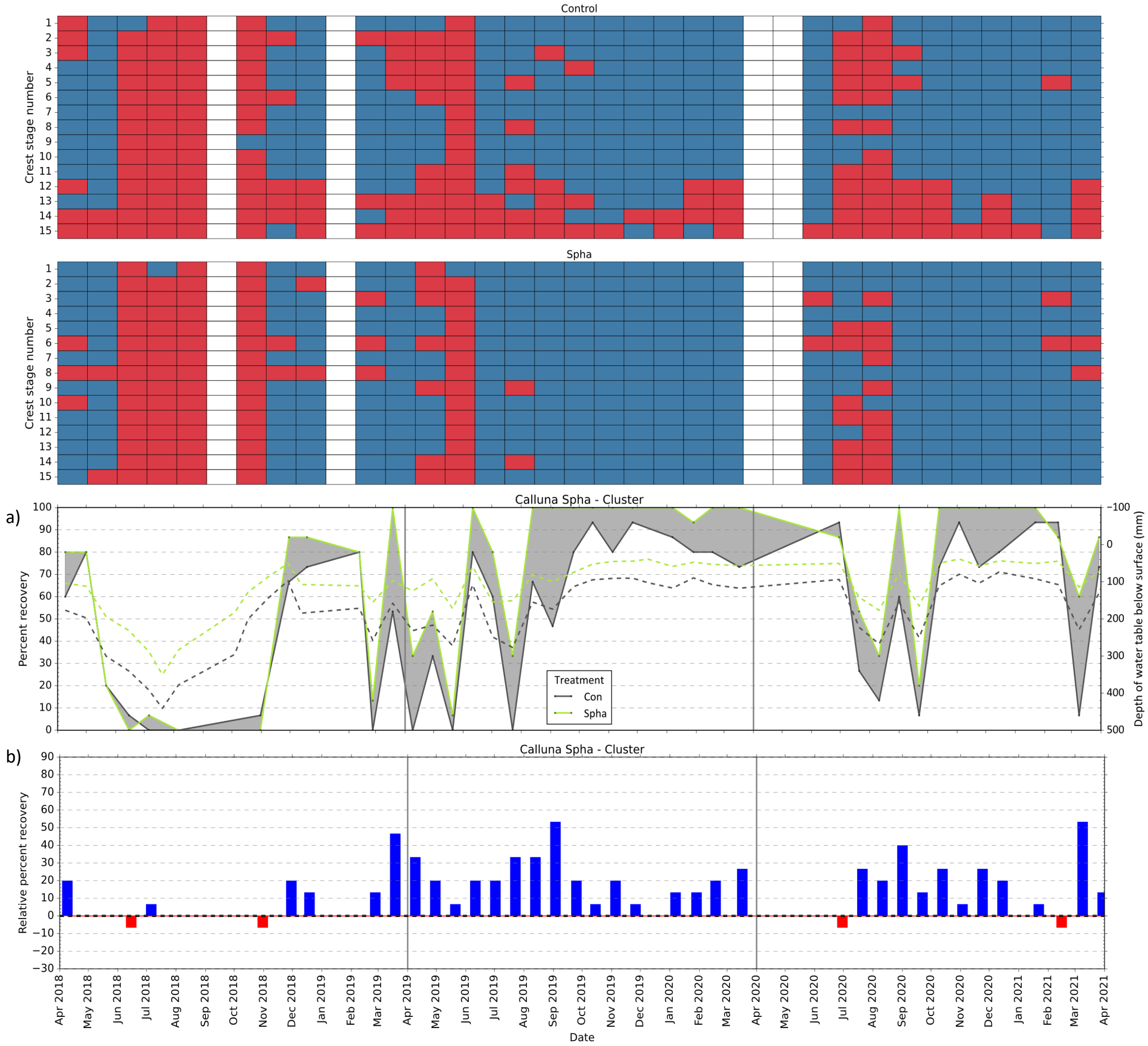


Figure 36. Time series of overland flow on *Calluna* site Con and Spha catchments.
Time series of a) percentage recovery from crest stage tubes from cluster locations at *Calluna* dominated catchments. Dotted lines show a combined mean water table level in these catchments (Con and Spha) from the 15 dipwells. Grey shading between percentage recovery lines highlights differences between treatment and control. Treatment minus control is displayed b) for each time step with blue values indicating treatment recovery greater than control and red treatment recovery less than control. The uppermost two figures give monthly presence (blue) or absence (red) values for water in each individual crest stage tube for each treatment.

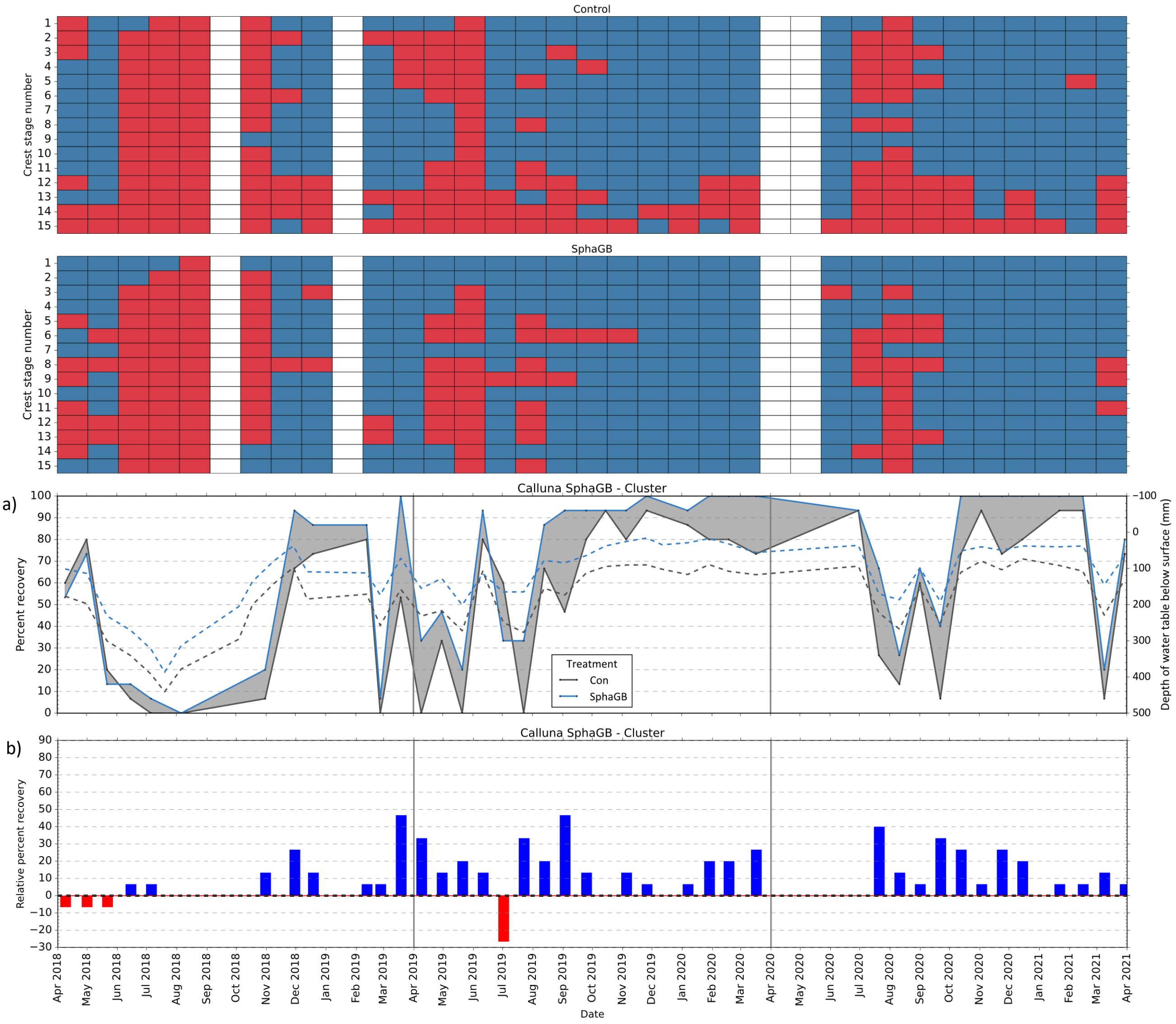


Figure 37. Time series of overland flow on *Calluna* site Con and SphaGB catchments.
Time series of a) percentage recovery from crest stage tubes from cluster locations at *Calluna* dominated catchments. Dotted lines show a combined mean water table level in these catchments (control and SphaGB) from the 15 dipwells. Grey shading between percentage recovery lines highlights differences between treatment and control. Treatment minus control is displayed b) for each time step with blue values indicating treatment recovery greater than control and red treatment recovery less than control. The uppermost two figures give monthly presence (blue) or absence (red) values for water in each individual crest stage tube for each treatment.

The relative (treatment minus control) percent recovery (recovery of water from crest stage tubes signifying overland flow) shows that the treated sites have experienced a greater increase in overland flow from the before to after-treatment period compared to the control. The increase although evident from year 0 (before-treatment) to year 1 (first year after-treatment) stabilises entering year 2 (Table 17; Figure 38 b) for both (Spha and SphaGB) treatments. Records of monthly recovery (presence or absence) for every single crest stage tube shows that there are no clear inconsistencies in behaviour either at control or the two treated mini catchments. Only tubes 14 and 15 in the control mini catchment appear to show persistent extreme trends suggesting that the 15 tubes in each mini catchment provide a good overall representation.

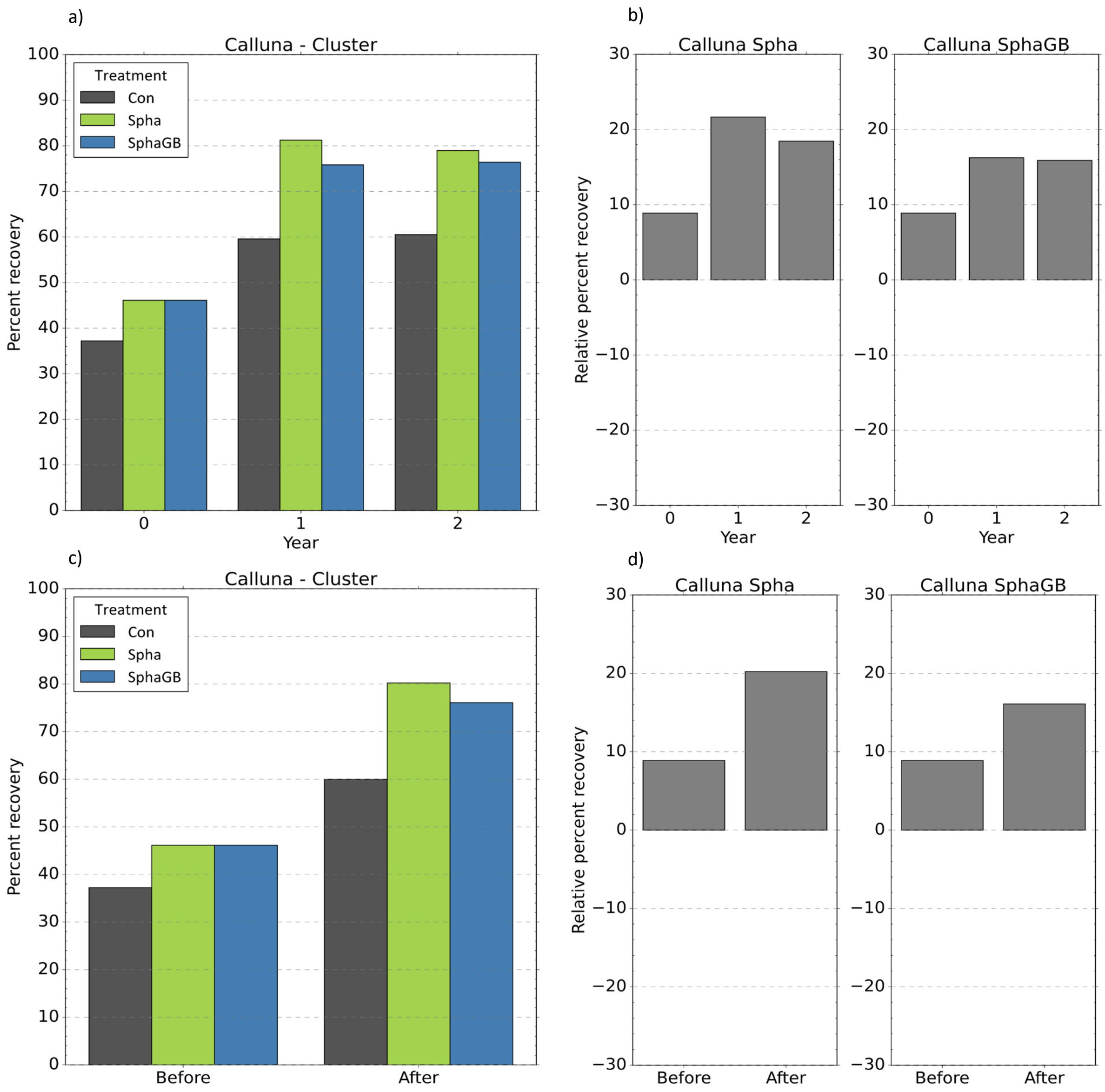


Figure 38. Crest stage tube percentage recovery at each mini-catchment cluster on *Calluna* site. Cluster crest stage tube a) percentage recovery at each treatment and b) difference between treatment and control for each year of project at the *Calluna* dominated sites. Figures c and d show the same data represented as before and after treatment.

4.2.3.2. Intensive plots

At the intensively *Sphagnum* planted plots an increase in overland flow at all treatments is observed from before to after-treatment periods (2018-09-01 to 2019-09-01 and 2019-09-01 to 2020-09-01), related to elevated rainfall and water tables in the after-treatment period as noted for the mini catchments (Table 18; Figure 39; Figure 40). Control plots had relatively high recovery percentages in the before-treatment year compared to the two treated sites (especially *Sphagnum* treated) but the subsequent increase in the after-treatment period has been greater at both treated (*Sphagnum* and *Sphagnum* and gully blocked) plots resulting in a change to less negative relative values (Table 18; Figure 40 b). It is evident from Figure 40 c that all control and *Sphagnum* gully blocked plots react in a similar way and magnitude as do plots 2 and 3 from the *Sphagnum* (Spha) treated site. Reaction at plot 1 at the *Sphagnum* treated site is more subdued and may be the reason for the lower combined percent recovery data displayed in Figure 40 a. It is noted therefore that there may be some clear systematic internal differences between this and plots 2 and 3 at the *Sphagnum* treated mini catchment.

Table 18. Intensive plot crest stage tube percentage recovery at each treatment for *Calluna* dominated sites.
Value are for before (year 0) and after (year 1) treatment. Differences between percentage recovery from treatment and control are also displayed. Recovery values here are based on presence or absence from all crest stage tubes in the 3 intensive plots. Counts are total number of crest stage data points and sums are the number of those data points with water being recorded as present.

	Treatment	Year	Sum	Count	% Recovery	Treatment - control
Calluna	Con	0	37	78	47.4	
	Con	1	56	72	77.8	
	Spha	0	13	72	18.1	-29.4
	Spha	1	42	72	58.3	-19.4
	SphaGB	0	32	78	41.0	-6.4
	SphaGB	1	57	72	79.2	1.4

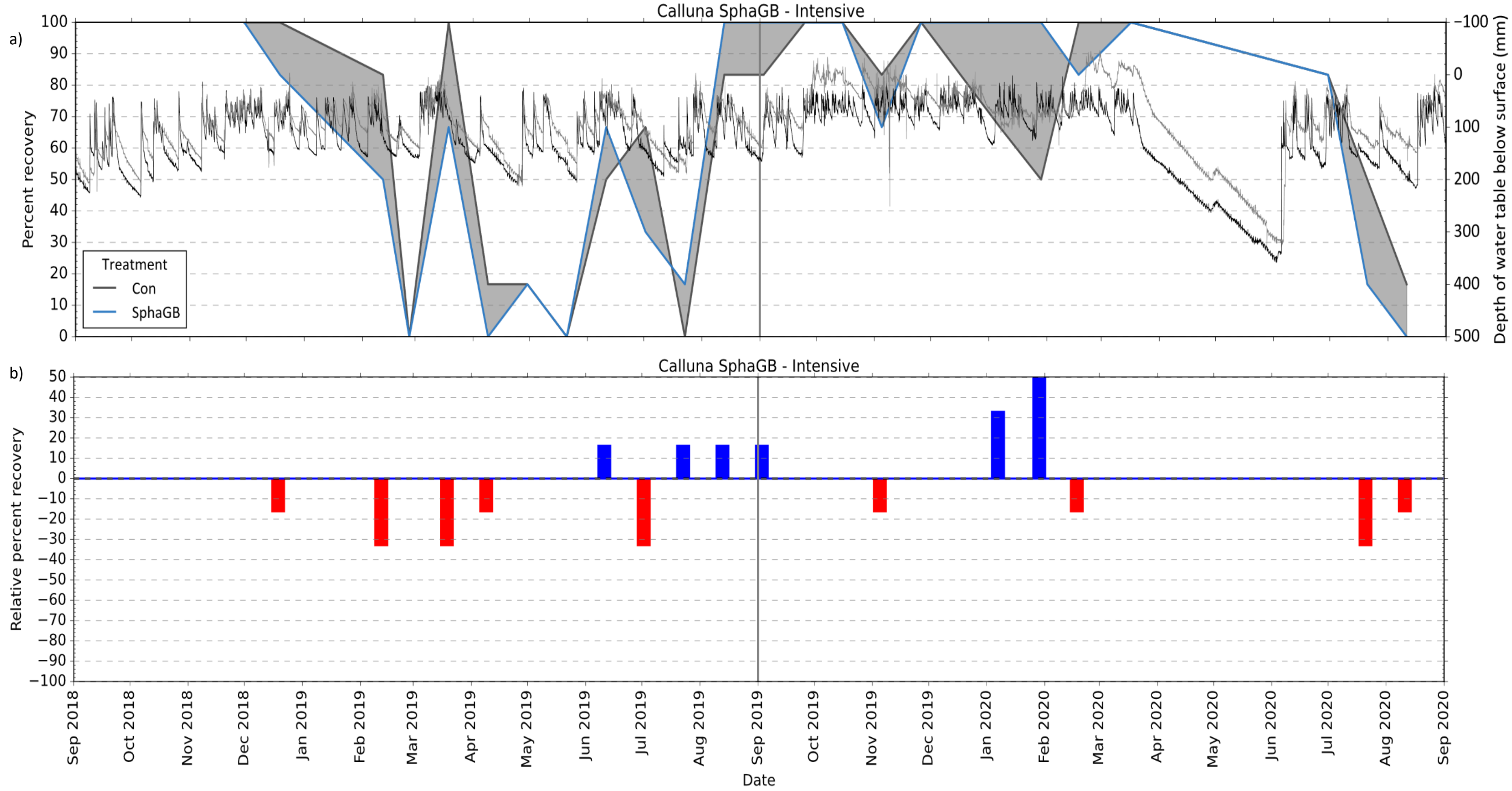


Figure 39. Time series of overland flow on *Calluna* site Con and SphaGB intensive plots.
Time series of a) percentage recovery from crest stage tubes from 'intensive' locations at *Calluna* dominated catchments. Grey shading between percentage recovery lines highlights differences between treatment (*Sphagnum* planting and gully blocking) and control. Black (Spha) and grey (Con) lines in background display continuous water table depths derived by automated sensors from '*Sphagnum*' treated and 'control' sites respectively. Treatment minus control is displayed b) for each time step with blue values indicating treatment recovery greater than control and red treatment recovery less than control.

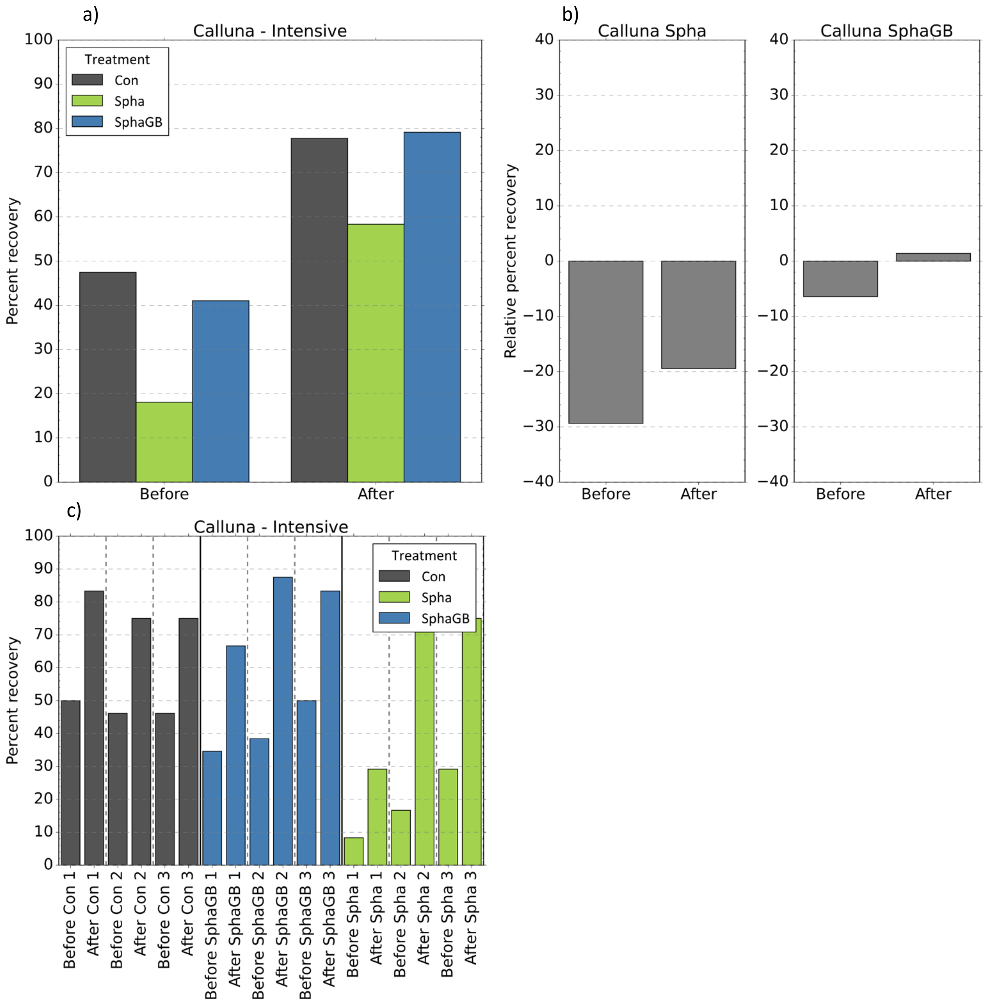


Figure 40. Crest stage tube percentage recovery at each intensive plot on *Calluna* site
Intensive plot crest stage tube a) percentage recovery at each treatment and b) the difference between treatment and control for before and after treatment time periods at the *Calluna* dominated sites. Percentage recovery at individual crest stage tube locations c) is also displayed for each treatment for before and after time periods.

4.3. *Eriophorum* dominated site

4.3.1. Manual water table

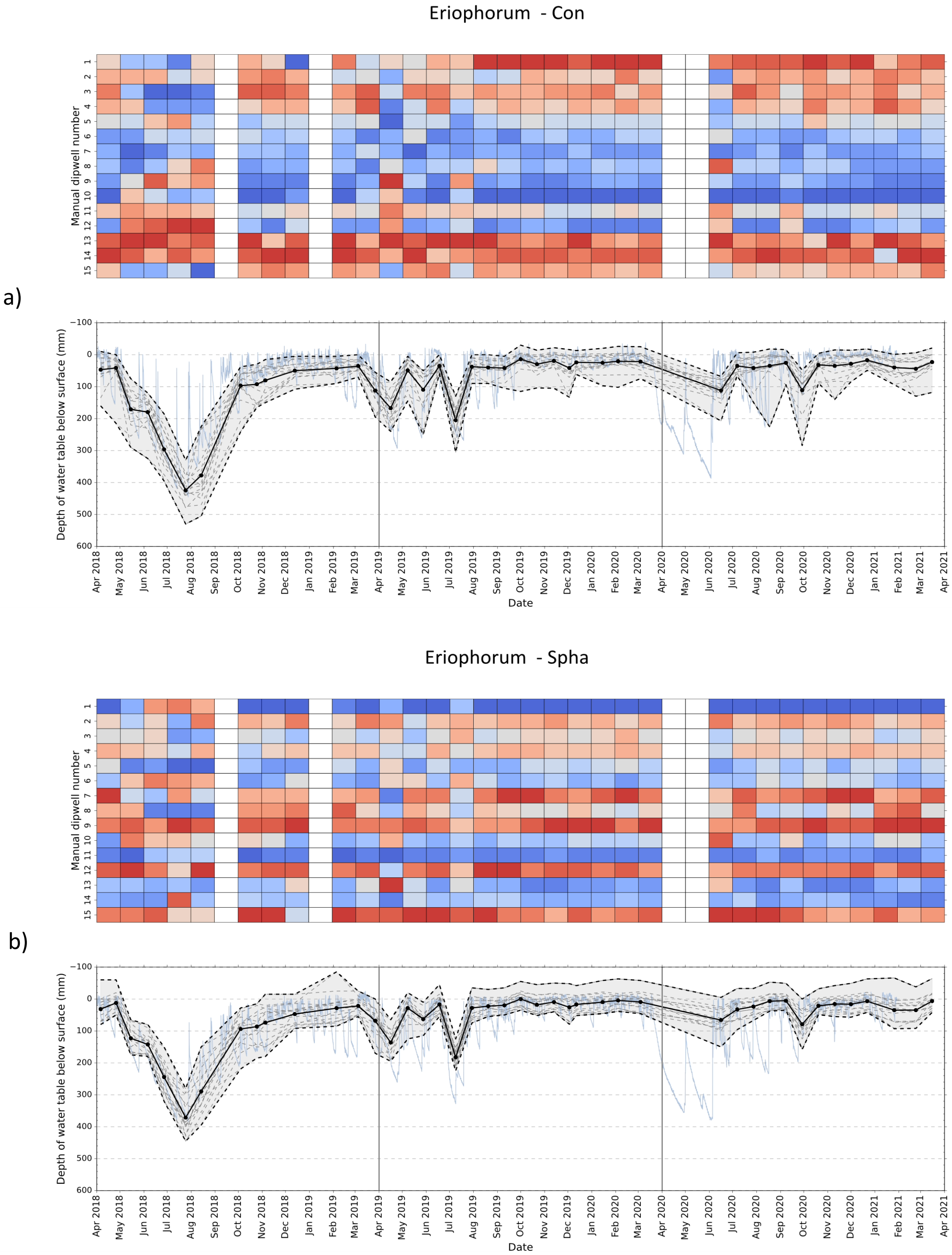


Figure 41. Time series and heat maps manual water tables in *Eriophorum* catchments

Figure 41 shows time series of manual water tables from all dipwells in both *Eriophorum* a) 'control' and b) '*Sphagnum*' treatment catchments (dashed grey lines). Mean dipwell depth from all 15 individual dipwells is displayed (black solid line) together with maximum and minimum depths (black dashed lines). Grey shading highlights the range of depths for each time step. Black vertical lines delimit the years (before and after treatment) of the study. Continuous water table records from the intensive plot sites are also displayed (blue line). Heatmaps above represent the monthly ranking of each dipwell to display inter-dipwell variation through time. Colours are from blue, shallowest water table, to red, deepest water table, for that time step.

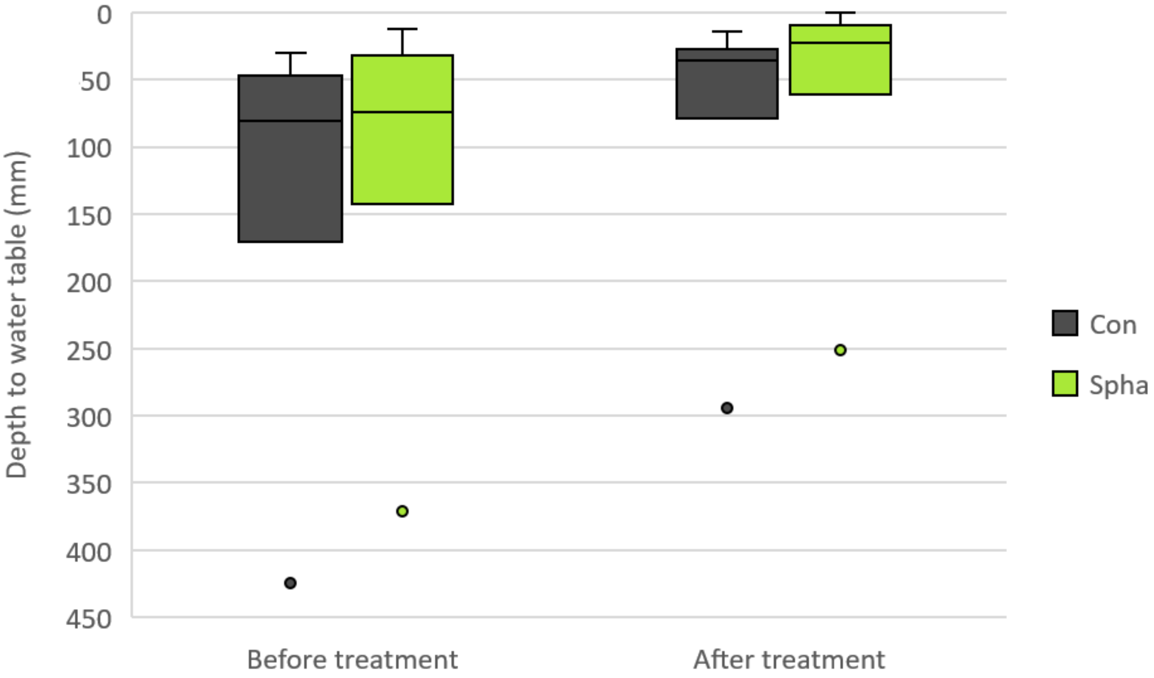


Figure 42. Boxplots of mean manually measured water table depth below surface (mm) for control and treatment catchment dipwell cluster on the *Eriophorum* site, before and after treatment.

Figure 42 shows boxplots of mean manually measured water table depth in the cluster dipwells (n = 15) before (year 0) and after (year 1 + 2) treatment in the two mini-catchments on the *Eriophorum* site allowing for a comparison of the overall changes seen in each catchment.

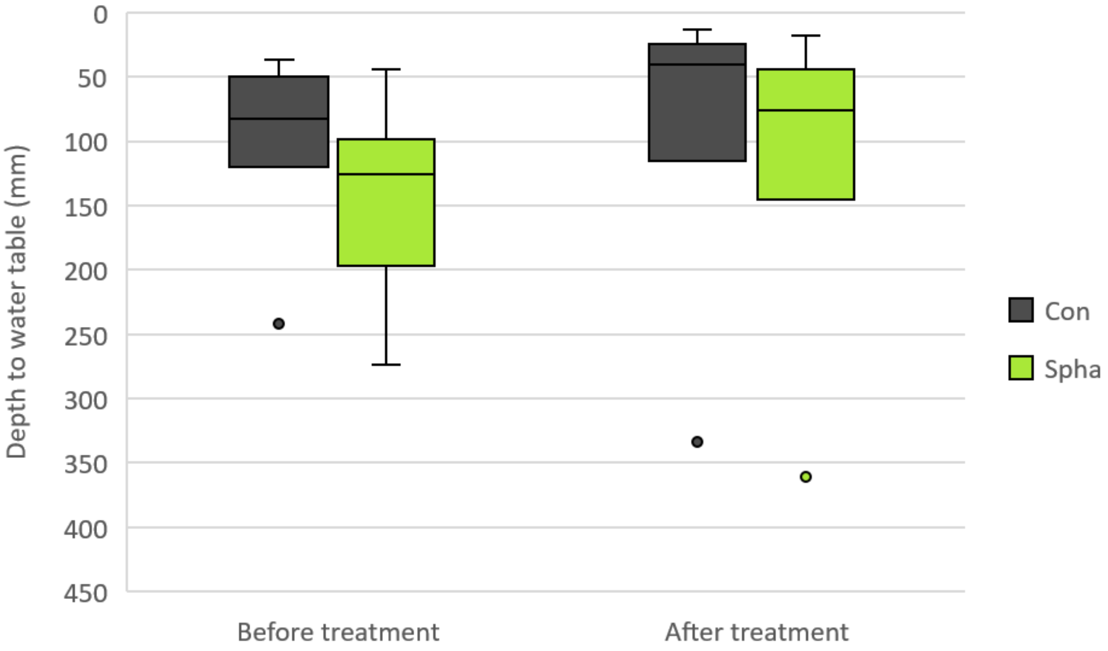


Figure 43. Boxplots of mean manually measured water table depth below surface (mm) for control and treatment intensive plot dipwells on the *Eriophorum* site, before and after treatment.

Figure 43 shows the equivalent data from the intensive plot dipwells (n = 6) before (year 0) and after (year 1) treatment.

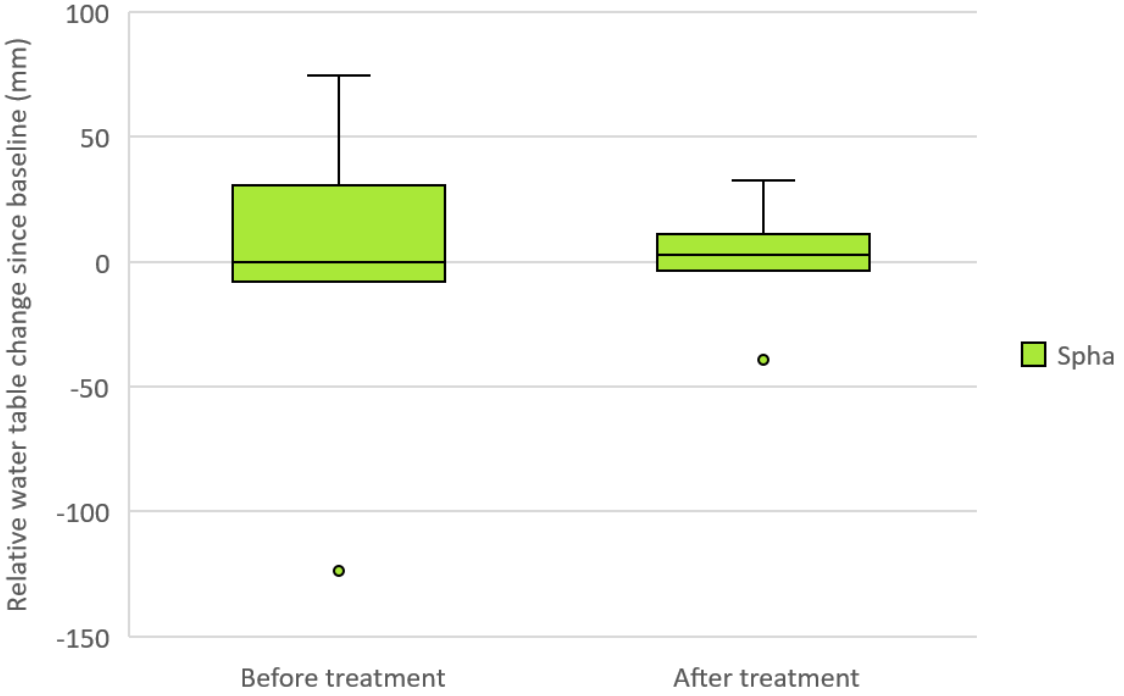


Figure 44. Boxplots of mean manually measured water table depth (mm) in treatment catchment cluster on *Eriophorum* site, relative to control (control – treatment), before and after treatment. 'Before' median value has been normalised to zero to show change since treatment.

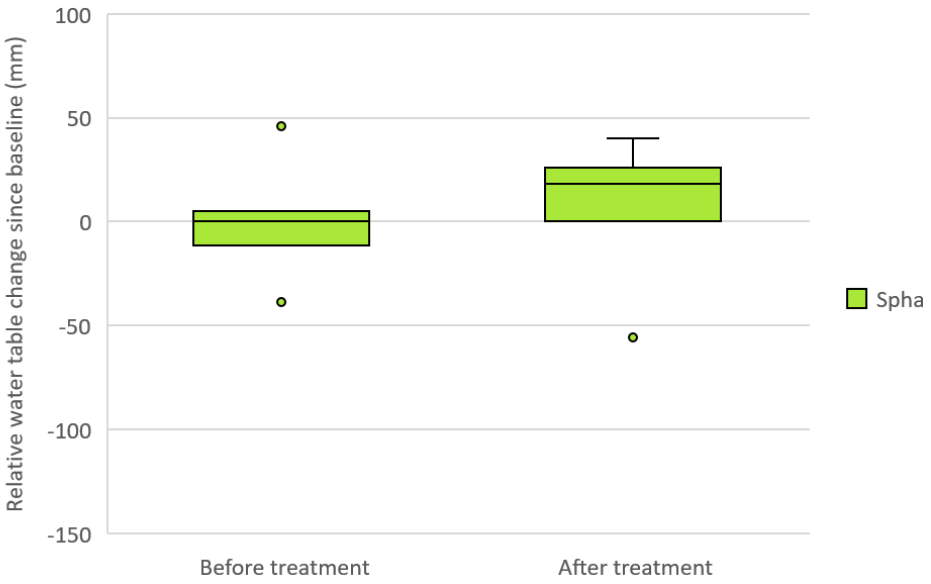


Figure 45. Boxplots of mean manually measured water table depth (mm) in treatment catchment intensive plot dipwells on *Eriophorum* site, relative to control (control – treatment), before and after treatment. Before median value has been normalised to zero to show change since treatment.

Figure 44 and Figure 45 show boxplots of the mean manually measured water table depth (relative to the control catchment) on the *Sphagnum* (Spha) treatment catchment. Relative figures were derived by subtracting treatment from control, to produce positive figures if the water table depth from surface decreases relative to control. Boxplots for the 'before' period are displayed with the median normalised to zero to allow for a simple visualisation of change over time.

Little change is evident in the treatment site cluster. However, a small rise in median relative water table of 18 mm was seen on the treatment site intensive plots, and this was found to be statistically significant (p= 0.031) using a Mann-Whitney U test. Relative differences before treatment (n = 17) had a smaller mean rank (13.82) than relative differences after treatment (n = 17; mean rank = 21.18).

Table 19. Descriptive statistics for manual water table depths at cluster before and after treatment on the *Eriophorum* site

		Control	Treatment	Difference
Before	Max	424	371	88
	Q3	171	142	44
	Median	80	74	14
	Q1	47	32	6
	Min	30	12	-110
After	Max	295	252	47
	Q3	79	61	25
	Median	35	22	17
	Q1	27	10	11
	Min	14	0	-25

Table 20. Descriptive statistics for manual water table depths in intensive plots before and after treatment on the *Eriophorum* site

		Control	Treatment	Difference
Before	Max	242	274	2
	Q3	120	197	-39
	Median	83	126	-44
	Q1	50	98	-56
	Min	37	44	-83
After	Max	334	361	-4
	Q3	116	145	-18
	Median	40	76	-26
	Q1	24	44	-44
	Min	13	18	-100

Table 19 and Table 20 show descriptive statistics for the cluster and intensive plots respectively. Table 21 shows the results of Mann-Whitney U tests to compare relative water table depths before and after-treatment. Significant differences at p <0.05 are highlighted.

Table 21. Results of Mann-Whitney U test employed to compare manual *Eriophorum* site water table depths before and after treatment.

	Spha Cluster	Spha INTS
Mann-Whitney U	293.5	82.0
P – value	0.938	0.031

4.3.2. Continuous water table

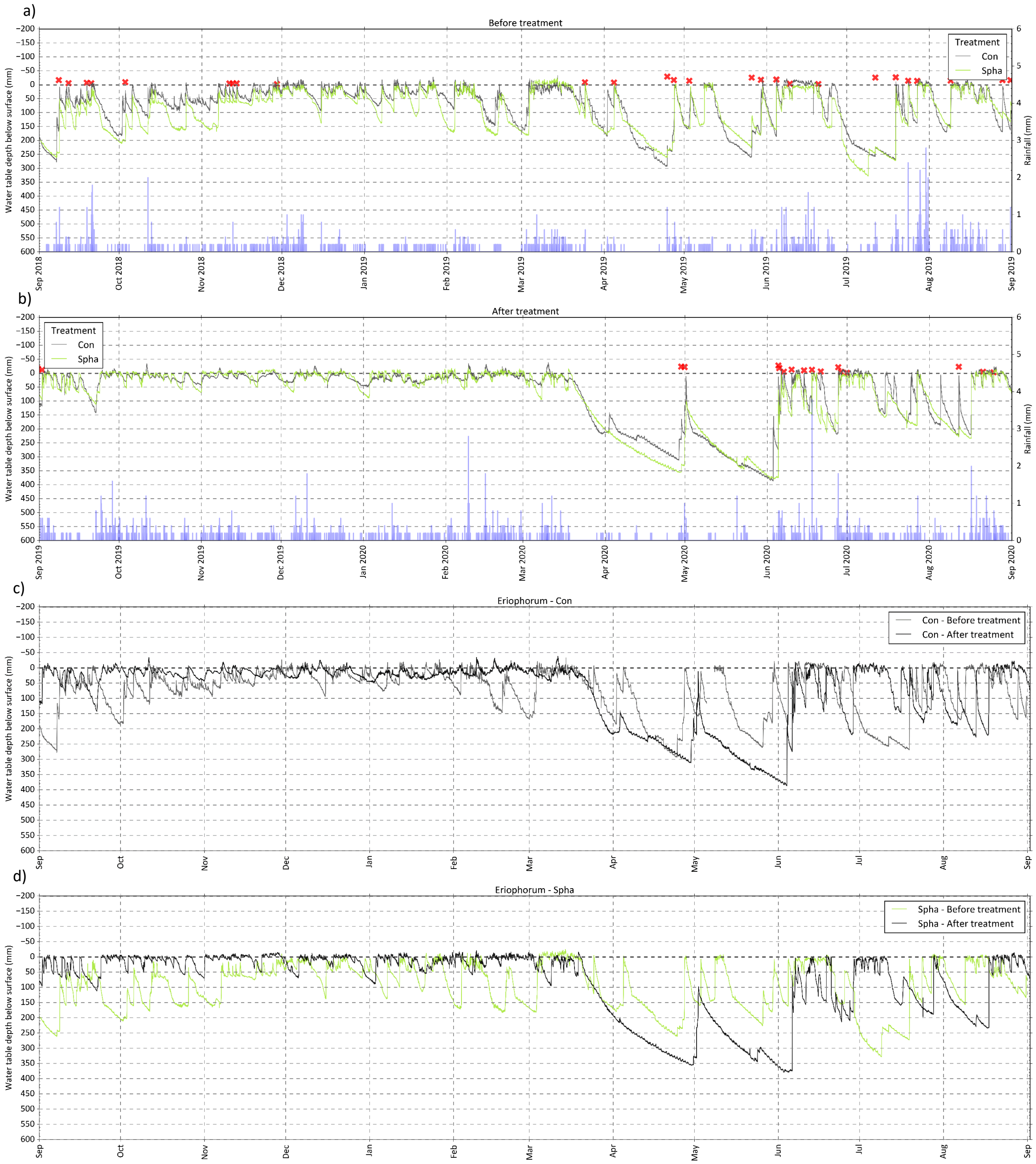


Figure 46. Full automated water table time series for *Eriophorum* species-dominated sites. Figures a–b display automated water table for each treatment for years 0 (before treatment) and 1 (after treatment) together with rainfall at 5-minute intervals. Red crosses indicate occurrences of storms used for later metric analyses. Figures c and d allow comparison of the same treatment with year 0 and 1.

Figure 46 a–d displays the full continuous water table record both before and after-treatment (*Sphagnum* plug planting) for each project year allowing comparison of general fluctuations at control and treated intensive plots. Both treatment catchments have similar ranges of water table (Figure 47 and Figure 48 (latter normalised to median of before-treatment year)). However, the median water table and interquartile range at the control mini-catchment is shallower in both before and after-treatment years. After contrasts with before-treatment years at both control and treated plots (Figure 46 c–d) with prolonged elevated water tables from October 2019 to mid-March 2020 followed by substantial drawdowns from April 2020 – June 2020. This reflects the effect of high and low rainfall totals for these months. The increase in rainfall from before to after-treatment periods is associated with rising median water table values from 52 to 24 mm and 79 to 33 mm at control and *Sphagnum* treated plot respectively.

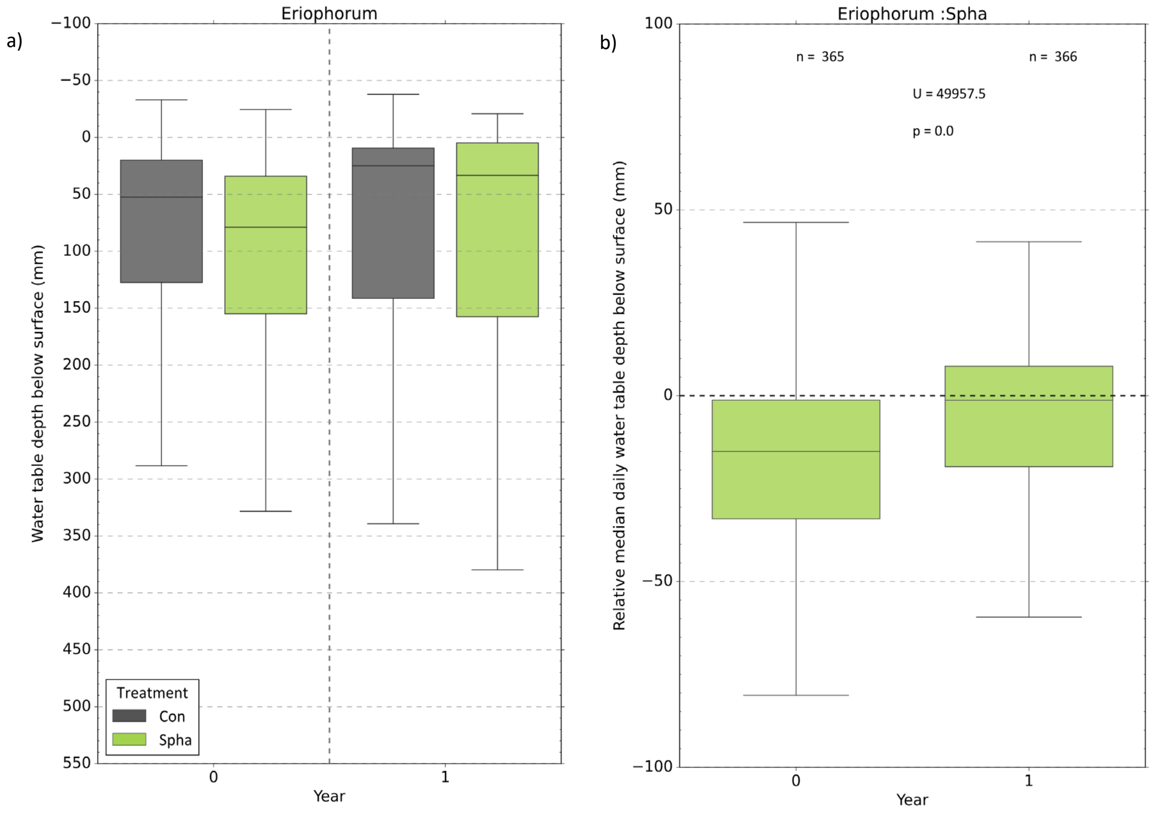


Figure 47. Boxplots of continuous water table depths before and after treatment, *Eriophorum* site. Boxplots of a) median daily water table depth below surface (mm) for each treatment and year (using 5 minutes interval data) and b) the water table depth relative to control for median daily water table depth for each year (control minus treatment for every day in year 0 and year 1) together with Mann-Whitney U statistical tests to determine significant differences. A change towards less negative values from year 0 to 1 in b indicates a reduced difference between control and treatment and vice versa.

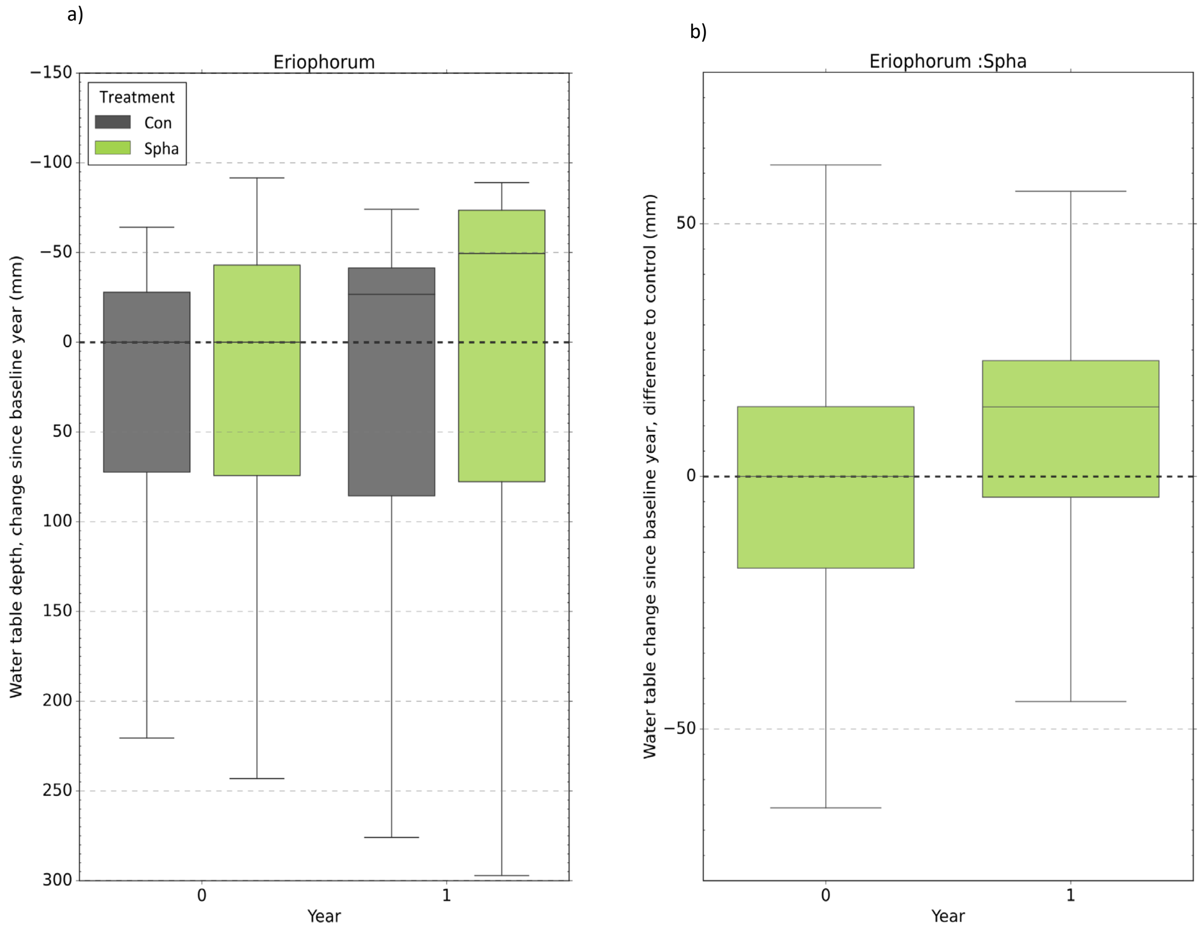


Figure 48. Boxplots of continuous water table depths standardised to zero before and after treatment, *Eriophorum* site.
Daily median water table depths standardised to year 0 median of each treatment and b) relative water table from daily median water table data standardised to year 0 median for each treatment. Change to above 0 from year 0 to 1 (more negative values) indicates a change to more elevated water tables in a. In b change to more positive values indicates the relative water table depth (control minus treatment every day) from year 0 to 1 has decreased.

Relative (control minus treatment) calculations for corresponding daily median water tables for before and after-treatment years demonstrate that after-treatment water tables at the treated plot have risen from -28.3 to -5.5 mm (Table 22b; Figure 47b). Relative values in year 0 and 1 are significantly different as determined by Mann-Whitney U tests (Figure 47b) and are also displayed with the year 0 (before) data normalised to zero (Figure 48b) where a change to a positive median relative water table of 13.8 mm is observed. Thus, indicating a small relative shallowing of water table at the treated plot.

Table 22. Descriptive statistics of continuous water table at *Eriophorum* site.
a) water table depth below surface at 5-minute intervals, b) median daily water tables for each treatment and year and c) relative water tables (control minus treatment of median daily water tables). Differences between medians statistics at control and treatment for each year are displayed in a–b and Year 1 minus Year 0 medians are displayed in c.

a)

			Water table depth below surface (mm)								
Year	Treatment	Count	Mean	Stdev	Min	LQ	Median	UQ	Max	Median difference	Rainfall sum (mm)
0	Con	104274	79.1	78.5	-33.1	19.9	52.4	127.3	293.1		1072.6
0	Spha	105120	98.8	77.4	-24.6	34.0	78.7	154.8	328.3	-26.3	1072.6
1	Con	105408	78.8	103.1	-37.9	9.3	24.8	141.3	387.1		1406.4
1	Spha	105408	88.3	110.6	-20.8	4.7	33.3	157.3	379.7	-8.5	1406.4

b)

			Water table depth below surface (mm)								
Year	Treatment	Count	Mean	Stdev	Min	LQ	Median	UQ	Max	Median difference	Rainfall sum (mm)
0	Con	363	78.9	77.2	-13.5	22.8	50.7	123.0	290.3		1072.6
0	Spha	365	98.6	76.6	-12.6	36.0	79.0	153.2	322.1	-28.3	1072.6
1	Con	366	78.3	102.9	-23.5	9.3	24.0	136.2	381.1		1406.4
1	Spha	366	87.4	110.4	-10.0	5.4	29.5	156.7	376.1	-5.5	1406.4

c)

			Relative water tables based on daily median values (mm)								
Treatment	Year	Count	Mean	Stdev	Min	LQ	Median	UQ	Max	Year 1 - Year 0 (median)	Rainfall sum (mm)
Spha	0	363	-19.5	34.2	-165.9	-33.2	-15.0	-1.2	54.9		1072.6
Spha	1	366	-9.1	29.3	-146.7	-19.1	-1.2	7.9	41.4	13.8	1406.4

Seasonal contrasts between water table at control and treated plots are most evident in spring and autumn in the before-treatment year and in summer in the after-treatment year. Distributions of relative values are significantly different for all seasons from year 0 to 1 except for summer with autumn exhibiting a substantial reduction as control and treatment catchments display similar water table activity in contrast to the before-treatment year (Figure 49a). Water table levels have a finite ceiling (the surface) and therefore the more elevated water tables at the control lack the potential to demonstrate a substantial rise to a given rainfall input.

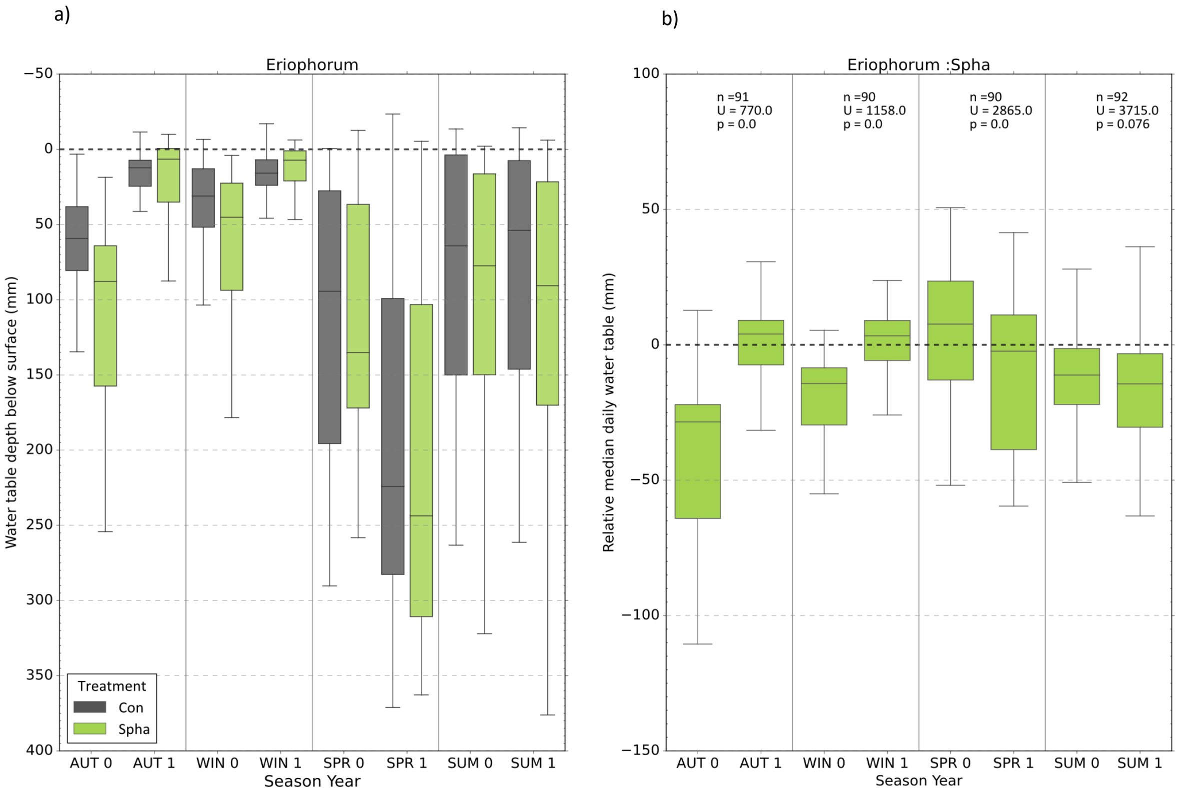


Figure 49. Boxplots of seasonal water tables on *Eriophorum* site.
a) Boxplots of seasonal water tables based on daily median values for each treatment and year and b) differences between control and treatment together with Mann-Whitney U statistical tests to determine significant differences.

Water residence curves (Figure 50) allow examination of the water table depth duration. Below 200 mm and above 50 mm, both control and treatment are similar. From 160 to 10 mm depth below surface the records diverge in the before-treatment year as the percentage of time water table is above these depths is substantially higher at the control site. In the after-treatment year, the water table residence curves coalesce as both demonstrate higher residence percentages above more elevated water table positions, as shown in Table 23.

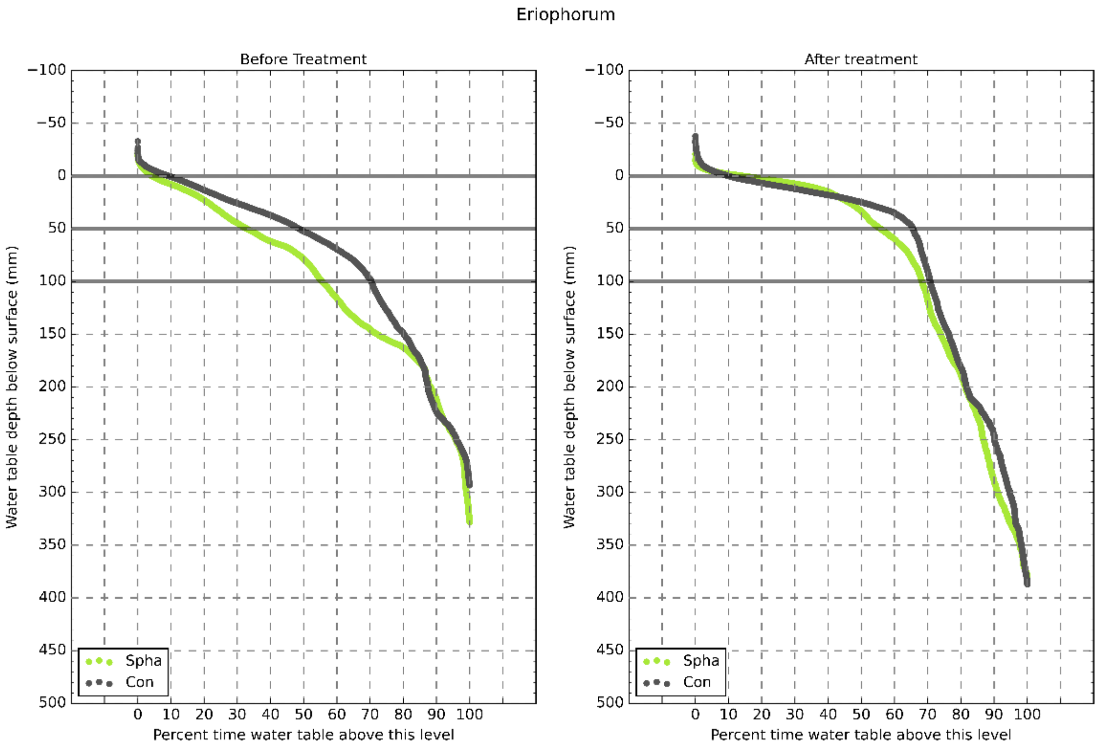


Figure 50. Water table residence time curves for *Eriophorum* site.
Residence time curves for each dipwell based on 5-minute sampling intervals. Curves display the percentage of time a water table exists above a certain water table level.

Table 23. Water table residence time descriptive statistics for *Eriophorum* site.
Percentage of time water table above and below 0 (surface), 50 and 100 mm depths for each year and treatment. Differences between treatments for each year are also displayed.

		Percent of time above water table level			Percent of time below water table level		
Water table depth (mm)	Year	Con	Spha	Relative	Con	Spha	Relative
0	0	10.105	4.390	5.714	89.895	95.610	-5.714
	1	10.069	14.607	-4.538	89.931	85.393	4.538
50	0	49.101	32.934	16.167	50.899	67.066	-16.167
	1	65.550	55.833	9.717	34.450	44.167	-9.717
100	0	70.594	55.497	15.097	29.406	44.503	-15.097
	1	70.760	68.268	2.492	29.240	31.732	-2.492

Percentage of time above 0, 50 and 100 mm (high water table points indicative of a healthy bog hydrological system) increases at both control and treatment plots. Relative residence percentages above these depths (control minus treatment) become less positive indicating the coalescence of both records. Relative residence percentage above 0 mm is negative in the after-treatment year suggesting longer periods of water table elevation above this level at the treated plot. The control plot has remained static at this depth (~10 %, Table 23) whereas the treatment plot has shifted from ~ 4 to ~15% suggesting an effect at the treatment site due to *Sphagnum* planting where the physical constituents of the peat have been altered.

Reaction to storm events (events are highlighted by red crosses in Figure 46) from both control and treatment plots have been analysed. In order to be considered, storm events were selected which met criteria listed in methods section 3.2.2. of this chapter. The different climate conditions experienced in before and after-treatment years mean that storms were not necessarily equally distributed across seasons. For example, there are no storms examined in the after-treatment year from October 2019 to April 2020 and the number examined in the after-treatment year (n = 17) is less than in the before-treatment period (n = 25). These storms are all paired events between treatments allowing direct examination of differences between rainfall and water table interactions from control and treated plots.

Relative (control minus treatment) temporal lags from the start and peak of rainfall events to the initiation and peak of rising water tables are displayed in Figure 51 a – b. From before to after-treatment year there is no significant change in median relative lag time of either peak or start lag metrics (Table 24 b). Interquartile ranges appear to increase for peak lag and decrease for start lag however, suggesting more instances of longer reaction times for peak lag at the treatment plot in the after-treatment year and less instances of extremes in reaction times for start lag relative to the control. The distributions however are not significantly different (Mann-Whitney U, see Figure 51 a–b).

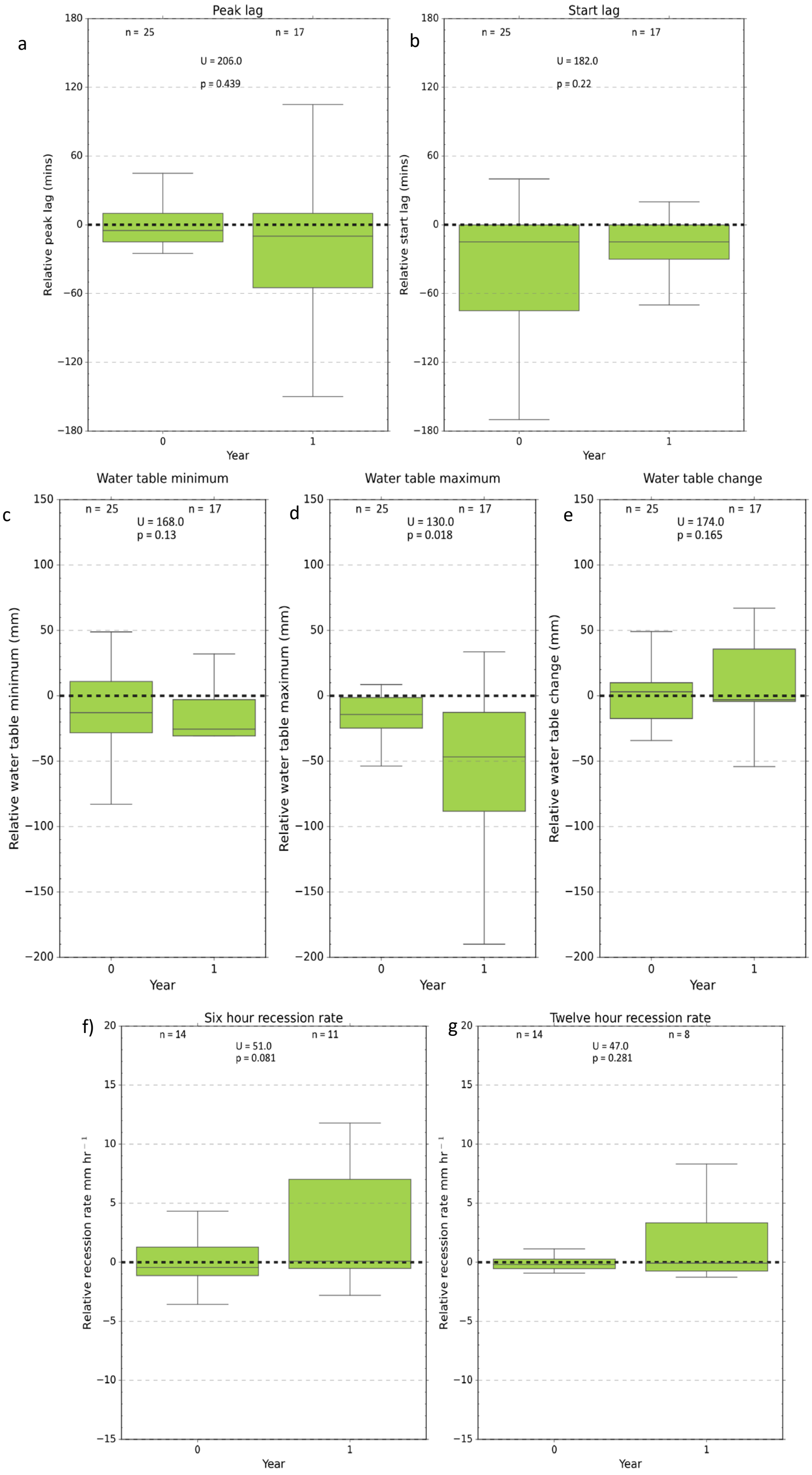


Figure 51. Relative metrics for water table storm responses, *Eriophorum* site
Relative metrics for selected storms (see methods) including time lags between rainfall and a) peak in water table (shallowing) and b) initial response peak response. Figures c – e display the relative difference for each year between firstly the initial water table levels at the start of a storm (c), secondly the most elevated water table achieved (d) and thirdly the change in water table during the storm. Figures f and g show the relative difference between control and treatments for each year for the rate of water table recession post storm after 6 and 12 hours. All derived from 5-minute interval data

Table 24. Descriptive statistics for water table storm responses, *Eriophorum* site.
a) Median start and peak lags between rainfall and water table and median minimum, maximum and changes in water table and recession rates for selected storm events for each year, for control and Sphagnum treatments. b) Median of relative (control minus treatment) metrics for all storms for pre and post treatment years. Count values refer to number of storm events used for each metric. For recession rates, counts in brackets refer to number of storm events used for 12-hour rates.

a)

			Median lags (mins)		Median water table (mm)				Median recession rates (mm hr^{-1})	
Treatment	Year	Count	Event start lag	Event peak lag	minimum	maximum	change	Count	Six hour	Twelve hour
Con	0	25	20	80	136.9	3.1	79.4	14	3.25	2.38
Spha	0	25	105	70	145.7	17.6	91.4	14	3.26	2.70
Con	1	17	25	70	120.4	-0.6	96.3	11 (8)	3.20	2.58
Spha	1	17	35	85	148.8	60.5	66.6	11 (8)	2.15	1.45

b)

		Median lags (mins)		Median water table (mm)				Median recession rates (mm hr^{-1})	
Year	Count	Event start lag	Event peak lag	minimum	maximum	change	Count	Six hour	Twelve hour
0	25	-15	-5	-12.9	-14.3	3.1	14	-0.45	-0.18
1	17	-15	-10	-25.4	-46.7	-3.1	11 (8)	0.08	-0.08

Relative (control minus treatment) water table minimum (value at start of event) and change (difference between value at start and peak of event) show no significant difference between before and after-treatment years with similar relative median values (Table 24 b; Figure 51 c–e). Relative water table maximum (value at peak of event, shallowest water table) does however show a significant albeit small relative change (from -14.3 to -46.7 mm) from before to after-treatment years as the treatment plot has marginally deeper water tables at the peak of the storm relative to the control. This may seem to be at odds with the evidence of the residence time curves (Figure 50) suggesting longer periods with water tables above the surface at the treated plot in the after-treatment year compared to the control. However, here a restricted subsection of storm events is examined that is not representative of the entire record. These storms are largely from summer and autumn periods and effectively capture relative changes within these seasons.

Rates of water table recession 6 and 12 hours after the peak in water table height are displayed in Table 24 a. Rates are relatively similar between treatments and years. Relative changes Table 24 a; Figure 51 f–e) in terms of median values also show little change from before to after-treatment years. The distribution of relative differences for each storm is wider and more positive in the after-treatment year for both 6- and 12-hour rates. This suggests the upper quartile of values are displaying slower rates at the treatment compared to the control. Mann-Whitney U tests (Figure 51 f–e) however suggest the distributions are not significantly different.

4.3.3. Overland flow generation

4.3.3.1. Cluster area

In both control and treated mini catchments from before-treatment year there has been successive increases in percentage recovery and therefore overland flow (Table 25; Figure 52 and Figure 53 a). The increase is greatest from before-treatment to the first after-treatment year with increases from 50.3 to 88.4% and 61.5 to 88.4% for control and *Sphagnum* planted mini catchments respectively. Examination of time series (Figure 52 a) reveals this rise is associated with more prolonged periods of elevated water table. The before-treatment year is associated with low water tables from the dry late-spring and summer of 2018. The relationship between control and treated mini catchment overland flow is also considered as 'before' and 'after' treatment (Table 25; Figure 53 c–d).

Table 25. Cluster crest stage tube percentage recovery at each treatment for *Eriophorum* dominated sites. Values are displayed for each treatment and each year of project as well as before and after treatment (after being a consolidation of years 1 and 2). Differences between percentage recovery from treatment and control are also displayed. Recovery values here are based on presence or absence from all 15 crest stage tubes in each catchment from each years / periods data. Counts are total number of crest stage data points and sums are the number of those data points with water being recorded as present.

		Treatment	Year	Sum	Count	% Recovery	Treatment - control
Eriophorum	All years	Con	0	98	195	50.3	
		Con	1	199	225	88.4	
		Con	2	186	195	95.4	
		Spha	0	120	195	61.5	11.3
		Spha	1	199	225	88.4	0.0
		Spha	2	191	195	97.9	2.6
	Before / after	Con	Before	98	195	50.3	
		Con	After	385	420	91.7	
		Spha	Before	120	195	61.5	11.3
		Spha	After	390	420	92.9	1.2

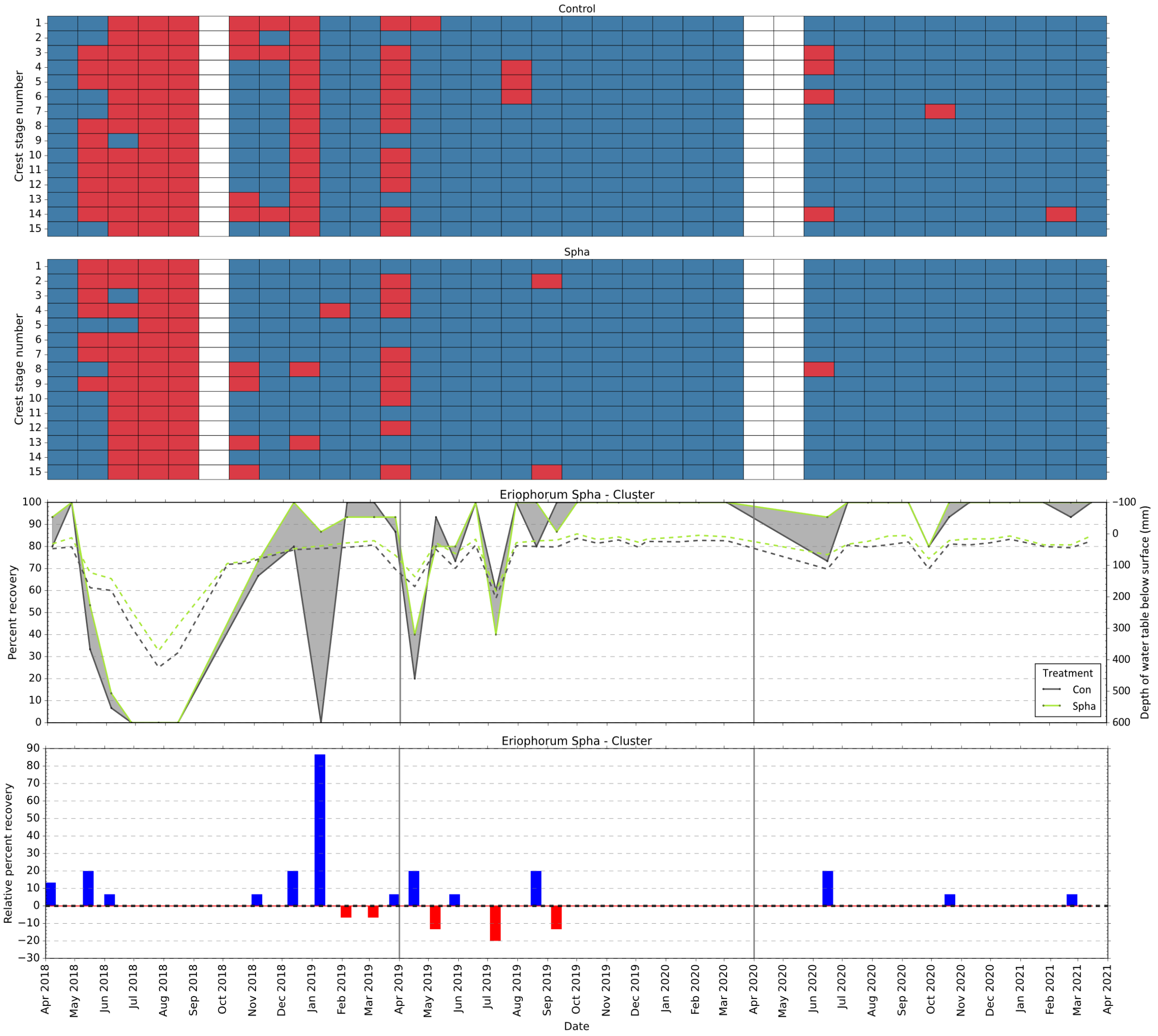


Figure 52. Time series of overland flow on *Eriophorum* site Con and Spha catchments.
Time series of a) percentage recovery from crest stage tubes from cluster locations at *Eriophorum* dominated catchments. Dotted lines show a combined mean water table level in these catchments from the 15 dipwells. Grey shading between percentage recovery lines highlights differences between treatment and control. Treatment minus control is displayed b) for each time step with blue values indicating treatment recovery greater than control and red treatment recovery less than control. The uppermost two figures give monthly presence (blue) or absence (red) values for water in each individual crest stage tube for each treatment.

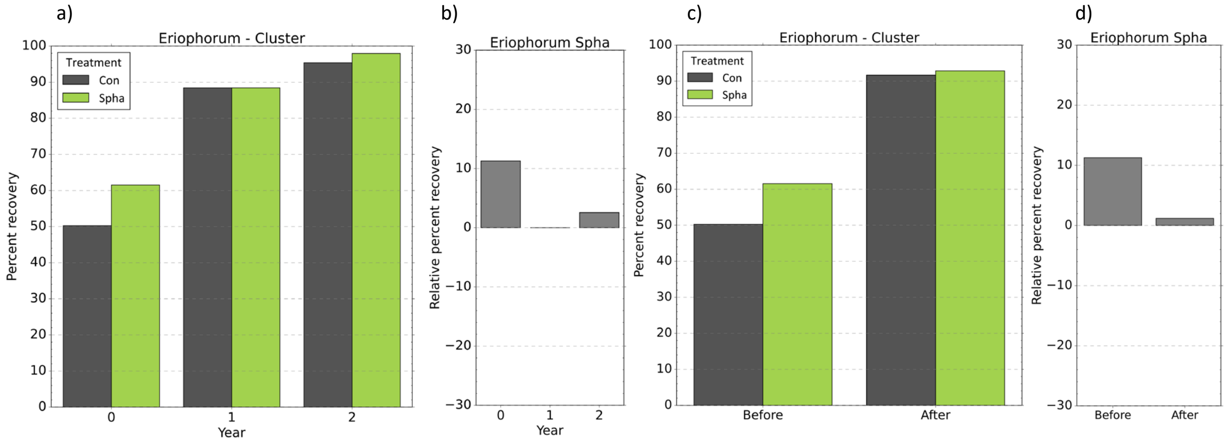


Figure 53. Crest stage tube percentage recovery at each mini-catchment cluster on *Eriophorum* site. Cluster crest stage tube a) percentage recovery at each treatment and b) difference between treatment and control for each year of project at the *Eriophorum* dominated sites. Figures c and d show the same data represented as before and after treatment.

Although change has largely been the same between control and treatment the relative difference (treatment minus control), has reduced in the after-treatment period. This suggests that the treatment has had a relative reduction in overland flow from before to after periods compared to the control. Internal variation of recovery from crest stage tubes within treatment has remained relatively consistent (Figure 52 heat maps) with no clear bias from individual or groups of crest stage tubes, thus providing a robust summary.

4.3.3.2. Intensive plots

Table 26. Crest stage tube percentage recovery from intensive plots at each treatment for *Eriophorum* dominated sites.
Values are for before (year 0) and after (year 1) treatment. Differences between percentage recovery from treatment and control are also displayed. Recovery values here are based on presence or absence from all crest stage tubes in the 3 intensive plots Counts are total number of crest stage data points and sums are the number of those data points with water being recorded as present.

	Treatment	Year	Sum	Count	% Recovery	Treatment - control
Eriophorum	Con	0	61	79	77.2	
	Con	1	70	72	97.2	
	Spha	0	57	78	73.1	-4.1
	Spha	1	68	72	94.4	-2.8

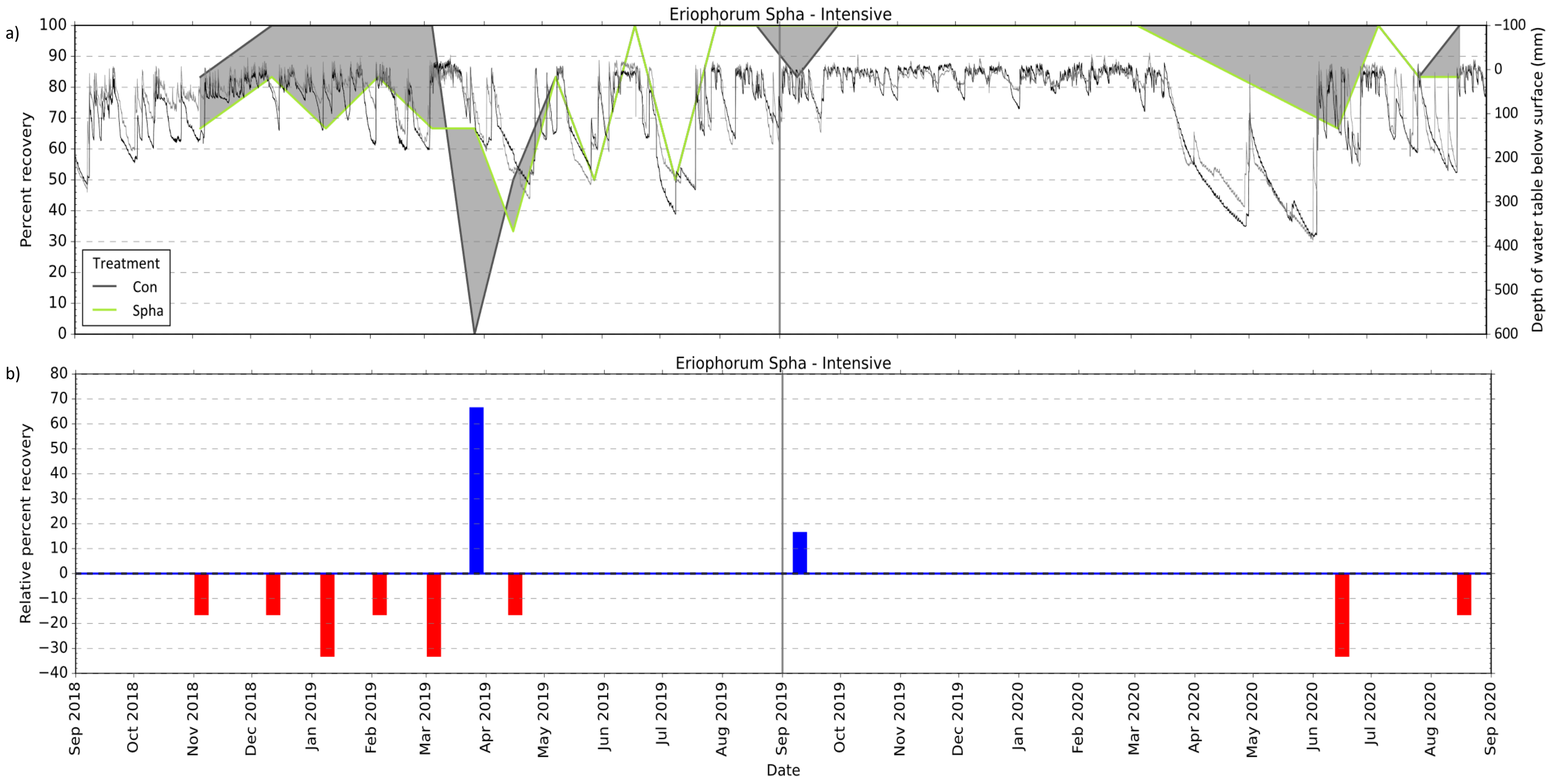


Figure 54. Time series of overland flow on *Eriophorum* site Con and Spha intensive plots.
Time series of a) percentage recovery from crest stage tubes from 'intensive' locations at *Eriophorum* dominated catchments. Grey shading between percentage recovery lines highlights differences between treatment and control. Black (Spha) and grey (Con) lines in background display continuous water table depths derived by automated sensors from *'Sphagnum'* treated and 'control' sites respectively. Treatment minus control is displayed b) for each time step with blue values indicating treatment recovery greater than control and red treatment recovery less than control.

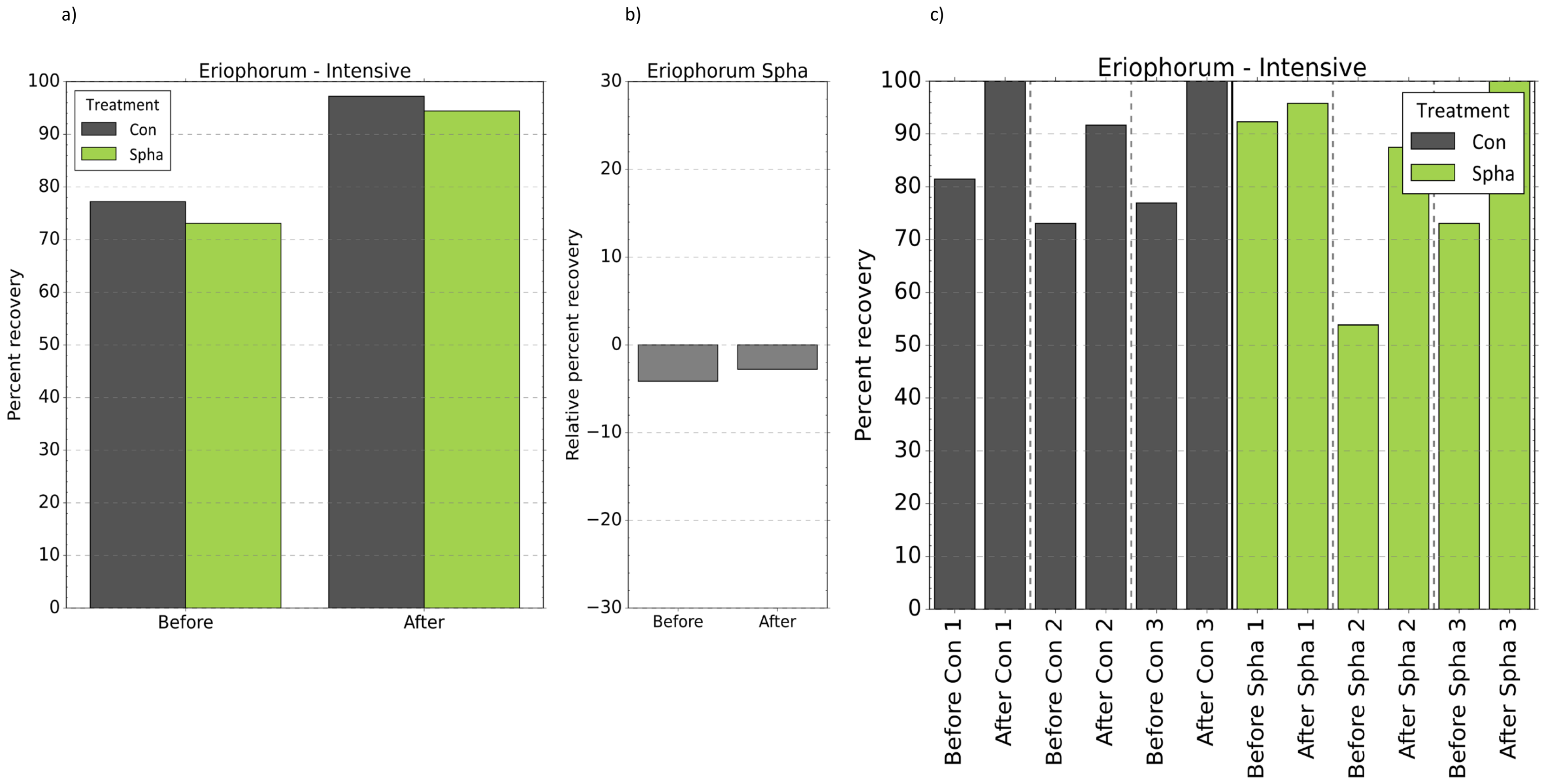


Figure 55. Crest stage tube percentage recovery at each intensive plot on *Eriophorum* site.
Intensive plot crest stage tube a) percentage recovery at each treatment and b) the difference between treatment and control for before and after treatment time periods at the Eriophorum dominated sites. Percentage recovery at individual crest stage tube locations c) is also displayed for each treatment for before and after time periods.

Table 27. Crest stage tube percentage recovery from intensive plots at *Eriophorum* sites. Data can be used to examine internal variation within each treatment state to determine any spatial bias.

	Treatment	Plot	Year	Sum	Count	% Recovery
Eriophorum	Con	Con 1	0	22	27	81.5
	Con	Con 1	1	24	24	100.0
	Con	Con 2	0	19	26	73.1
	Con	Con 2	1	22	24	91.7
	Con	Con 3	0	20	26	76.9
	Con	Con 3	1	24	24	100.0
	Spha	Spha 1	0	24	26	92.3
	Spha	Spha 1	1	23	24	95.8
	Spha	Spha 2	0	14	26	53.8
	Spha	Spha 2	1	21	24	87.5
	Spha	Spha 3	0	19	26	73.1
	Spha	Spha 3	1	24	24	100.0

Overland flow before and after-treatment from intensive plots show a similar response to that of the cluster derived data (Table 26; Figure 54 and Figure 55). From before to after treatment years an increase of c. 20% to greater overland flow at both control and *Sphagnum* treatments is evident (Table 26; Figure 55 a–b) and is related to more prolonged periods of more elevated water tables. Relative change at the treatment location from -4.1 to -2.8 reflects a relative increase of overland flow compared to the control although this is only minor. Recovery from each of the individual 3 m^2 plots in each treatment and year is displayed (Table 27; Figure 55 c) so any in treatment plot bias can be detected. From the 3 treated plots plot 2 shows a substantially higher increase in recovery from before to after treatment years. Despite this, the trend is comparable within all treatment plots thus providing a robust summary.

4.4. *Molinia* dominated site

4.4.1. Manual water table

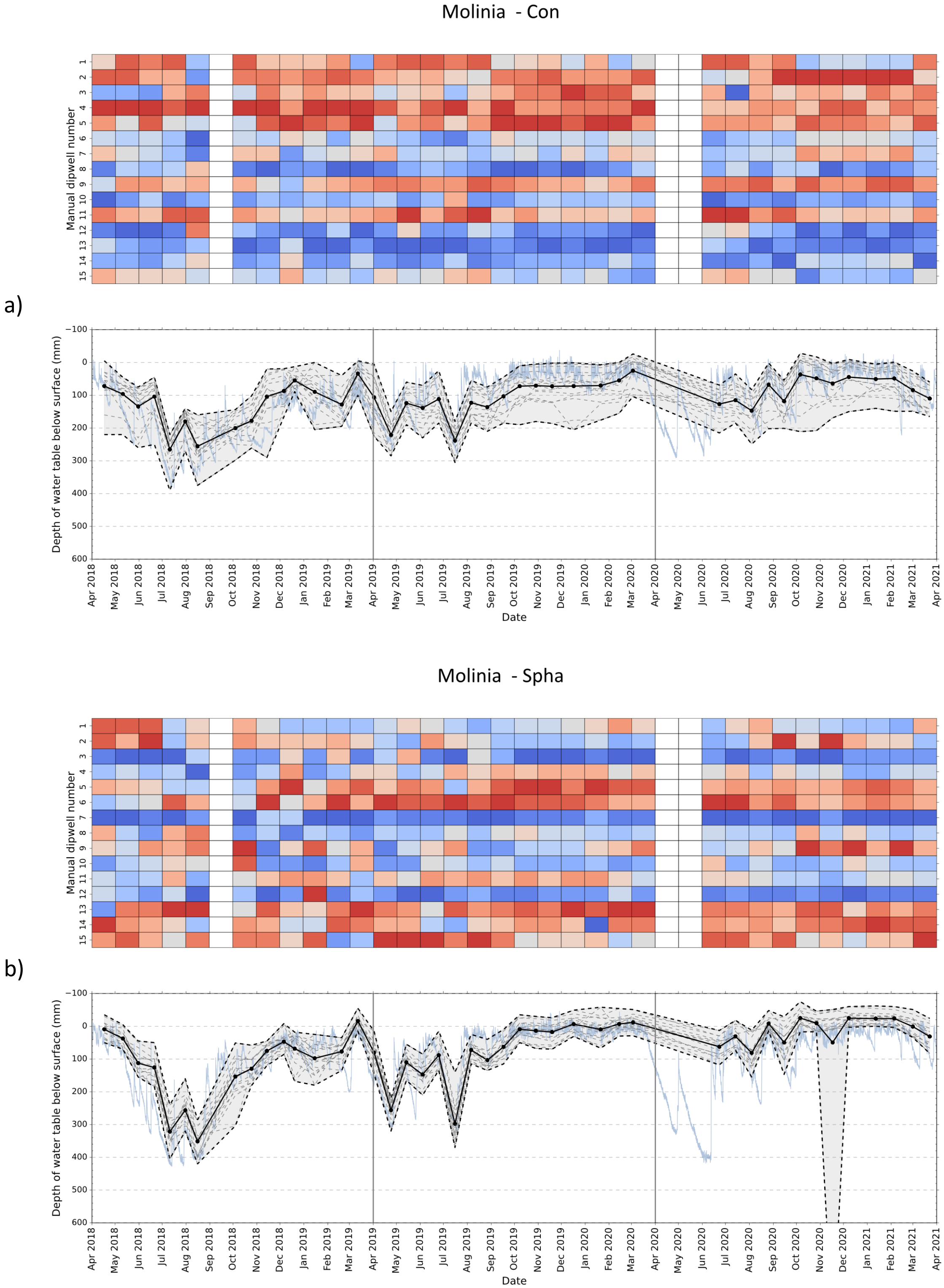


Figure 56. Time series and heat maps of manual water tables in *Molinia* catchments.

Figure 56 shows time series of manual water tables from all dipwells in both *Molinia* a) control and b) *Sphagnum* treatment catchments (dashed grey lines). Mean dipwell depth from all 15 individual dipwells is displayed (black solid line) together with maximum and minimum depths (black dashed lines). Black vertical lines delimit the years (before and after treatment) of the study. Grey shading highlights the range of depths for each time step. Continuous water table records from the intensive plot sites are also displayed (blue line). Heatmaps above represent the monthly ranking of each dipwell to display inter-dipwell variation through time. Colours are from blue, shallowest water table, to red, deepest water table, for that time step.

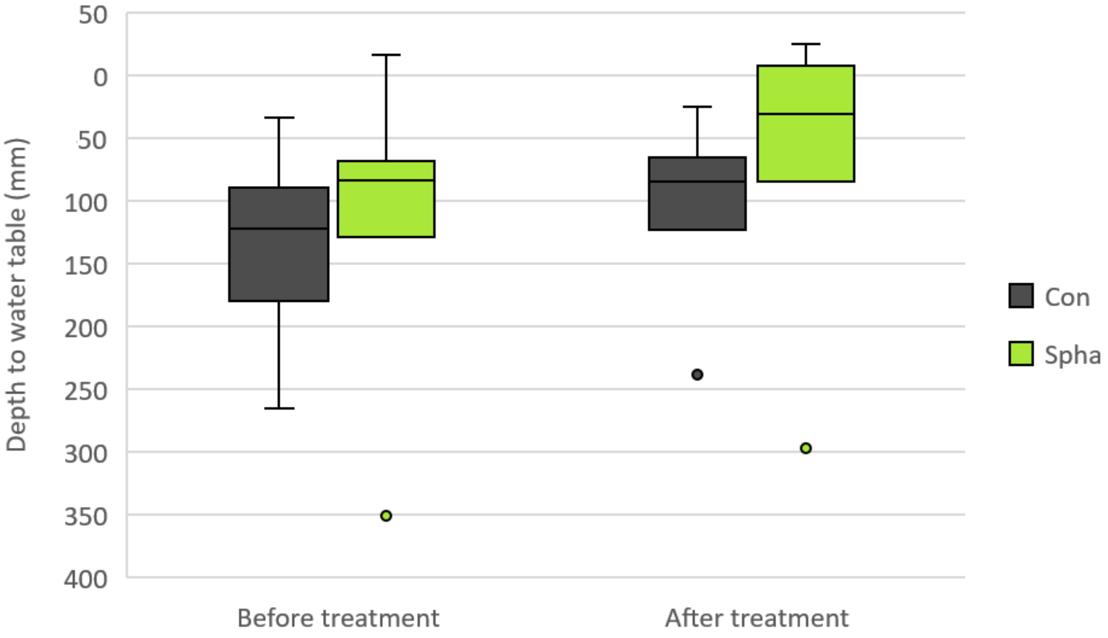


Figure 57. Boxplots of mean manually measured water table depth below surface (mm) for control and treatment catchment dipwell cluster on the *Molinia* site, before and after treatment.

Figure 57 shows boxplots of mean manually measured water table depth in the cluster dipwells (n = 15) before (year 0) and after (year 1 + 2) treatment in the two mini-catchments on the *Molinia* site allowing for a comparison of the overall changes seen in each catchment.

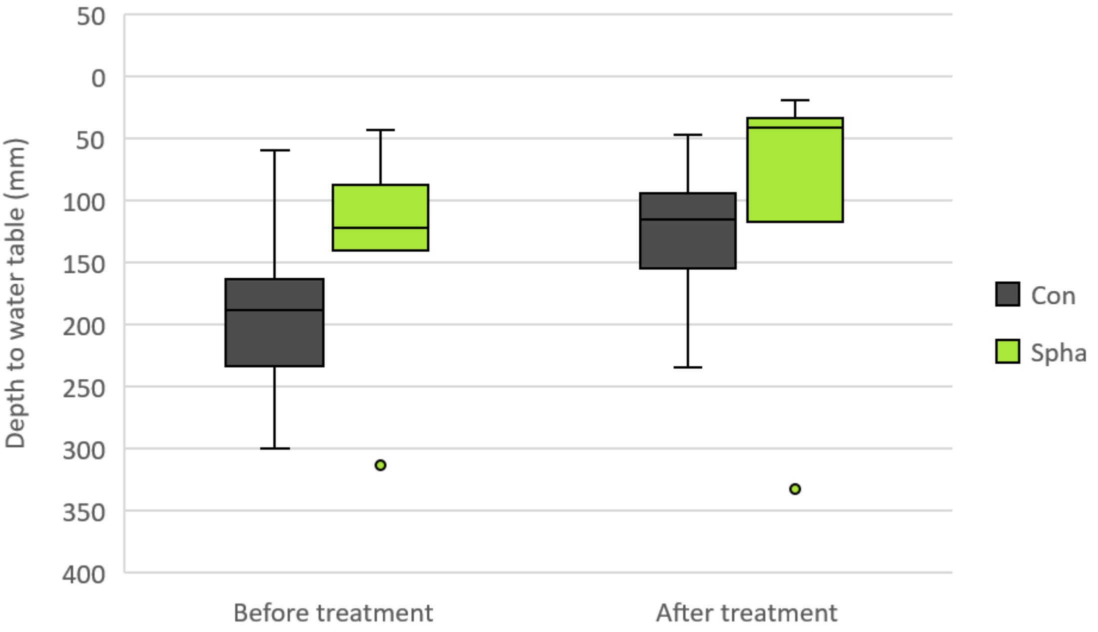


Figure 58. Boxplots of mean manually measured water table depth below surface (mm) for control and treatment intensive plot dipwells on the *Molinia* site, before and after treatment.

Figure 58 shows the equivalent data from the intensive plot dipwells (n = 6) before (year 0) and after (year 1) treatment.

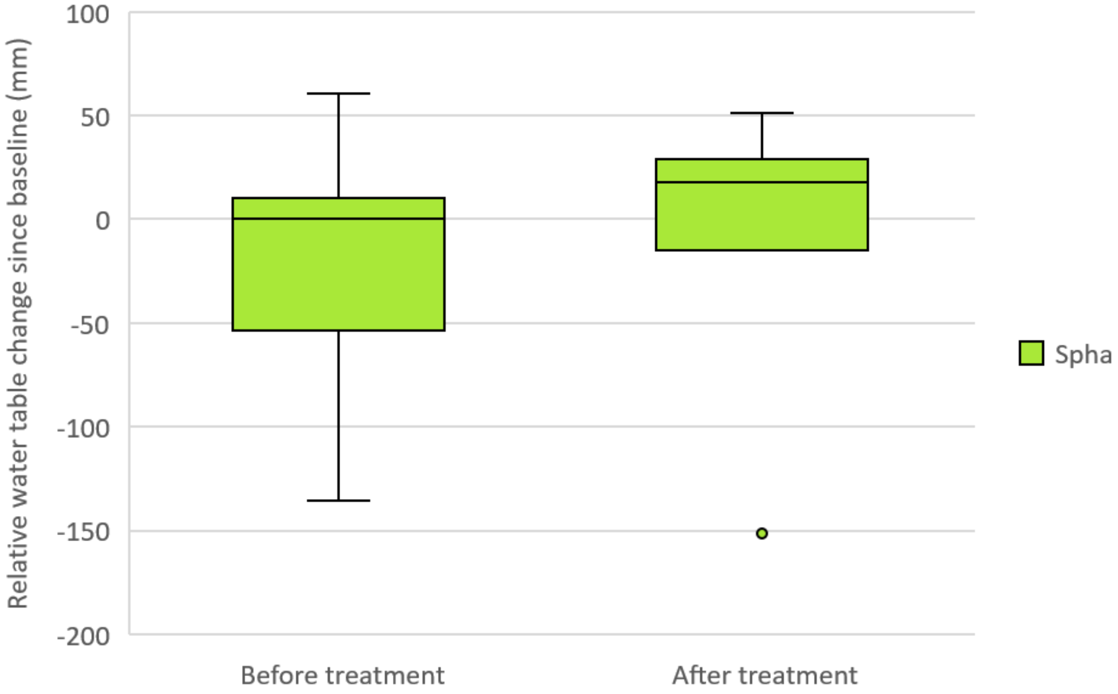


Figure 59. Boxplots of mean manually measured water table depth (mm) in treatment catchment cluster on *Molinia* site, relative to control (control – treatment), before and after treatment. 'Before' median value has been normalised to zero to show change since treatment.

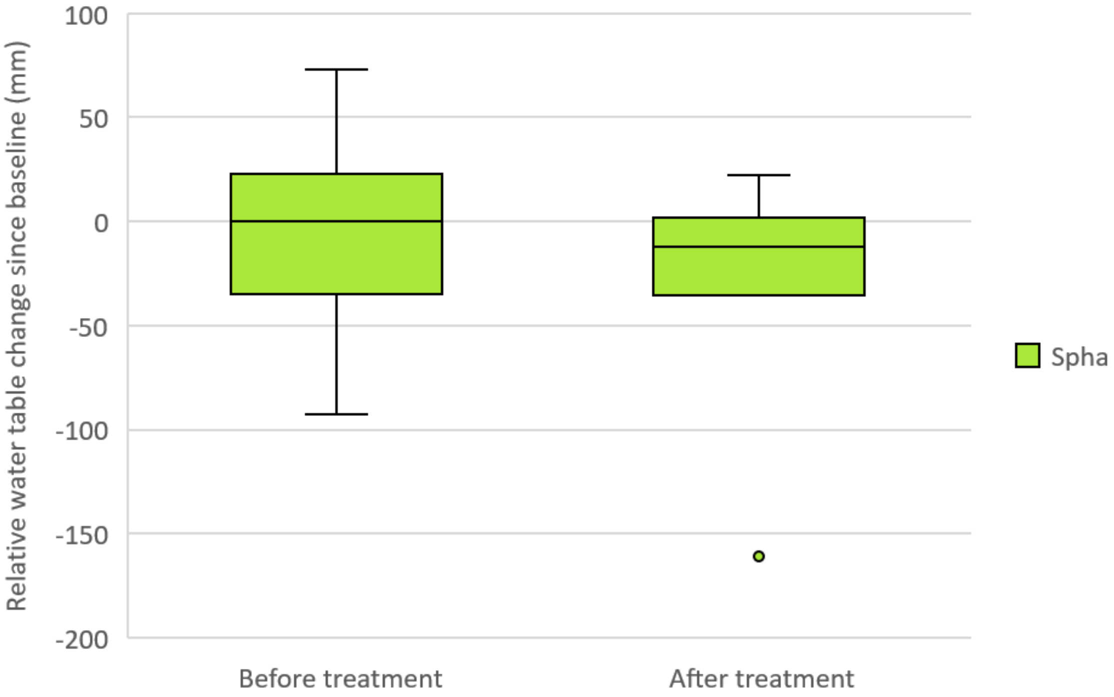


Figure 60. Boxplots of mean manually measured water table depth (mm) in treatment catchment intensive plot dipwells on *Molinia* site, relative to control (control – treatment), before and after treatment. 'Before' median value has been normalised to zero to show change since treatment.

Figure 59 and Figure 60 show boxplots of the mean manually measured water table depth (relative to the control catchment) on the *Sphagnum* (Spha) treatment catchment. Relative figures were derived by subtracting treatment from control, to produce positive figures if the water table depth from surface decreases relative to control. Boxplots for the 'before' period are displayed with the median normalised to zero to allow for a simple visualisation of change over time.

A rise in relative median water table of (18 mm) was found on the treatment site cluster, and this was found to be statistically significant ($p = 0.043$) using a Mann-Whitney U test. Relative differences before-treatment ($n = 17$) had a smaller mean rank (20.41) than relative differences after-treatment ($n = 35$; mean rank = 29.46). A small fall in median relative water table of 12 mm was seen on the treatment site intensive plots, but this was not found to be statistically significant.

Table 28. Descriptive statistics for water table depths at cluster before and after treatment on *Molinia* site

		Control	Treatment	Difference
Before	Max	265	351	100
	Q3	180	129	50
	Median	122	84	40
	Q1	90	69	-13
	Min	34	-16	-96
After	Max	238	298	91
	Q3	124	85	69
	Median	85	31	58
	Q1	66	-7	25
	Min	25	-25	-112

Table 29. Descriptive statistics for water table depths in intensive plots before and after treatment on *Molinia* site

		Control	Treatment	Difference
Before	Max	300	313	136
	Q3	233	140	86
	Median	188	123	63
	Q1	163	88	28
	Min	60	43	-30
After	Max	235	333	85
	Q3	155	117	65
	Median	115	42	51
	Q1	94	34	28
	Min	47	20	-98

Table 28 and Table 29 display descriptive statistics for the cluster and intensive plots respectively. Table 30 display the results of Mann-Whitney U tests to compare relative water table depths before and after-treatment. Significant differences at p <0.05 are highlighted, showing that the water table in the cluster area was significantly higher after treatment, relative to control.

Table 30. Results of Mann-Whitney U test employed to compare *Molinia* site manual water table depths before and after treatment.

	Spha Cluster	Spha INTS
Mann-Whitney U	194.0	121.0
P – value	0.043	0.303

4.4.2. Continuous water table

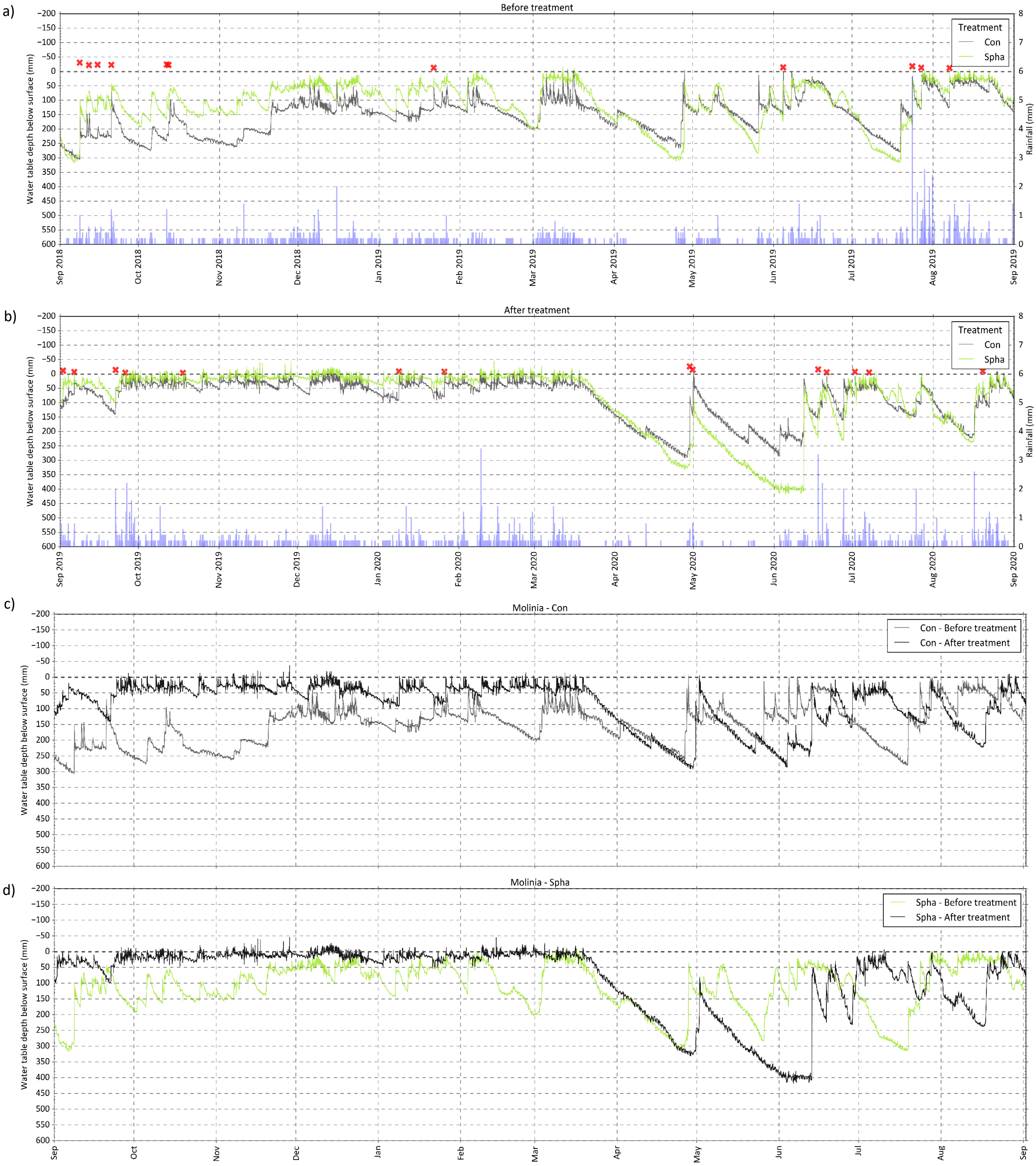


Figure 61. Full automated water table time series for *Molinia* species-dominated sites.
Figures a–b display automated water table for each treatment for years 0 (before treatment) and 1 (after treatment) together with rainfall at 5-minute intervals. Red crosses indicate occurrences of storms used for later metric analyses. Figures c and d allow comparison of the same treatment with year 0 and 1.

The control intensive plot for both before and after-treatment had generally deeper water tables than that of the treated plot in autumn, winter, and spring months (Figure 61 a–d).

Drawdowns in summer of before and after-treatment years however were deeper at the *Sphagnum* treated plot. From the time series the relationship between the two despite treatment appeared relatively similar from year 0 to 1 of the project. Both control and *Sphagnum* treated plots displayed more elevated water tables in the after-treatment year reflecting increased rainfall totals. Median values reduced from c. 140 to 53 mm and c. 99 to 30 mm Figure 62 a–b; Table 31 a–b) at both the control and *Sphagnum* treated plots respectively.

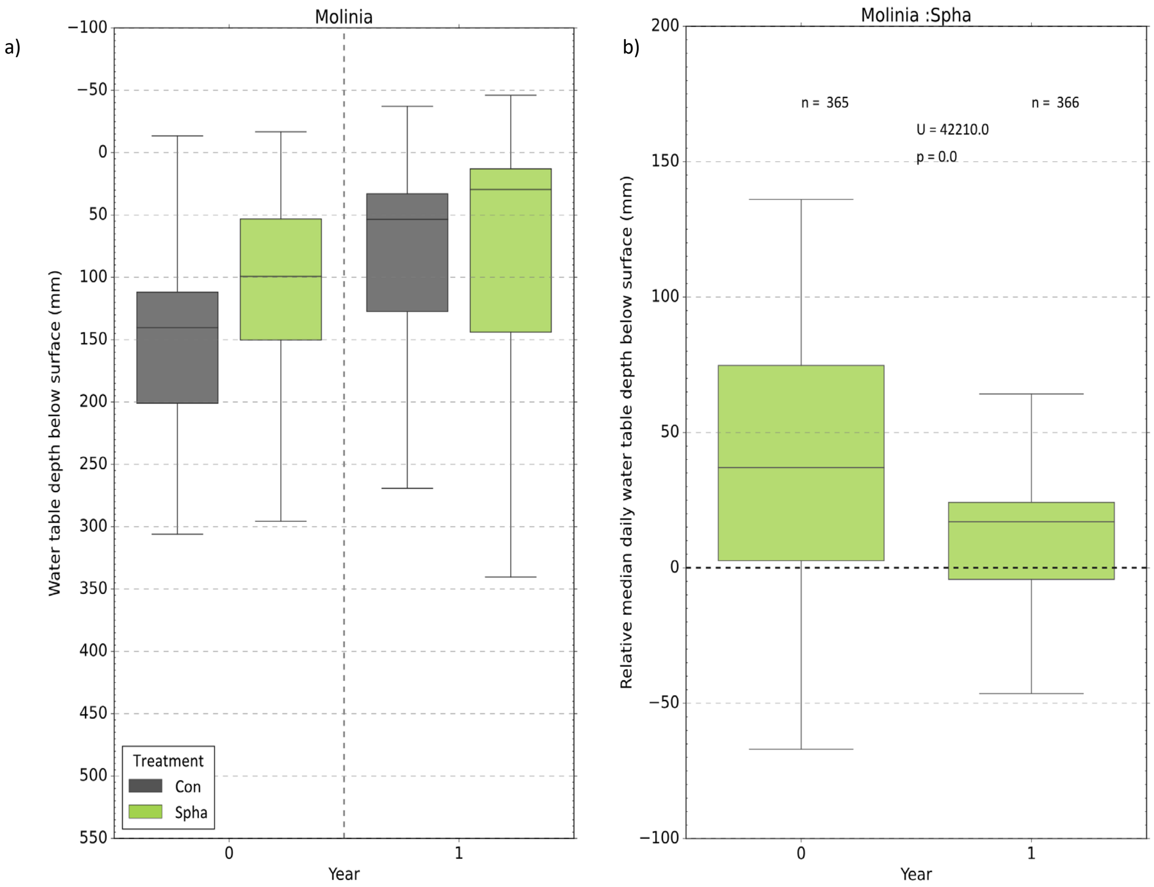


Figure 62. Boxplots of continuous water table depths before and after treatment, *Molinia* site a) median daily water table depth below surface (mm) for each treatment and year (using 5 minutes interval data) and b) the water table depth relative to control for median daily water table depth for each year (control minus treatment for every day in year 0 and year 1) together with Mann-Whitney U statistical tests to determine significant differences. A change towards less positive values from year 0 to 1 in b indicates a reduced difference between control and treatment and vice versa

Table 31. Descriptive statistics of continuous water table at *Molinia* site
a) water table depth below surface at 5-minute interval and b) median daily water tables for each treatment and year and c) relative water tables (control minus treatment of median daily water tables). Differences between medians statistics at control and treatment for each year are displayed in a–b and Year 1 minus Year 0 medians are displayed in c.

a)

			Water table depth below surface (mm)								
Year	Treatment	Count	Mean	Stdev	Min	LQ	Median	UQ	Max	Median difference	Rainfall sum (mm)
0	Con	105120	150.0	64.0	-13.4	111.9	140.3	200.9	306.0		1167.8
0	Spha	105120	112.8	75.3	-16.7	53.2	99.3	150.2	317.6	41.0	1167.8
1	Con	105408	86.2	71.7	-37.2	33.0	53.5	127.5	291.4		1480.4
1	Spha	105408	88.6	111.4	-46.0	12.9	29.5	143.9	418.0	24.0	1480.4

b)

			Water table depth below surface (mm)								
Year	Treatment	Count	Mean	Stdev	Min	LQ	Median	UQ	Max	Median difference	Rainfall sum (mm)
0	Con	365	151.6	63.4	27.4	112.3	140.7	202.9	299.7		1167.8
0	Spha	365	114.1	75.1	11.5	54.7	98.9	151.3	310.7	41.8	1167.8
1	Con	366	87.1	71.1	8.6	33.2	52.8	125.9	282.6		1480.4
1	Spha	366	88.7	111.0	-8.2	13.1	29.6	143.9	401.6	23.2	1480.4

c)

			Relative water tables based on daily median values (mm)								
Treatment	Year	Count	Mean	Stdev	Min	LQ	Median	UQ	Max	Year 1 - Year 0 (median)	Rainfall sum (mm)
Spha	0	365	37.5	48.9	-165.7	2.6	37.0	74.7	136.1		1167.8
Spha	1	366	-1.6	50.8	-191.8	-4.2	17.1	24.2	64.2	-20.0	1480.4

Relative change (control minus treatment, Figure 62 b) has altered from 41 to 24 mm with the control reducing the median depth to water value more than that seen at the treatment plot. Mann-Whitney U tests show that relative water table depths from before and after-treatment are significantly different (Figure 62 b). Relative change displayed with the year 0 (before) data normalised to zero (Table 31 c; Figure 63 b) shows a negative median value in year 1, thus indicating a relative deepening of water table at the treated plot. However, the generally shallower median values of the treated plot mean there is diminishing potential to reduce depth to water table compared to the deeper control thus given equal forcing the control would likely provide a greater reduction. Seasonal change at both treatments is most evident from autumn and winter with median water table depths at both reducing substantially in the after-treatment year. All relative seasonal changes are shown to be significant using Mann-Whitney U tests (Figure 64 b).

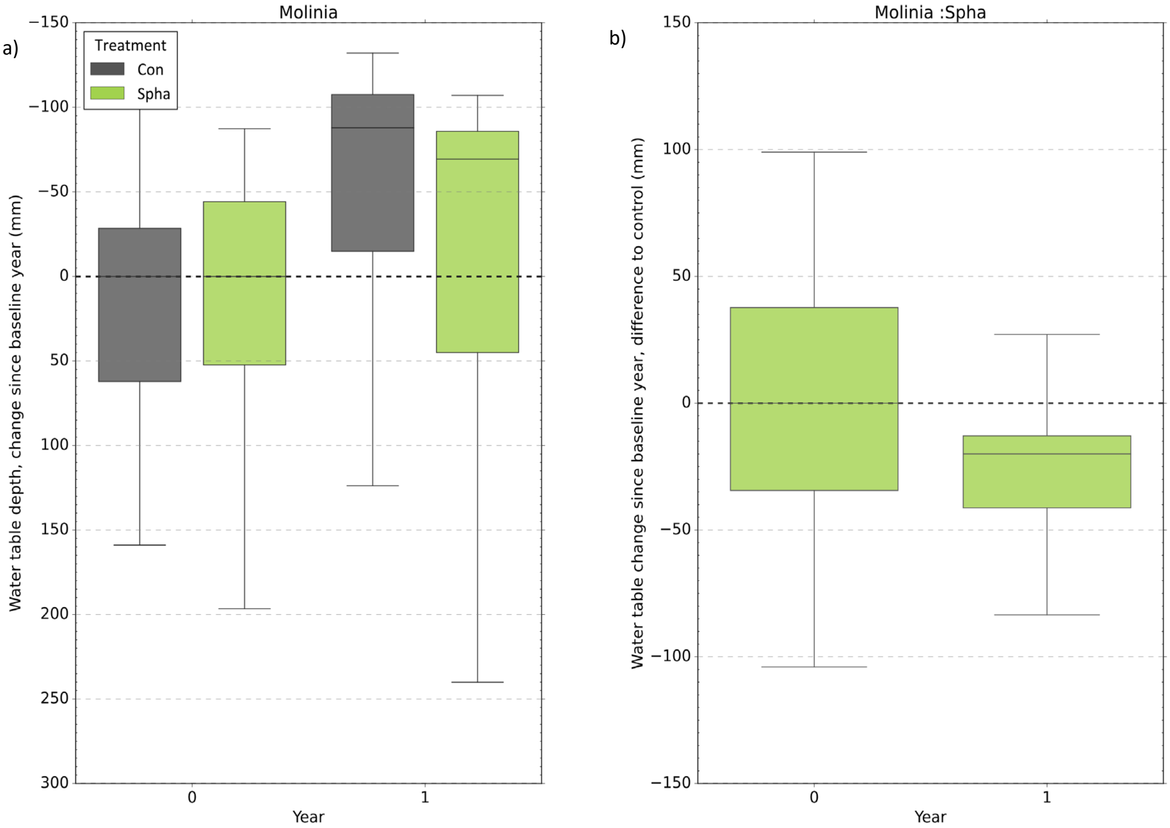


Figure 63. Boxplots of continuous water table depths standardised to zero before and after treatment, *Molinia* site
a) Daily median water table depths standardised to year 0 median of each treatment and b) relative water table from daily median water table data standardised to year 0 median for each treatment. Change to above 0 from year 0 to 1 (more negative values) indicates a change to more elevated water tables in a. In b change to more negative values indicates the relative water table depth (control minus treatment every day) from year 0 to 1 has increased.

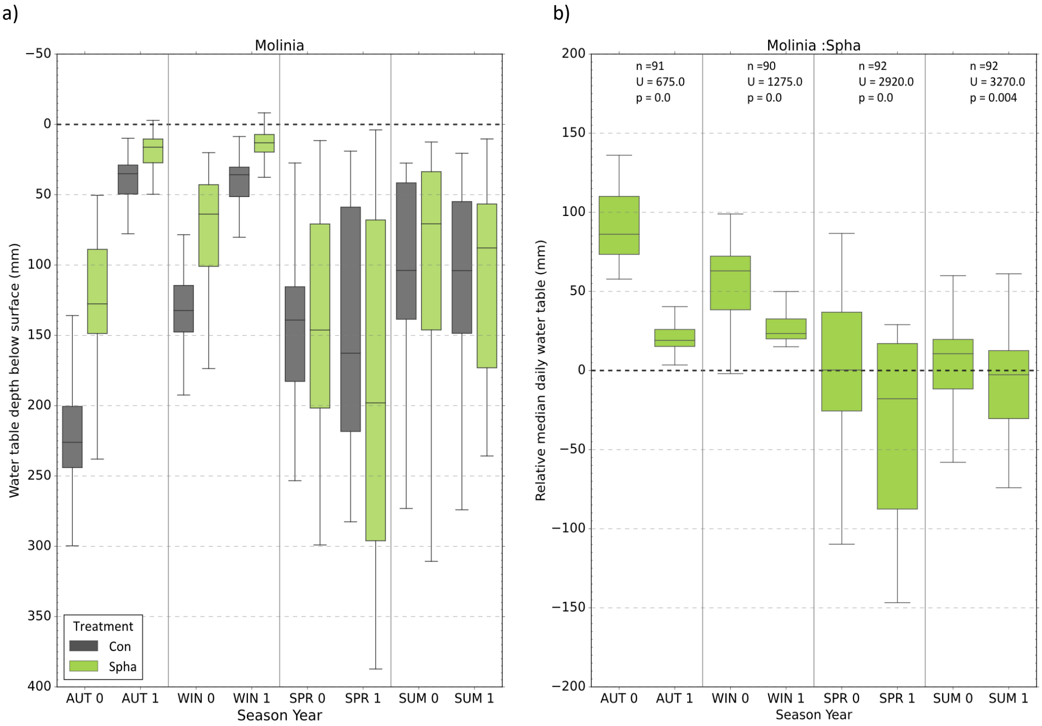


Figure 64. Boxplots of seasonal water table on *Molinia* site.
Boxplots of a) seasonal water tables based on daily median values for each treatment and year and b) differences between control and treatment together with Mann-Whitney U statistical tests to determine significant differences.

Water residence curves provide further detail regarding the changes in water table activity from before and after treatment years (Figure 65). Both control and treatment display a more bowed curve towards the upper right of Figure 65 in the after-treatment year as a greater percentage of time is spent at shallower water table depths. Intersections exist where the generally shallower *Sphagnum* treated plot record switches to exhibiting comparatively more time with deeper water tables. This is evident at 250 mm in year 0 but shifts to 110 mm in year 1 showing that the treated site is more susceptible to deeper drawdowns compared to the control in the after-treatment year, a finding reflected in the increased length of whiskers in Figure 62 a.

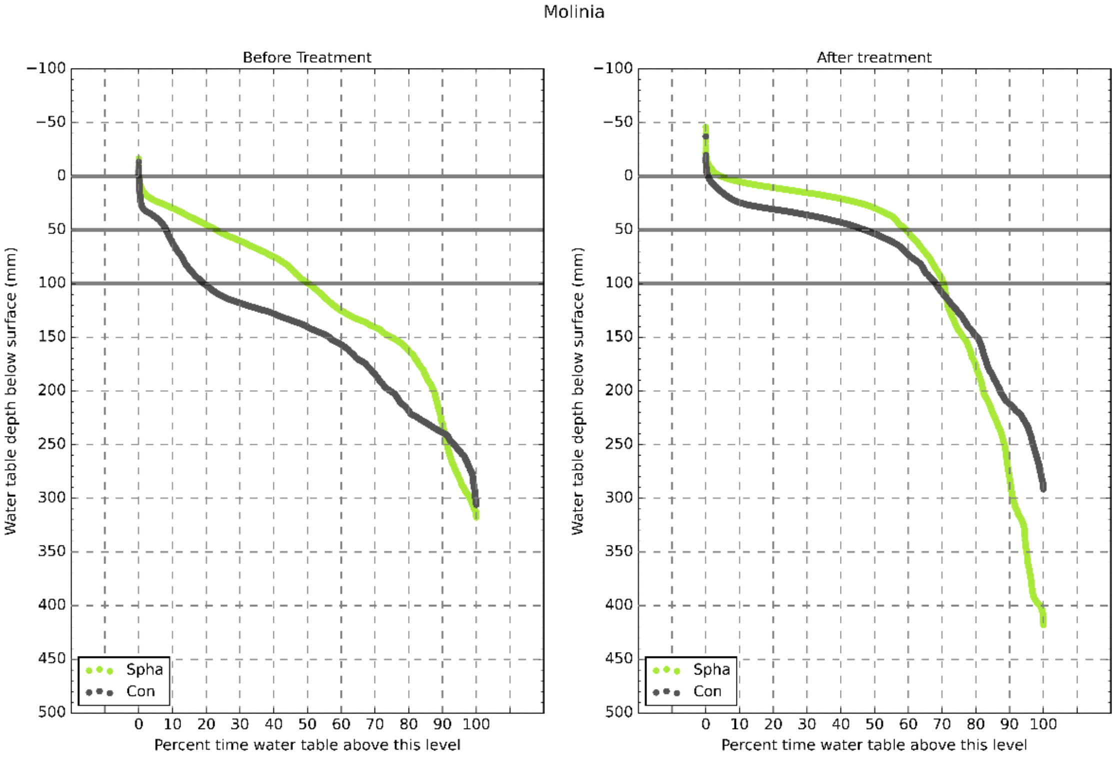


Figure 65. Water table residence time curves for *Molinia* site.
Residence time curves for each dipwell based on 5 minute sampling intervals. Curves display the percentage of time a water table exists above a certain water table level.

Table 32. Water table residence time descriptive statistics for *Molinia* site.
Percentage of time water table above and below 0 (surface), 50 and 100 mm depths for each year and treatment. Differences between treatments for each year are also displayed.

		Percent of time above water table level			Percent of time below water table level		
Water table depth (mm)	Year	Con	Spha	Relative	Con	Spha	Relative
0	0	0.030	0.037	-0.007	99.970	99.963	0.007
	1	0.690	4.541	-3.851	99.310	95.459	3.851
50	0	8.076	22.991	-14.914	91.924	77.009	14.914
	1	47.266	59.442	-12.176	52.734	40.558	12.176
100	0	19.386	50.332	-30.946	80.614	49.668	30.946
	1	68.142	70.432	-2.290	31.858	29.568	2.290

Percentage of time above 0, 50 and 100 mm (high water table points indicative of a healthy bog hydrological system) increase at both control and treatment plots as both display impacts of generally wetter conditions supplied by greater rainfall (Table 32; Figure 65). Similarly to the *Eriophorum* species dominated *Sphagnum* treated plot, the relative percentage of time above 0 mm becomes more negative (control minus treatment) indicating a relative increase of above surface water at *Sphagnum* treated plot in the after-treatment year. Relative percentage above 50 mm remains similar, whereas relative percentage above 100 mm becomes substantially less negative indicating a substantial increase in percentage of time above 100 mm at the control, alongside a more subdued response at the *Sphagnum* treated plot. As water tables become shallower the potential for a high magnitude change to shallower water tables is reduced as the surface is approached. The *Sphagnum* treated plot was already at a relatively high percentage for this level in year 0 which would reduce its potential magnitude of response in comparison to the control.

Fewer storms are used to determine storm response metrics (Table 33; Figure 66) compared to the *Eriophorum* species dominated plot as the record exhibits substantially more sensor derived noise (Figure 61 a–b; red crosses indicate dates of each storm). Steps to reduce this were attempted but negatively impacted temporal resolution. Therefore fewer, less noise impacted events, are examined.

Table 33. Descriptive statistics for water table storm response, *Molinia* site.
a) Median start and peak lags between rainfall and water table and median minimum, maximum and changes in water table and recession rates for selected storm events for each year for control and Sphagnum treatments. b) Median of relative (control minus treatment) metrics for all storms for pre and post treatment years. Count values refer to number of storm events used for each metric. For recession rates, counts in brackets refer to number of storm events used for 12-hour rates.

a)

			Median lags (mins)		Median water table (mm)				Median recession rates (mm hr^{-1})	
Treatment	Year	Count	Event start lag	Event peak lag	minimum	maximum	change	Count	Six hour	Twelve hour
Con	0	11	85	100	221.1	93.9	70.0	14	6.43	2.38
Spha	0	11	40	80	131.4	80.2	41.8	14	1.63	2.70
Con	1	14	42.5	47.5	83.4	48.9	13.6	11 (8)	3.14	2.58
Spha	1	14	32.5	52.5	64.3	41.4	22.9	11 (8)	4.18	1.45

b)

		Median lags (mins)		Median water table (mm)				Median recession rates (mm hr^{-1})	
Year	Count	Event start lag	Event peak lag	minimum	maximum	change	Count	Six hour	Twelve hour
0	11	25	10	68.1	30.6	8.5	7 (6)	3.81	3.15
1	14	0	-2.5	11.9	-1.2	13.9	7	-0.98	-0.30

The median of start and peak lags are reduced in both control and *Sphagnum* treated plots from before to after treatment years (Table 33 a). Relative median start lag has reduced from 25 to 0 minutes as the water table response time at the control has reduced substantially compared to the relatively subdued change at the treated plot. Change in relative peak lag continues this trend as a substantial change at control is reflected by a more subdued response at the treated plot as relative median values decrease from 10 to -2.5 minutes. Mann-Whitney U tests however, (Figure 66 a–b) indicate the distribution of relative data in before and after treatment years for both lags are not significantly different.

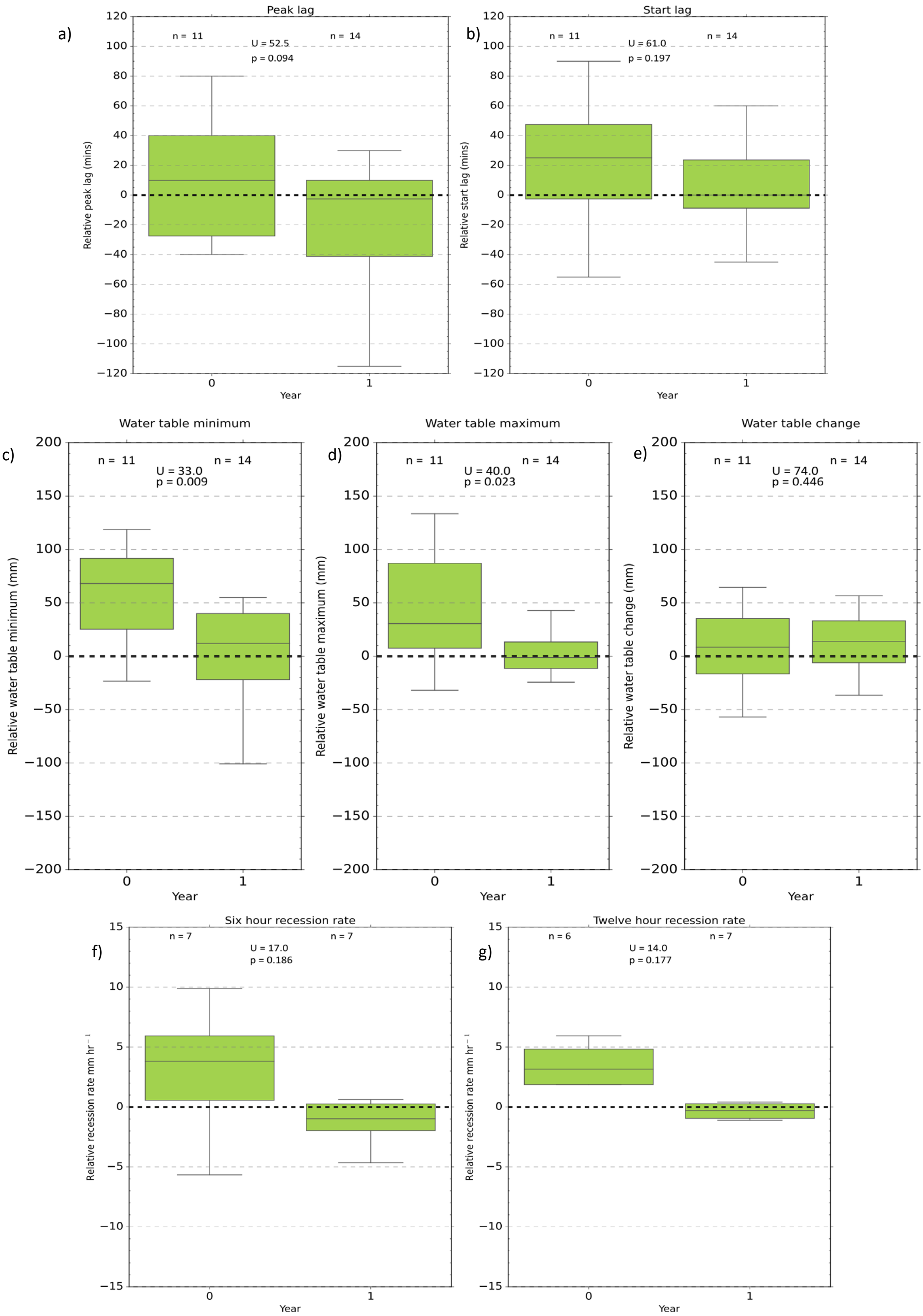


Figure 66. Relative metrics for water table storm responses, *Molinia* site.
Relative metrics for storm responses for selected storms (see methods) including time lags between rainfall and a) peak in water table (shallowing) and b) initial response peak response. Figures c – e display the relative difference for each year between firstly the initial water table levels at the start of a storm (c), secondly the most elevated water table achieved (d) and thirdly the change in water table during the storm. Figures f and g show the relative difference between control and treatments for each year for the rate of water table recession post storm after 6 and 12 hours.

A change to a flashier response at the control is not reflected in the treated site and maybe a consequence of the already relatively elevated water table positions that existed in the before and after treatment years at the treated plot for large percentages of the time (Figure 65). Shallower water tables exhibited at the treated plot are likely to be moving through peat of lower hydraulic conductivity allowing a faster response to rainfall events in the before treatment year with more elevated water tables in the after-treatment year not resulting in a proportional change in response times compared to that of the deeper water table at the control. Alternatively, the treatment at the treated plot has buffered a corresponding decrease in lag times like that seen at the control.

Relative (control minus treatment) water table minimum (value at start of event) and maximum (value at peak of event) show significant differences between before and after-treatment years distributions (Table 33; Figure 66 c–e). Median relative minimum and maximum values become less positive from 68.1 to 11.9 mm and from 30.6 to -1.2 mm respectively because of water tables exhibiting generally more elevated levels in the after-treatment year at the control compared to the treated plot.

Six-hour recession rates have increased at the treated site and reduced at the control (Table 33 a–b) from the before to after treatment year. The treated plot appears to have changed to a relatively faster 6-hour recession rate post treatment. The twelve-hour recession rate shows substantially less differences between treatments before and after periods. The distributions of before and after relative six- and twelve-hour recession metrics however are not significantly different (Mann-Whitney U; Figure 66 f–g).

4.4.3. Overland flow generation

4.4.3.1. Cluster area

Percentage recovery, recording evidence of overland flow, has increased year on year from before to after-treatment for control and *Sphagnum* treated mini catchment clusters (Table 34; Figure 67 and Figure 68 a) and is associated with more prolonged periods of elevated water tables. Relative change (Figure 68 b) is stable between before and year 1 after treatment. From year 1 to 2 after treatment however percentage recovery continues to increase at the treated plot (85.4 to 99.0%) whereas it remains stable at the control (68.3 and 71.3%).

Grouped by before and after-treatment relative percent recovery changes from 16.7 to 21.8% as the treated plot records relatively greater overland flow after treatment.
Internal variation at each treatment site is relatively consistent (Figure 67 heatmaps) especially at the *Sphagnum* treated mini catchment. Tubes 4 and 5 at the control catchment appear to be in areas less likely to provide overland flow but overall, this is unlikely to skew the data detrimentally.

Table 34. Cluster crest stage tube percentage recovery at each treatment for *Molinia* dominated sites. Values are displayed for each treatment and each year of project as well as before and after treatment (after being a consolidation of years 1 and 2). Differences between percentage recovery from treatment and control are also displayed. Recovery values here are based on presence or absence from all 15 crest stage tubes in each catchment from each year's / period's data. Counts are total number of crest stage data points and sums are the number of those data points with water being present.

		Treatment	Year	Sum	Count	% Recovery	Treatment - control
Molinia	All years	Con	0	88	180	48.9	
		Con	1	164	240	68.3	
		Con	2	139	195	71.3	
		Spha	0	118	180	65.6	16.7
		Spha	1	205	240	85.4	17.1
		Spha	2	193	195	99.0	27.7
	Before / after	Con	Before	88	180	48.9	
		Con	After	303	435	69.7	
		Spha	Before	118	180	65.6	16.7
		Spha	After	398	435	91.5	21.8

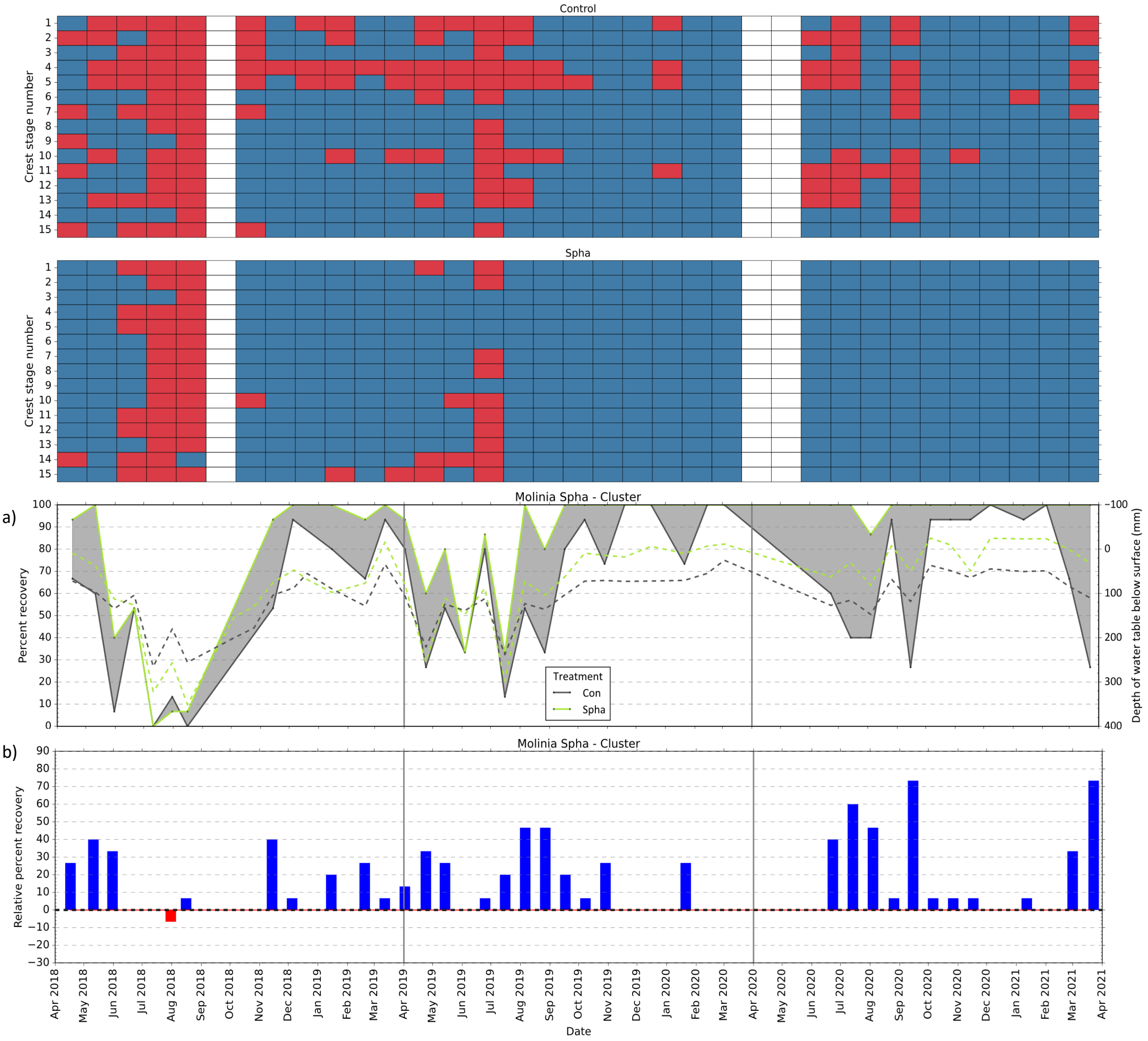


Figure 67. Time series for crest stage tubes at clusters on *Molinia* site.
a) percentage recovery from crest stage tubes from cluster locations at *Molinia* dominated catchments. Dotted lines show a combined mean water table level in these catchments from the 15 dipwells. Grey shading between percentage recovery lines highlights differences between treatment and control. Treatment minus control is displayed b) for each time step with blue values indicating treatment recovery greater than control and red treatment recovery less than control. The uppermost two figures give monthly presence (blue) or absence (red) values for water in each individual crest stage tube for each treatment.

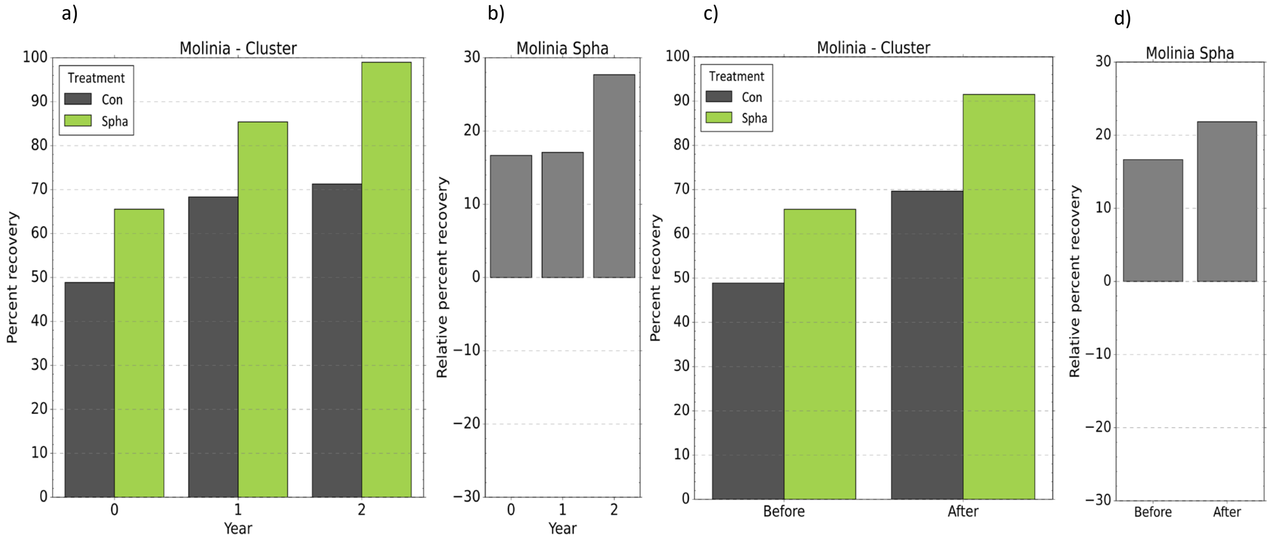


Figure 68. Crest stage tube percentage recovery at each mini-catchment cluster on *Molinia* site. Cluster crest stage tube a) percentage recovery at each treatment and b) difference between treatment and control for each year of project at the Molinia dominated sites. Figures c and d show the same data represented as before and after treatment.

4.4.3.2. Intensive plots

Substantial increases in percentage recovery and therefore overland flow are evident from before to after-treatment years for both combined control and *Sphagnum* planted plots (38.5 to 81.9% and 65.4 to 90.3%) and again are associated with prolonged periods of elevated water tables (Table 35; Figure 69; Figure 70). The relative recovery (treatment minus control) reduces substantially in the after-treatment year as the control approaches the recovery rate achieved by the *Sphagnum* planted plots. Internal variation within treatments is consistent with few data responses likely to skew the combined data. However, plot 3 for the control site does exhibit a substantially reduced response from before to after treatment years compared to those at control plot 1 and 2.

Table 35. Crest stage tube percentage recovery from intensive plots at each treatment for *Molinia* dominated sites.
Value are for before (year 0) and after (year 1) treatment. Differences between percentage recovery from treatment and control are also displayed. Recovery values here are based on presence or absence from all crest stage tubes in the 3 intensive plots. Counts are total number of crest stage data points and sums are the number of those data points with water being recorded as present.

	Treatment	Year	Sum	Count	% Recovery	Treatment - control
Molinia	Con	0	30	78	38.5	
	Con	1	59	72	81.9	
	Spha	0	51	78	65.4	26.9
	Spha	1	65	72	90.3	8.3

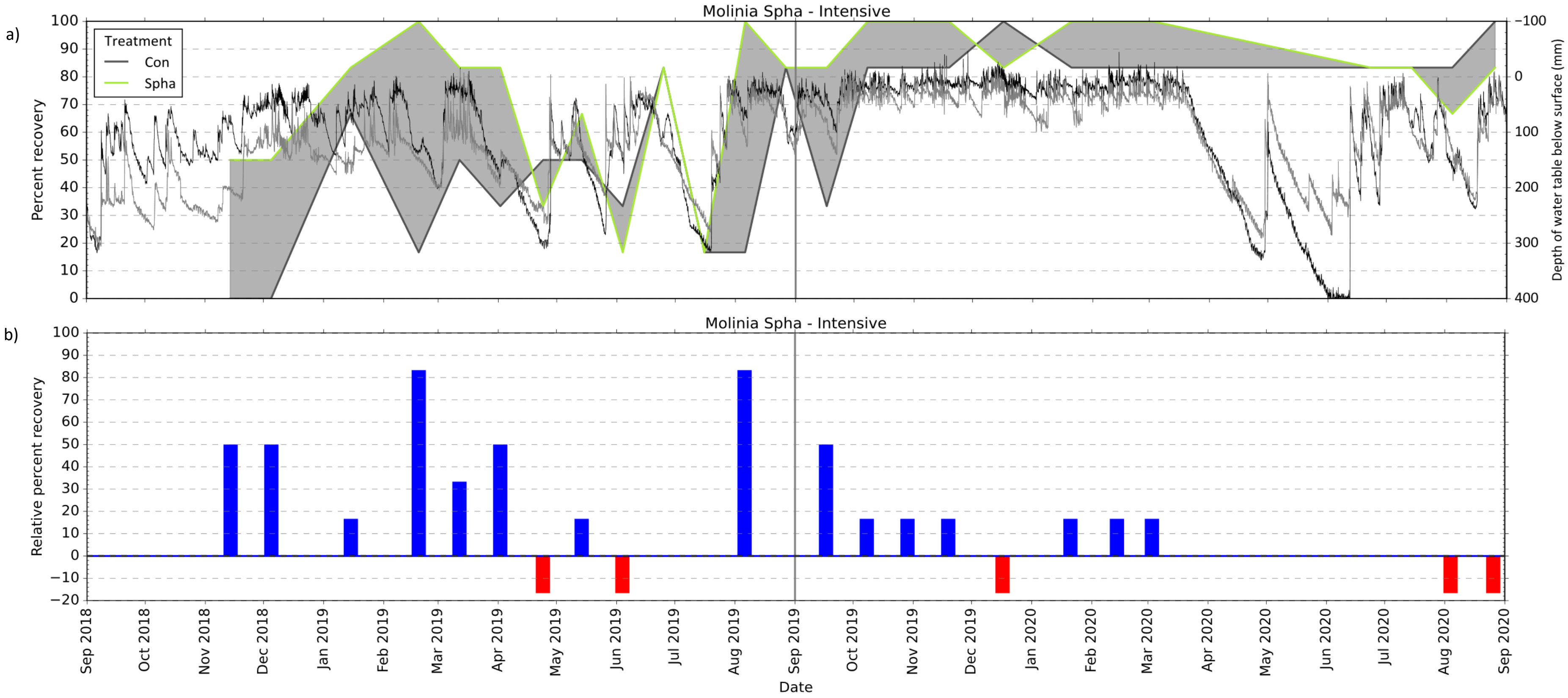


Figure 69. Time series of overland flow on *Molinia* site Con and Spha intensive plots.
Time series of a) percentage recovery from crest stage tubes from 'intensive' locations at *Molinia* dominated catchments. Grey shading between percentage recovery lines highlights differences between treatment and control. Black (Spha) and grey (Con) lines in background display continuous water table depths derived by automated sensors from '*Sphagnum*' treated and 'control' sites respectively. Treatment minus control is displayed b) for each time step with blue values indicating treatment recovery greater than control and red treatment recovery less than control.

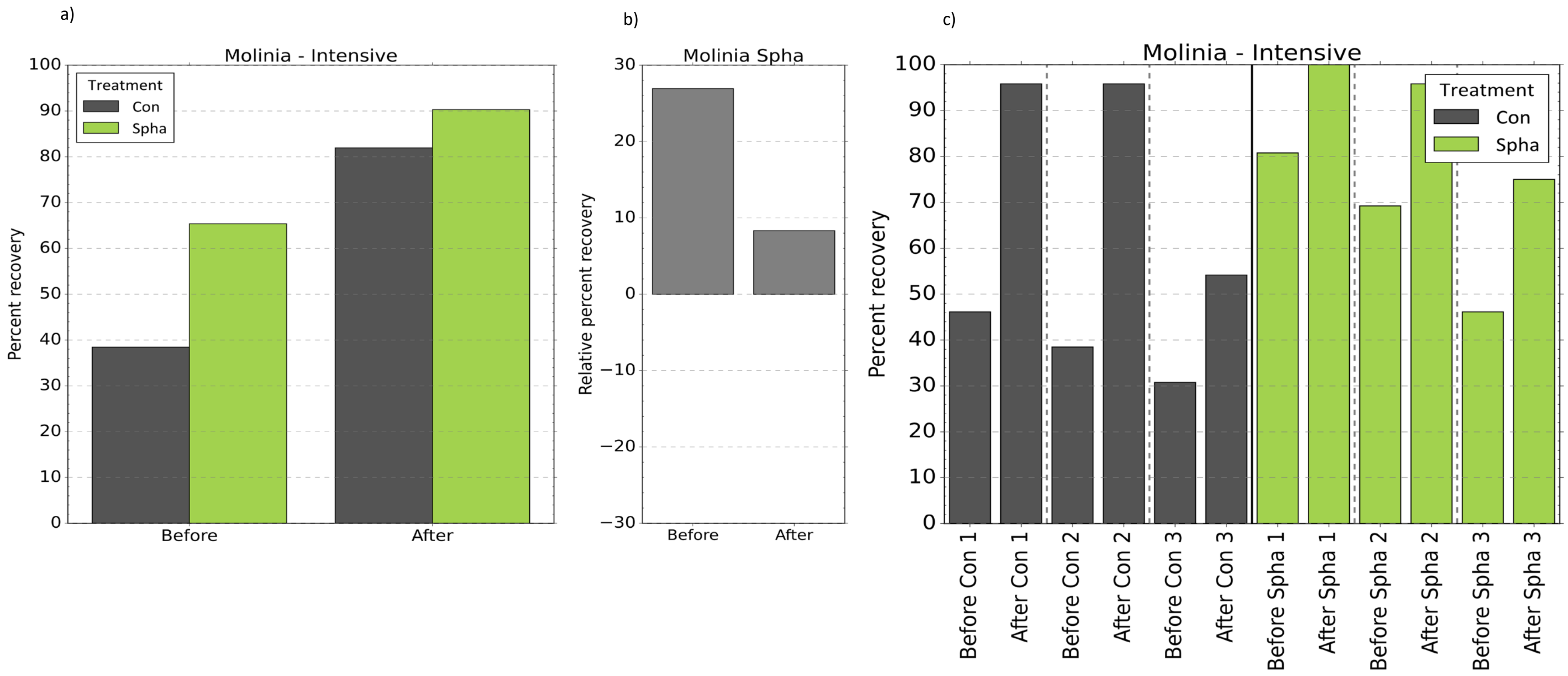


Figure 70. Crest stage tube percentage recovery at each intensive plot on *Molinia* site
Intensive plot crest stage tube a) percentage recovery at each treatment and b) the difference between treatment and control for before and after treatment time periods at the Eriophorum dominated sites. Percentage recovery at individual crest stage tube locations c) is also displayed for each treatment for before and after time periods.

5. Discussion

5.1. Bare peat sites

5.1.1. Manual water table

Water tables rose as a result of treatment at a rate of approximately 6 mm yr^{-1} over ten years following treatment at the clusters on Kinder Scout which were installed away from the potential effects of gully blocks or *Sphagnum* planting. This finding was supported by data from an extensive set of 'wider context' sites from around the South Pennines, where water tables were observed to rise by approximately 8 mm yr^{-1} over 17 years.

Water tables rose as a result of treatment at a rate of approximately 7 mm yr^{-1} over six years at the clusters on Kinder Scout which were installed in areas of dense *Sphagnum* planting. Due to the lack of data from before initial revegetation at these newer dipwells, it was not possible to compare conditions to the control site when both were bare peat. To date, data are insufficient to confirm whether there is an additional effect on water table depth related to the growth of *Sphagnum* mosses, which had created almost continuous cover across much of these two clusters by 2021.

Aside from changes in weather (predominantly precipitation, temperature and wind), there are multiple factors which may affect water table depth on degraded and restored peatlands:

- **Density/connectivity of drainage networks (gullies, macropores, micropores)**
  - Higher density results in shorter flow pathways into major channels and therefore limits the potential for water tables to remain close to the surface during/following rainfall events, leading to ***lowered water tables***

- **Size/depth of drainage routes (gullies, macropores, micropores)**
  - Severe gullying causes water table drawdown within 2 m of gully edges (Evans *et al,* 2009), leading to ***lowered water tables***

- **Presence of gully blocks**
  - Impermeable gully blocks may have a localised effect of raising water tables, especially in areas where gullies are shallow (where gullies are deep this effect is likely to be restricted predominantly to within 2 m of the gully edge), leading to ***raised water tables***
  - Permeable gully blocks affect water tables similarly to impermeable gully blocks, but only during periods when a pool has formed upstream of the gully block, leading to ***raised water tables***

- **Extent of bare peat surfaces**
  - Bare peat may become hydrophobic and/or compacted by rain splash, increasing the likelihood of infiltration-excess overland flow and limiting recharge of the water table, leading to ***lowered water tables***
  - Evaporation from bare peat surfaces may be elevated as compared to vegetated surfaces as they may have reduced albedo and are more exposed to wind, leading to ***lowered water tables***

- **Density/species composition of vegetation cover**
  - Evapotranspiration from vegetated surfaces may be elevated as compared to bare peat surfaces due to plant activity (especially where vegetation is deep-rooted), leading to ***lowered water tables***
  - Infiltration rates could be reduced due to interception by (and subsequent evaporation from) the canopy layer, leading to ***lowered water tables***

- Infiltration rates could be increased due to increased residence times of water on the surface as the vegetation layer insulates the peat surface, increasing albedo and reducing evaporation, leading to ***raised water tables***
- Infiltration rates could be increased due to penetration of the peat surface by plant roots, leading to ***raised water tables***

The observed rise in relative water tables (control – treatment) at the treated mini-catchments on Kinder Scout and the wider context sites suggests that the effects of increased infiltration rates outweigh those of increased evapotranspiration and interception in the canopy layer. The presence of a dense *Sphagnum* moss layer appears to accelerate water table rise (although data are noisy and there is limited replication), which may be due to increased residence time of water on the peat surface in the dense and complex structure of the *Sphagnum* layer and lack of roots, facilitating increased infiltration and reduced evapotranspiration rates.

Insufficient replication of dipwell clusters with different combinations of similar topography, vegetation type and gully-blocking type meant that it was not possible to assess the relative magnitude of the effects of gully blocking (including using different techniques) and revegetation on water tables. The severity of erosion and formation of deep and extensive gully networks may limit water table rise following restoration, but this limiting effect appears not to have stopped recovery at restored sites up to 17 years following treatment.

5.1.2. Continuous water table

Continuous water table data produced results comparable to those from manual Autumn-only surveys. Median water tables rose by 10–20 mm yr^{-1}, with variability between sites likely due to severity/extent of drainage networks (both superficial and subsurface) limiting the potential for water tables to recover following revegetation. The slightly higher rates of water table rise observed through these continuous data (as opposed to from the manual surveys) could be due to the inclusion of the summer season, and associated drier conditions, as compared to the Autumn-only manual surveys. In the wettest conditions, all sites (bare peat or revegetated) had near-surface water tables – so the difference between control and treatment may have been limited. By contrast, in prolonged dry periods (more common in the summer), the revegetated sites may have dried out more slowly than the bare peat control, resulting in a bigger difference. It should be noted that, while results from the four loggers used in this study were relatively consistent with each other, there was not sufficient replication to provide great certainty in these results. Furthermore, control data were not available from the bare peat site on Bleaklow (where three of the revegetated sites were located), as the water table was consistently too deep for the logger to monitor it effectively.

5.1.2.1. Water table response to precipitation

Results of analyses of water table response to rainfall events were consistent with those of daily mean water table depth data. Peak water table depth (the closest-to-surface water table depth values observed during/following rainfall) rose towards the surface as a result of revegetation at O at a comparable rate (~10 mm yr^{-1}) to mean daily water table depth. This indicates that the water table came closer to saturating the surface of the peat during/following rainfall as a result of revegetation.

No changes to lag times (peak rainfall intensity to peak water table depth) or recession rates in the 6 or 12 hours following peak water table depth were observed. This would suggest that the water table became no more or less flashy in its response to rainfall, at least in the first 12 hours following peak water table depth. Further investigations may reveal changes to recession rates over longer time periods. Initial soil moisture data appear to show a different response in near-surface soil moisture, as described below.

5.1.3. Overland flow generation and soil moisture

Allott *et al.* (2015) found that surface ponding (and therefore overland flow generation) increased as a result of revegetation. While results from 2018–20 appear to suggest a reversal of this trend, these more recent results are believed to be void. The crest-stage runoff traps work well on bare peat and in young, sparse vegetation. However, maturing vegetation around the tubes appeared to restrict the entry of water into the traps, meaning that surface ponding and overland flow generation at sites O and N was likely under-recorded in 2018, 2019 and 2020.

Initial soil moisture data from experimental sensors installed in January 2021 may suggest that moisture is retained in the top 12.5 cm of the peat in locations where there is a dense (in particular *Sphagnum*-rich) vegetation canopy, whereas the top 12.5 cm of the peat in locations where it is bare displays more rapid and wide-ranging fluctuations in soil moisture. This is consistent with the hypothesis of Allott *et al.* (2015) – that the vegetation canopy provides an insulating layer for the near-surface peat, reducing evaporation of moisture from the surface. Additionally, the vegetation canopy (and in particular, *Sphagnum* mosses) may retain moisture at and above the surface, contributing to surface ponding and rehydration of the near-surface peat.

The rapid fluctuations in near-surface soil moisture at F suggest that moisture is not retained in the top 12.5 cm – either it passes down rapidly into the water table, or exits the peat (by evaporation from the surface or through subsurface drainage networks). By contrast, near-surface soil moisture at both O and N appears to remain predominantly at close-to-saturation levels, only drying out in prolonged periods without precipitation. This difference supports the hypothesis that overland flow generation is driven primarily by infiltration-excess at F but by saturation-excess at O and N (and in particular at N).

The discrepancy between results from the crest-stage runoff traps and soil moisture probes, in combination with the more likely hypothesis that revegetation increases near-surface wetness and surface ponding rather than decreases it, supports the suggestion that the crest stage tubes are no longer functioning as an appropriate measure of surface ponding at sites with matured and dense vegetation. There is potential for modification of the method, by using larger tubes, with larger diameter holes. This could reduce the issue of vegetation surrounding the tubes restricting the ingress of water into the traps.

It should be noted that the soil moisture probes are a new and somewhat experimental technology, requiring further testing. In this study, three replicates were installed at control and treated sites; data were collected from March to October 2021 and some gaps exist in the data due to initial problem-solving and in-field development of the technology. In July 2022, additional sensors were installed, along with a signal repeater to boost connectivity and reduce data gaps. This increased replication (four sensors at each of the three sites), improving confidence in results, although the time period of available data was limited (55 days). Results from these first 55 days support the findings of the pilot study; a longer time series would greatly enhance confidence in these initial findings. However, these initial data suggest that this could be an important method for assessing the impacts of bare peat restoration on soil moisture and the structural recovery of degraded peat.

5.2. Species dominated sites

5.2.1. Water tables

Changes in water table at either cluster or intensive locations will be primarily due to change in the balance of in inputs such as rainfall and water supply from subsurface flow from more elevated land and outputs via evapotranspiration and loss of water via subsurface flow away from the location. All median water levels have risen from before to after treatment periods due to elevated levels of precipitation in the after-treatment years. Comparison with control means general meteorological differences should be factored out.

Extensive planting of *Sphagnum* plugs across the mini catchments and the intensive plots will not affect the hydraulic conductivity of the peat below especially in the time frame of this report. However, at least for the intensively planted plots it may affect the water tables due to changes in evapotranspiration and the opportunity for infiltration. The former could result in part due to changes in albedo and therefore surface temperature and to a lower percentage of more efficient conductive route ways for water to transpire from, especially from deeper depths if planted *Sphagnum* is replacing vascular plants especially ericaceous ones (Farrick and Price, 2009). Intensive planting may potentially alter and in certain environments increase surface roughness thus slowing flow and possibly increasing residence times of water (Holden *et al.*, 2008; Bond *et al.*, 2020; Bond *et al.*, 2021) potentially allowing more opportunity for infiltration. More likely may be a change in soil moisture at this early stage than a change in water table. After many years and the establishment of a substantial *Sphagnum* carpet it may be possible for the hydrological gradient between the potentially damaged present-day surface to be such that the carpet can draw water up from the peat below (McCarter and Price, 2013) although this may not be possible without further 'restoration' measures to raise the water table.

The low density of *Sphagnum* planting in the mini catchments means any effect on the water table is likely to be negligible without any other complementary restoration techniques especially at this early stage, only a year on since planting. Surveyed *Sphagnum* coverage at the mini catchments at most has increased to 10% at the *Eriophorum Sphagnum* treated mini catchment. However, the only statistically significant change in water table at the cluster scale is evident at the *Molinia* dominated site where a relative change to shallower water tables at the treatment site is recorded despite only a relatively small increase in *Sphagnum* coverage from 0 to 3.25%. At the *Eriophorum* mini catchment no clear change compared to control is reported, and at the *Calluna* dominated site a minor deepening of water tables relative to control at both treatments are not statistically significant.

The observation at the *Molinia* mini catchment (and the relative deepening of water table at the *Calluna* treatment sites, although not significant) needs to be viewed with caution until further data from years with contrasting climate is obtained. It is evident from Figure 56 that the *Molinia* mini-catchments contrast in their general hydrological behaviour. The treatment site in the before year is clearly capable of exhibiting more elevated water tables than the control in favourably wet conditions but is also able to draw down much further exhibiting very deep-water tables in the drought in 2018. The response of the treatment site therefore before treatment shows extremes of hydrological ranges compared to the control.

The two substantially wetter years after treatment have led the *Molinia* treatment site to tend to higher water tables without the more extreme drawdowns seen in the 'before' year. A drawdown is evident from the automated data in year 2 of the after period (Figure 56) but was missed by the manual data due to Covid-19 restrictions over fieldwork. The tendency to extremes at the treatment site of either highly elevated or drawn down water tables dependent on climate contrasts with the greater stability at the control and likely points towards an internal difference between the two in how the water table is supported/supplied potentially due to the morphology of the site or even a difference in hydraulic conductivity. This could be an issue of a lack of lateral recharge when aerial water supply is lacking. To detect any effect due to *Sphagnum* planting numerous cycles of contrasting climate are likely to be required.

Any effect of *Sphagnum* planting on water tables is more likely to be observed in the densely planted intensive plots. A significant small relative elevation in water table is reported by both manual and continuous dipwell data from before to after treatment at the *Eriophorum* intensive plots contrasting with the lack of change in the mini catchment. However, the proportional change is similar, as both control and treatment have reduced depth to water table by around half (Table 20;Table 22). The deeper water tables evident at the treatment in the before year have more potential to rise compared to the control which already had an elevated median in the before treatment year of less than 100 mm. This apparent lack of any significant change is also reflected in the storm metrics. An observed relative deepening of water table at the *Molinia* intensive plots compared to control, although reflecting the observation at the mini catchment scale, is not statistically significant. It is likely that the same explanation for the result at the mini catchment scale can be applied here and to the only significant storm metric findings.

A very small yet significant relative rise in median water table (4.1 mm) is evident from the continuous record at the *Calluna Sphagnum* treated plot and is reflected, albeit not significant, in the manual record. This highlights the fact that the observations are more likely to be significant from the continuous record as there are simply many more data points as daily summary data has been employed. The general high elevation of the water table at the control site compared to the treatment means that any increase in rainfall and water table is likely to provide a relative increase in that of the treatments. There is therefore a need to observe trends over many more years to observe shifting water table behaviours.

An increase in the duration of water table above the surface after treatment is evident at both *Eriophorum* and *Molina* intensively planted plots. These continuous water table records are only based in one of the three intensively planted plots for control and treatment at the site so are less representative of the entire site. However, the clear increase compared to control is of interest as both treatment locations, unlike the controls, have had substantial *Sphagnum* growth with the *Eriophorum* and *Molinia* sites exhibiting changes in cover from 0 to 53% and 0.3 to 11% respectfully. The reasons for this are not clear.

However, the before treatment period (2018-09-01 – 2019-08-31) follows an extremely warm dry summer in 2018 which at the *Molinia* 'treatment' intensive site especially led to a deep drawdown compared to that of the control location (Figure 41 and Figure 56). The start of the 'before treatment' year encompasses the recovery from this drought at both control and treatment locations, however the deeper drawdown at the treatment location may suggest a more prolonged time to recharge and regain more normal hydrological functioning compared to the control plot. The after-treatment year by contrast encompasses a period of very high rainfall from October 2019 to March 2020 as control water table exhibits similar time above the surface to the before treatment period whereas the treated plot exhibits c.4% more. It is likely that the increase here is simply a recovery post drought to more typical behaviour at the treatment plot which was more severely affected than the control. Data derived for late in 2017 (Not used in the overall analysis as does not form a complete project year) from this site confirms similar behaviour between the control and the treatment location reflecting that evident in the post treatment year. This further suggests that the duration above surface finding is more a differential reaction after the droughts of 2018. This explanation is less valid at the *Eriophorum* locations as the difference in drawdown between control and treatment is less. Continued monitoring will provide more clarity on the observations here.

5.2.2. Overland flow

Overland flow on a peatland surface is generated either by, or as a combination of, a surface of low permeability retarding infiltration or by high water tables effectively providing the former. Years with greater rainfall are more likely to provide higher water tables producing more opportunity for overland flow. Overland flow on blanket bog locations may occur as both a rapid flow above the surface or as a much slower within the upmost litter layers (Holden *et al*., 2008). The shallow nature of flows observed mean that surface vegetation, litter, and constituents of the acrotelm may exert a substantial effect on flow generation and may be able to attenuate flood hydrographs and extend response lags. Increased *Sphagnum* may have the effect of reducing the rate that water exits via overland flow.

The higher rainfall in the 'after' treatment period for both mini catchments and intensive plots mean all control and treated locations have recorded an increase in overland flow. No significant lags in water table responses have been observed from the continuous records from the *Molinia* and *Eriophorum* plots despite substantial increases in *Sphagnum* cover suggesting that any flow attenuation has not affected the water tables below thus far. Although, spreading laterally, the planted *Sphagnum* has not had sufficient time to attain any depth to substantially affect surface roughness.

Despite the greatest increases in *Sphagnum* cover at the intensive plot scale at the *Eriophorum* dominated site there has been little change in relative overland flow. Although a relative decrease is observed for the mini catchment after treatment this may in part simply reflect recovering after the droughts of 2018 to more normal conditions especially as the ceiling of 100% recovery is approached by both control and treatment in the post treatment years. The lack of substantial relative change is commensurate with the relatively stable water table from before to after treatment periods. Planted *Sphagnum* has spread least at the *Molinia* plots and mini catchment and at the mini catchment level the relative overland flow has only changed (increased) by 5% however, in the intensive plots there is a relative reduction of 18.6%. Again, these observations need to be used cautiously when remarking upon any affect due to *Sphagnum* due to the lack of time since planting and the recovery of control and treated locations from drought in the before treatment years. It is essential to continue monitoring to observe changes in overland flow and water table over a much longer period firstly to allow *Sphagnum* to gain greater coverage and depth but also to observe reactions to various climate conditions.

6. Conclusions

6.1. Bare Peat

Lowering of the peat surface at bare peat control sites, through compression, oxidative losses and/or surface erosion confounds relative water table depth-below-surface data (Lindsay, 2010). In this study, a fixed datum (the top of the dipwell tube) was used in place of the peat surface when comparing water table depths at control and treatment sites. Using this method, water tables were observed to rise towards the peat surface by ~8 mm yr^{-1} (weekly manual surveys, Autumn-only) and ~16 mm yr^{-1} (daily mean data from loggers, year-round) throughout the monitoring period (up to 17 years at some sites), with no apparent slowing of the rise. Results were spatially variable, an effect likely due primarily to topographical differences (depth and density of gullies) and the extent of subsurface drainage networks. Insufficient replication of sites with a range of topographies and treatment regimes limited the possibility of determining the relative importance of these various controls on water table recovery.

While water table data from loggers at revegetated bare peat sites suggested limited change in behavioural response to precipitation (response remained flashy at control and treatment sites), data from soil moisture probes suggested a significant increase in the retention of water in the near-surface peat following precipitation where there was a vegetation cover (in particular where *Sphagnum* cover was extensive) as compared to bare peat. This has strong implications for the processes determining the generation of overland flow: in bare peat it is likely that overland flow generation was driven primarily by infiltration-excess, whereas in revegetated sites it is likely that overland flow was driven primarily by saturation-excess. The loggers used in this study are still under development and may require further optimisation for use in peat soils (and data were only available March – October 2021 and August–September 2022 so Winter data were not available), but these initial findings suggest they could be an important tool in furthering our understanding of the processes affected by restoration of degraded peatlands.

6.2. Species dominated

The species dominated sites experienced higher rainfall in the period after treatment, compared with the hot and dry period before, which included the spring and summer of 2018. The relatively low density of *Sphagnum* planting in the mini-catchment cluster areas mean that any effect on water table was likely to be negligible only a year after planting. However, *Sphagnum* cover on some of the intensively planted plots did increase substantially during period of the monitoring. This was the case on the *Calluna* and *Eriophorum,* and to a lesser extent *Molinia* sites. When considering the conclusions the relative dominance of each species type should be noted.

Overland flow on a peatland surface is generated either by, or as a combination of, a surface of low permeability retarding infiltration or by high water tables effectively providing the former.

On the *Calluna* dominated site there was no clear overall change in water tables observed during the monitoring. There was a minor deepening found relative to control at both cluster treatment sites, but this was not statistically significant. In contrast a small rise was observed in the intensive plots. During the period of monitoring the *Sphagnum* cover in the Spha intensive plots increased from 0% to ~18% (year 1) to ~21% (year 2); and in the SphaGB intensive plots from 0% to ~26% (year 1) and ~48% (year 2). The continuous water table record from the intensively planted plots (Spha) showed a very small, yet significant, rise in median water table (4.1 mm) – and a small rise (~30 mm) was also found from the manual measurements in both treatment intensive plots (Spha and SphaGB), albeit not a statistically significant change. These findings needs to be viewed with caution until further data from years with contrasting climate is obtained. The treatment site (Spha and SphaGB) cluster areas showed a greater increase in overland flow from the before to the after periods, compared to the control cluster.

On the *Eriophorum* dominated site, at the lower density planted cluster area, there was no statistically significant change in water table compared to control. However, a small but significant relative rise in median water table was observed by both manual (18 mm) and continuous (13.8 mm) dipwell data at the intensively planted plots. In these plots the *Sphagnum* cover had increased from 0% to a mean of ~28% cover one year after planting, and to ~53% after two years. These plots also showed an increase in the duration of water table above the surface after treatment. No significant lags in water table responses in the intensive plots were observed from the continuous water table record despite the increase in *Sphagnum* cover – suggesting that any flow attenuation has not affected the water tables below thus far. Although, spreading laterally, the planted *Sphagnum* has not yet had sufficient time to attain enough depth to change surface roughness substantially.

The *Molinia* dominated site was the only vegetation type to show statistically significant change in water table and in the lower density planted cluster area, despite *Sphagnum* cover only increasing from 0% to ~3.5% in that area during the monitoring. The manual dipwell measurements showed a small but significant rise in water table of 18 mm.
Both the manual and continuous records showed a small (~12 mm; manual, insignificant) (~17mm, continuous; significant) fall in water table in the intensive plots.

The treatment plot showed generally shallower raw median values throughout. This meant there was diminishing potential to reduce depth to water table, compared to the deeper control. Thus given equal forcing the control would likely provide a greater reduction. Throughout the monitoring, the treatment site tended to display more extremes of highly elevated or drawdown water tables depending on conditions – contrasting with the relatively stable control site. This observation points to a probable internal difference between the sites in how the water table in supported and/or supplied – possibly due to site morphology or even differences in hydraulic conductivity.

An increase in the duration of water table above the surface was also observed in the treatment plots. It is likely that this is simply a recovery post-drought (before period), to more typical behaviour at the treatment plot, which was more severely affected than the control. Like the *Eriophorum* site, this suggests that any flow attenuation has not affected the water tables below thus far. Although, spreading laterally, the planted *Sphagnum* has not yet had sufficient time to attain enough depth to change surface roughness substantially

No significant lags in water table responses were observed from the continuous water table record, despite increases in *Sphagnum* cover in the intensive plots.

The observations in this conclusion need to treated with caution when remarking upon the effects of *Sphagnum* due to the short time since planting, and the recovery of the sites from drought in the before treatment years. It is essential to continue monitoring to observe changes in overland flow and water table over a much longer period firstly to allow *Sphagnum* to gain greater coverage and depth but also to observe reactions to various climate conditions.

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MoorLIFE 2020

Published by MoorLIFE 2020, a Moors for the Future Partnership project in the EU designated South Pennine Moors Special Area of Conservation. Delivered by the Peak District National Park Authority as the lead and accountable body (the Coordinating Beneficiary). On the ground delivery was largely undertaken by the Moors for the Future staff team with works also undertaken by staff of the National Trust High Peak and Marsden Moor Estates, the RSPB Dove Stone team and the South Pennines Park (the Associated Beneficiaries).

Funded by the EU LIFE programme and co-financed by Severn Trent Water, Yorkshire Water and United Utilities. With advice and regulation from Natural England and the Environment Agency, and local advice from landowners.

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