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

CHAPTER 5: STREAM DISCHARGE

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

Chapter 5: Stream Discharge

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1. Summary

1.1. Bare peat sites

Heavily degraded blanket bog sites dominated by large areas of bare peat with deeply incised erosion gullies were revegetated, leaky dams were installed in the gullies and *Sphagnum* mosses were planted. Three mini-catchments were monitored (one untreated control; one revegetation only; one revegetation, gully blocking and – four years after initial treatment – *Sphagnum* planting) for ten years following initial treatment to assess effects on streamflow quantity and timing during storm events.

Restoration of bare peat by re-vegetation (by nurse crop grasses and plug plants of vascular species) immediately and significantly altered storm runoff. Storm flow was less flashy, with reductions in peak discharge and increases in lag times. Gully blocking enhanced the benefits of re-vegetation. There were no further changes to runoff as the vegetation and gully blocks matured.

The re-introduction of *Sphagnum* mosses provided significant additional benefits of flow attenuation which increased over time as the *Sphagnum* spread. *Sphagnum* cover of 10–15% was necessary before flow was altered; by the end of monitoring *Sphagnum* cover was estimated to be approaching 25% across the catchment and 85% in the flow pathway network. This resulted in a 65 percentage point (*pp*) reduction in peak discharge (4.2 $L\,s^{-1}\,ha^{-1}$) and a 650 *pp* increase in lag time (160 minutes). The changes are ongoing (both in terms of *Sphagnum* growth and flow attenuation) so the end point of the trajectory is unknown. There was no change in the volume of runoff leaving the system following any of the interventions, indicating that increased surface roughness is the key driver of flow attenuation.

The observed attenuation of storm flow was maintained in the most extreme events recorded at both treatment mini-catchments, suggesting that the restoration interventions were not overwhelmed in high flow conditions.

These findings suggest that restoration of bare peat by re-vegetation, gully blocking, and *Sphagnum* planting can contribute to natural flood management at the headwater scale. Modelling has suggested that, if the restoration techniques used at site N were applied to the 1,520 ha of suitable peatland in the Glossop catchment (4,000 ha), peak storm flows in 5–100 year return period events may be reduced by 5–12% in "long-blunt events" and 6–24% in "short-sharp events." This has important implications for designing flood management strategies at the catchment scale.

1.2. Species dominated sites

Based on the findings from the bare peat sites, *Sphagnum* may have a significant effect on storm flow characteristics in the future. However, the relatively low cover of *Sphagnum* (10% or less by 2021) in the mini-catchments only two years after planting mean that any effects on streamflow quantity or timing were likely to be negligible. Any changes to stormflow observed during this monitoring period are unlikely to be solely due to *Sphagnum* planting.

At the *Calluna* dominated site, relative peak discharge decreased at both treatment plots, albeit not significantly. The difference from control was similar for both treatment plots suggesting that gully blocking was not the significant factor in the changes seen. On both sites the relative peak lag time became significantly longer in the post-treatment period. Comparing sites suggest that gully blocking may have had more effect on peak lag than *Sphagnum* planting alone during these early post-treatment years. Both sites also saw a significant decrease in relative run-off co-efficient after treatment, suggestive of *Sphagnum* increasing the holding capacity of the catchment. No difference was found in the Hydrograph Storm Index.

At the *Eriophorum* site, relative peak discharge was reduced at the *Sphagnum* treatment weir in both years 1 and 2 post-treatment. The effect size although small, was statistically significant. The relative peak lag time at the treatment catchment was longer post-treatment, but not significantly. Run-off co-efficient results were unclear, due to the possible influence of confounding factors – however no significant changes were found, although a small decline in median relative run-off was seen in years 1 and 2 post-treatment. The relative Hydrograph Storm Index at the treatment plot was also lower in years 1 and 2 post-treatment, albeit this was not a significant result.

At the *Molinia* site, relative peak discharge was higher at the treatment catchment in the post-treatment years, but not significantly so. There were very small differences found between peak lag times in each catchment. Relative to control, treatment peak lag time was marginally lower, but not significantly. This change is unlikely to be related to the treatment. There were clear differences in the runoff-co-efficient between the control and treatment catchments both before and after treatment. In all three years, the *Sphagnum* catchment mean runoff was around 30%, suggesting that the catchment was storing a significant proportion of the rainfall during storm events. This supports findings in the water table chapter of this report suggesting that the catchments are hydrologically dissimilar. Relative to control, run-off co-efficient at the *Sphagnum* site was similar before and after planting. There was no clear trajectory in the relative runoff percentage after intervention. Relative to control, the Hydrograph Storm Index showed no change after planting. It should be noted that the treatment catchment showed different characteristics to the control before the intervention.

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.

Blanket peatlands are naturally hydrologically 'flashy' systems with streamflow responding rapidly to rainfall events, relatively short hydrograph lag times (time from peak rainfall intensity to peak discharge) and high peak flows relative to total storm runoff volumes (Evans *et al.* 1999). Degradation of blanket peatlands as described above can further increase the flashiness of streamflow response leading to higher stormflow peaks (Grayson *et al* 2010). Bare peat surfaces are relatively smooth (compared to vegetated surfaces), enabling rapid progress of rainfall over the surface and into stream channels. Areas of extensive bare peat are associated with dense drainage networks (erosional gullies and subsurface micropores, macropores and peat pipes), increasing drainage efficiency. This results in reduced lag times and higher stormflow peaks, with implications for areas downstream which may be at increased risk of flooding.

Areas dominated by a single vegetation species due to the loss of key blanket bog species such as *Sphagnum* mosses may have less rough surfaces than those with a greater diversity of species. Holden *et al.* (2008) found that overland flow velocities were significantly reduced by the presence of *Sphagnum* mosses as compared to surfaces dominated by grasses, suggesting that the planting of *Sphagnum* mosses in areas of dominance by single species could have benefits for reducing flood severity.

Landscape-scale restoration of degraded peatlands, through gully blocking, revegetation of bare peat, and diversification of vegetation communities is now extensive through the Peak District and South Pennines as well as other areas of the UK.

Allott *et al.* (2015) studied the effects of gully blocking and revegetation at bare peat sites on Kinder Scout in the first three years following the treatment works. Initial reductions in peak discharge and Hydrograph Shape Index and increases in lag time were observed; there was no observable change in rainfall-runoff percentage. The observed changes were best characterised by step changes (an immediate difference compared to baseline, but no clear continuation of any trends). The study found that restoration of bare peat "significantly alters peatland storm runoff behaviour, delaying the release of storm-flow from headwater catchments with benefits for downstream flood reduction".

The current study extended the dataset for the same bare peat sites as used in Allott *et al* (2015), adding six years of new data to the original study. Additionally, stream discharge was monitored at three sites dominated by single vegetation species or genus (*Calluna vulgaris, Eriophorum vaginatum, Molinia caerulea*), which were each diversified by the planting of *Sphagnum* mosses to assess whether this treatment affects storm runoff behaviour. The sites monitored in this study are presented in Table 1. The effects of leaky timber dams on stream velocity were monitored through a pilot study at an additional site – Robin Hood Moss.

Table 1: Sites at which stream discharge was monitored

Bare peat starting state (Kinder Scout)	Species dominated starting state
N	Heather (*Calluna*) – Derwent and Howden
O	Cotton-grass (*Eriophorum*) – Birchinlee
F (bare peat control)	Purple moor-grass (*Molinia*) – Moss Moor
P (intact reference)	

The study of stream discharge also provides context to other processes being monitored including water tables, water chemistry, and vegetation diversity.

Water tables in intact blanket peatlands are typically close to the ground surface (Evans *et al,* 1999), resulting in limited temporary in-soil water storage and rapid generation of saturation-excess overland flow during significant rainfall events. Degraded peatlands may have depressed water tables, which could increase temporary in-soil water storage (but also cause the extension of subsurface drainage networks). Bare peat surfaces are subject to the development of hydrophobicity (Egglesman *et al.* 1993) and potentially to surface compaction by raindrop action, both of which could reduce infiltration rates and result in infiltration excess overland flow production in high intensity rainfall events (Allott *et al.* 2015). Restoration of bare peat surfaces through revegetation could affect multiple hydrological processes, with potentially confounding effects on overland flow generation, as outlined in Table 2.

Table 2: Possible effects of revegetation on overland flow generation

Effect on hydrological process	Effect on overland flow generation
Vegetation cover increases albedo and insulation of previously bare peat, reducing evaporation from drying effects of sun and wind: water tables stay closer to the surface	Saturation-excess overland flow increases
Vegetation cover holds water on the peat surface (within the canopy and on the surface between vegetation clumps), slowly releasing it into the peat: water tables are continuously replenished and stay closer to the surface	Saturation-excess overland flow increases
Vegetation roots break up the peat surface, increasing infiltration rates; water tables stay closer to the surface	Infiltration-excess overland flow reduces; saturation-excess overland flow increases
Vegetation cover increases evapotranspiration rates: water tables are lowered	Saturation-excess overland flow is reduced

Allott *et al.* (2015) observed an increase in overland flow generation two years after revegetation of bare peat at the study sites on Kinder Scout – suggesting that the process leading to increases in saturation-excess overland flow generation outweighed those leading to reductions in infiltration-excess overland flow. In the current study, extended datasets were assessed to determine whether this initial trend was continued. Soil moisture probes were also installed to compare soil moisture at a range of depths below the peat surface at the revegetated and untreated bare peat control sites, allowing a more detailed assessment of saturation/infiltration behaviour. In addition, sites that were already vegetated and dominated by a single species had *Sphagnum* moss plug plants introduced in order to measure the effects of this introduction on the hydrological processes taking place on the site.

2.1. Treatment regimes

2.1.1. Bare peat sites

The bare peat restoration process carried out on the Kinder sites is described in detail in the Introduction 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, fertilizer and plug plants of moorland species. In addition, erosion gullies were blocked with both stone and timber dams. In 2015–2018 *Sphagnum* mosses were reintroduced to some areas in the form of mixed species plug plants. The treatments applied, and dates of application for each of the main field sites are summarised in Table 3 below. The success of the revegetation works at experimental mini-catchments O and N is described in the Diversity section of this report. In 2010 there was extensive bare peat at both mini-catchments; by 2015, they were both fully vegetated. In the following years a succession process replaced nurse crop species with more natural moorland species and the thickness and density of the canopy increased. At N, *Sphagnum* cover in monitored quadrats (representing hillslopes/undulating ground) increased from 0% prior to planting in 2015 to ~25% in 2021. *Sphagnum* cover in the network of flow pathways/streams at N increased from 0% prior to planting in 2015 to ~73% in 2021.

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:

The 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 3 below.

Table 3: Summary of treatments applied to main monitoring sites

Restoration process	Bare Peat sites				*Calluna* sites			*Eriophorum* sites		*Molinia* sites	
	F	**P**	**O**	**N**	Cal.con	Cal.spha	Cal.spha.gb	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	-	-	-	-	-	-	-
Plug plants (moorland species)	-	-	2011	2011	-	-	-	-	-	-	-
Sphagnum planting	-	-	-	2015, 2018	-	2019	2019	-	2019	-	2019

2.1.3. Gully blocking trial

Six leaky timber dams were installed at approximately 7 m intervals in one gully (width ~2.5 m at top of each dam) at trial site Robin Hood Moss in January 2019. The dams were each constructed using 4 or 5 wooden planks (150 mm tall) across the gully, attached to 75 x 75 mm vertical posts, with a 20 mm gap between each plank. The gaps were observed to block up frequently with heather debris and eroded peat sediment. In November 2019 the gap height was increased to 30mm at all dams. No other treatment was applied.

3. Methodology

3.1. Experimental design

Field labs based on mini-catchments were established to monitor changes in streamflow behaviour within 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 where these were required. 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.

Catchment discharge was monitored by installing 'V' notch weirs at the outflow point of each mini-catchment, whilst on the species dominated sites overland flow was also monitored by installing three 'intensive plots' in each mini catchment, using rain-gauge tipping buckets to measure the volume of water flowing from the surface of each plot.

At the gully blocking trial site, no v-notch weirs or rain gauges were installed. Water stage height was monitored (using automatic water level sensors) in the pools created by the top and bottom dams of a series of six leaky timber dams installed in a single gully, in order to monitor the travel time of peak stage from the top dam to the bottom dam. Water level sensors (capacitance probes) were installed in the gully three months before the installation of gully blocks, to collect baseline data. Data collection then continued until July 2021. The post-treatment period was divided into two sections – 20 mm slots (January – November 2019); 30 mm slots (December 2019 – July 2021).

3.2. Field set up

3.2.1. Rainfall

Rainfall was monitored using rain gauges with tipping buckets installed at each site. These recorded total rainfall every 10 minutes at the bare peat sites and every 5 minutes at the species dominated sites. It should be noted that these rain gauges also record snowmelt. Snowfall accumulates in the rain gauge collector and is recorded by the logger only at the time it melts.

3.2.2. Overland flow

The occurrence of overland flow on the species dominated sites was detected using 'run-off plots', also referred to elsewhere in this report as 'intensive plots'. These comprised of a plastic gutter with one side inserted horizontally into the peat surface below the plot, which was itself bounded by thin sheets of marine plywood – representing an area of 3 m^2. The gutter was slightly angled sideways, and flow that emerged from the ground surface within the plot was diverted along its length, via a pipe and into a tipping bucket rain gauge.

The tipping bucket rain gauges were set to continuously monitor flow at 5 minute intervals. However, due to operational issues associated with monitoring remote field locations, there were periods where no data were collected for some sites, resulting in gaps in the record.

3.2.3. Discharge

V-notch weirs and pressure transducers were installed at the catchment outlets of all sites, with the angle of the v-notch aperture at each weir being selected to match expected discharge rates, based on the size of the mini-catchment (see Table 4)

Pressure transducers recorded the stage height of water (cm) flowing over the v-notch weir, which was subsequently converted to discharge (L sec^{-1}). Discharge values were then standardised by dividing by catchment area (ha) to produce discharge values that could be compared between the different catchments (L sec^{-1} ha^{-1}). The pressure transducers were set to monitor stage height continuously at 10-minute (bare peat sites) or 5-minute (species dominated sites) intervals. These data were converted to v-notch stage height using calibration relationships based on in-field measurements of v-notch stage height using a thin metal ruler. Rain gauges were also installed, and set to continuously monitor rainfall at 10-minute (bare peat sites) or 5-minute (species dominated sites) intervals.

Table 4: Angle of v-notch and logging interval at each monitored mini-catchment

Mini-catchment	V-notch angle	Logging interval (mins)
F	90	10
N	90	10
O	90	10
P	45	10
Calluna	45	05
Eriophorum	45	05
Molinia	45	05

In the bare peat mini-catchments, rainfall and discharge data were available for each catchment from May 2010 to December 2021. In the species dominated mini-catchments rainfall and discharge data were available from April 2018 to end March 2021. However, due to operational issues associated with monitoring remote field locations, there were periods where no data were collected for some sites, resulting in gaps in the record.

The weirs at the bare peat sites were installed at the start of the Making Space for Water project (2010) and required replacement during MoorLIFE 2020. The severity and rate of erosion within the gully channels on the Kinder plateau presented a challenge to all 3 weirs in terms of maintaining a watertight seal at the sides and base of the weirs. Due to the restoration works at mini-catchments O and N and the subsequent stabilisation of the gully banks, this pressure was mainly restricted to the first years after installation, but the weirs, on inspection, were still vulnerable to failure. At weir F (the untreated bare peat control mini-catchment), the ongoing erosional forces led to a series of partial failures from summer 2017 and a full failure in November 2017, with a channel opening under the base of the weir, allowing the stream to bypass the v-notch in the top of the weir entirely.

It was decided to replace all three weirs, in order to reinstate flow monitoring at F, and safeguard against possible future failures at O and N. The new weirs were constructed using the same design as the originals, although 18 mm birch plywood was used, as opposed to 12 mm marine plywood as used in the originals, in order to maximise the lifespan of the weirs. The new weirs were installed as close as practicable to the original weir locations. In all cases, this resulted in moving the weir 1–3 metres upstream. Where possible (F and O), the new weirs were installed flush to the upstream face of plywood baffles installed at the start of the Making Space for Water, providing some extra protection against erosion. Rocks were placed against the upstream and downstream faces of all the new weirs, to reduce the erosional force of streamflow. A wooden access stairway and platform was constructed at each new weir, allowing access for monitoring, maintenance, calibration readings, downloads and water sampling without causing any foot erosion to the bank or streambed around the weirs. The dates of the weir replacements were as follows:

- F on 7/12/2017
- N on 19/8/2018
- O on 26/8/3028

3.3. Data analysis

3.3.1. Bare peat sites

3.3.1.1. Hydrograph extraction

Following the same method as in Shuttleworth *et al* (2019), storm hydrographs were extracted from the continuous rainfall runoff record for all rainfall events where: (i) total rainfall exceeded 4 mm; and (ii) rainfall occurred as a discrete event with a single associated discernible main peak in discharge. Complex multi-peak hydrographs were excluded. The rainfall and runoff data from these hydrographs were used to calculate four key metrics: (i) lag time between peak rainfall and peak flow (lag); (ii) peak storm discharge (peakQ); (iii) Hydrograph Shape Index (HSI) (the ratio of peak storm discharge to total storm discharge, a measure of hydrograph intensity whereby high numbers indicate flashy hydrographs and low numbers indicate more attenuated flow); and rainfall runoff coefficient (*C*).

3.3.1.2. Data quality control

As storm-flow characteristics are influenced by antecedent conditions and the nature of rainfall events (Evans *et al*, 1999), the mismatch in storm events at the different sites could lead to substantial bias when comparing metrics between catchments. 258 storms were captured at all three sites. By considering only the hydrographs derived from these storm events for which metrics could be extracted for all three catchments, runoff behaviour resulting from similar rainfall and antecedent conditions could be compared directly. This reduced dataset allows for a strict and robust comparison of the data, and is the primary dataset used for all subsequent statistical analysis.

As outlined in Shuttleworth *et al* (2019) and Edokpa *et al* (2022), there is considerable 'noise' even in the reduced dataset, due to the range of rainfall behaviours and antecedent conditions; total rainfall per event ranges from 4 to 48 mm, and maximum event rainfall intensity ranges from 1.8 to 47 mm h^{-1}. There were no significant differences in rainfall metrics during the three phases of restoration (Kruskal Wallis 1-way ANOVA, $p > 0.05$ for both parameters). However, there was a high degree of variability within each phase, leading to a wide range of runoff responses in the storm-flow metrics. By standardising the metrics derived at the treatment catchments against the control catchment we can differentiate responses due to restoration treatment from natural variation. This was achieved by deriving the relative difference (treatment minus control) between the metrics produced by control and treatment sites.

3.3.1.3. Statistical analyses

Many of the variables of interest do not follow a normal distribution, so non-parametric tests of difference were employed to determine the statistical significance of the influence of restoration.

Shuttleworth *et al* (2019) showed that there were initial step changes in some metrics immediately following restoration, with no discernible trends in the first three years after the first phase of restoration works in 2011. The same method was followed in this study, using a Before-After-Control-Impact design. Kruskal Wallis one-way ANOVA tests were used to assess similarity between the three sites during the pre-restoration baseline period and Mann-Whitney U tests to assess the magnitude and significance of step changes following restoration. Additionally, break point analysis (Topál *et al* 2016) was conducted to determine any longer-term trends following an initial step change, in particular to investigate the impact of increasing *Sphagnum* cover at site N. All relationships were tested at the 95% level ($p \leq 0.05$).

In using non-parametric analyses, it was not possible to assess the additional benefit of gully blocking or the impact of *Sphagnum* planting statistically, as there is no non-parametric equivalent of a 2-way ANOVA which would allow the examination of the effect of the interaction of the two factors ('before/after restoration' and 'treatment type') in an unbalanced dataset. Consequently, any impacts of additional treatments are discussed in terms of additional magnitude of change relative to re-vegetation alone.

3.3.1.4. Extreme storm events

To assess the potential utility of peatland restoration as an NFM (Natural Flood Management) measure in upland catchments, it is important to understand the degree to which changes in runoff delivery are maintained in high magnitude events. In particular, if hillslope and channel storage control runoff, then NFM efficacy may be reduced in large storms since storage as a proportion of storm runoff would be reduced. To investigate whether NFM benefits were sustained for the full range of storm sizes in the dataset, the metrics derived from the post-restoration data were compared to estimates of how the treatment catchments would have behaved had no intervention taken place for the full range of observed storm sizes in 2014 (representing the end of phase one, before the application of *Sphagnum* at site N) and 2021 (representing the end of phase two/the end of the monitoring period). These estimates were derived for each metric using the relationship between the treatment and control catchments during the pre-restoration period. All metrics produced moderate to strong statistically significant linear relationships (Table 5).

For metrics with no apparent trends between the observed values and the deviations from the pre-intervention trend, simple *t*-tests were used to assess differences between the two phases of restoration. For metrics that displayed significant trends in the relationship between observed values at the control site and deviations, general linear models (GLM) were used to assess differences between the two phases of restoration (see Shuttleworth *et al* 2017).

Table 5: Relationships between the control and the two treatment catchments during the pre-restoration period

	R^2	p-value	Equation of line
F vs O			
Lag	0.942	< 0.0001	y = 0.9607x – 4.7359
Peak Storm Q	0.944	< 0.0001	y = 1.2286x – 0.3610
HSI	0.917	< 0.0001	y = 0.9472x + 0.0198
C	0.610	< 0.0001	y = 0.8789x + 9.0399
F vs N			
Lag	0.958	< 0.0001	y = 1.0896x – 4.3971
Peak Storm Q	0.931	< 0.0001	y = 0.8678x + 0.5631
HSI	0.658	< 0.0001	y = 0.8436x + 0.0495
C	0.701	< 0.0001	y = 0.7658x + 4.3098

3.3.2. Species dominated

3.3.2.1. Overland flow

Obtaining overland flow records from tipping buckets at the intensive plots proved problematic over the period of the study. Equipment failures and challenges of a hostile environment in terms of weather and wildlife created issues in terms of data quality and completeness. One issue in the design was that the tipping buckets became overwhelmed with water and thus underestimated the volume of water at high flow. Issues were most apparent at the *Molinia* dominated sites where no useable data were collected. To utilise the records obtained in the most robust way it was decided to avoid measures related to volume due to underestimation at high flows and instead concentrate on timing lags of events between a) the start of a rainfall and the start of the rising limb of the associated overland flow hydrograph and b) the peak in rainfall and the peak in associated overland flow hydrograph.

The rainfall time series record at each species dominated site was divided into events. To qualify as an event there needed to be at least a two-hour gap with zero rainfall between preceding and new events. The timing of the start and peak of the rainfall event was recorded. Secondly, the tipping bucket data were analysed to differentiate storm events by searching for changes in the slope of the hydrograph allowing separation of peak and baseflow. Baseflow here would generally equate to zero. Within these storm events the start of the rising limb of the event and peak flow were recorded. The rainfall events were then associated with the storm events and the metrics of a) lag from rain start and start of hydrograph rising limb and b) lag from rainfall peak and hydrograph peak were derived.

Although many events were found, selective filtering occurred by examining individual hydrographs (an example is show in Figure 1) to ensure robust quality comparisons. Events used in the analysis were reduced to those with simple hydrographs ideally with a single peak or at least a clear dominant peak. Records that showed signs of the tipping buckets being overwhelmed with flow were discarded unless this was for a minimal period. Although as part of the analysis unpaired storms have been displayed, the more powerful comparisons are between control and treatment plots when the storms compared at both are paired and therefore relate to the same storm event. This latter condition led to a substantial reduction of useable events at the sites.

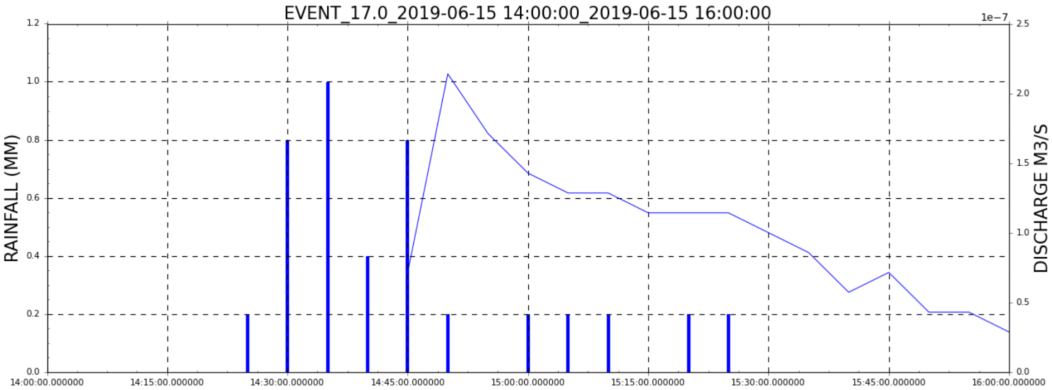

Figure 1: Example of an overland flow event at the *Eriophorum*-species dominated site in plot 1

Lag metrics were derived for records from each of the three intensive plots from the two treatments (total of six records) at the *Eriophorum* and three treatments (total of nine records) at the *Calluna* dominated sites. Paired storm events at each species dominated location were found when events from any of the three control intensive plots were matched temporally with recorded events from any of the three treatment intensive plots. There could potentially be three hydrographs derived for a control and three for the treatment for the same event and therefore the mean of the lag metric was produced and presented.

3.3.2.2. Discharge

The rainfall records at each site were used to identify periods of high rainfall intensity – more than 4 mm of rain in less than 8 hours. These were classed as 'high rainfall events'. The discharge on the two or three weirs at each vegetation type during the high rain events were automatically plotted, alongside the rainfall. From these data and plots, the beginning of the storm (the start of the rainfall), the end of the storm (when the discharge had returned to baseflow) and various other metrics were calculated for each storm. Not every high rainfall event resulted in storm metrics.

There were 363 high rainfall events at *Calluna*, 337 at *Eriophorum* and 388 at *Molinia*. There needed to be reliable discharge data from all three *Calluna* weirs, and both weirs at *Eriophorum* and *Molinia* sites. Any high rainfall events that took place when the air temperature was less than 5°C were discarded, to remove the potential confounding factor of snow and ice melt. High rainfall events that included a low-intensity rainfall over several hours did not qualify as storms. Where several high rainfall events occurred consecutively, discharge did not return to baseflow conditions, so these were not included in further analysis. After final quality checks, there were 80 storms at *Calluna*, 79 at *Eriophorum* and 90 at *Molinia* (Table 6).

Table 6: Number of storm events used in further analysis from each vegetation type during each BACI year.
Year 0 is before any intervention, year 1 is the first 12 months after catchment interventions, and year 2 is the second 12 months after catchment interventions

	Number of storm events analysed		
BACI year	*Calluna*	*Eriophorum*	*Molinia*
0	24	41	27
1	38	20	34
2	18	18	29
Total	80	79	90

The metrics calculated for each storm were: (i) peak discharge (the highest total discharge during each storm – peakQ); (ii) lag (time between peak rainfall and peak discharge); (iii) rainfall runoff coefficient (the proportion of the rainfall over the catchment that was discharged via the weir); and

(iv) HSI (hydrograph shape index – a measure of the storm ‘intensity’ calculated from peak storm discharge volume and total storm discharge volume).

Examples of storm hydrographs from the *Calluna* site are shown in Figure 2 (note the range in peak discharge)

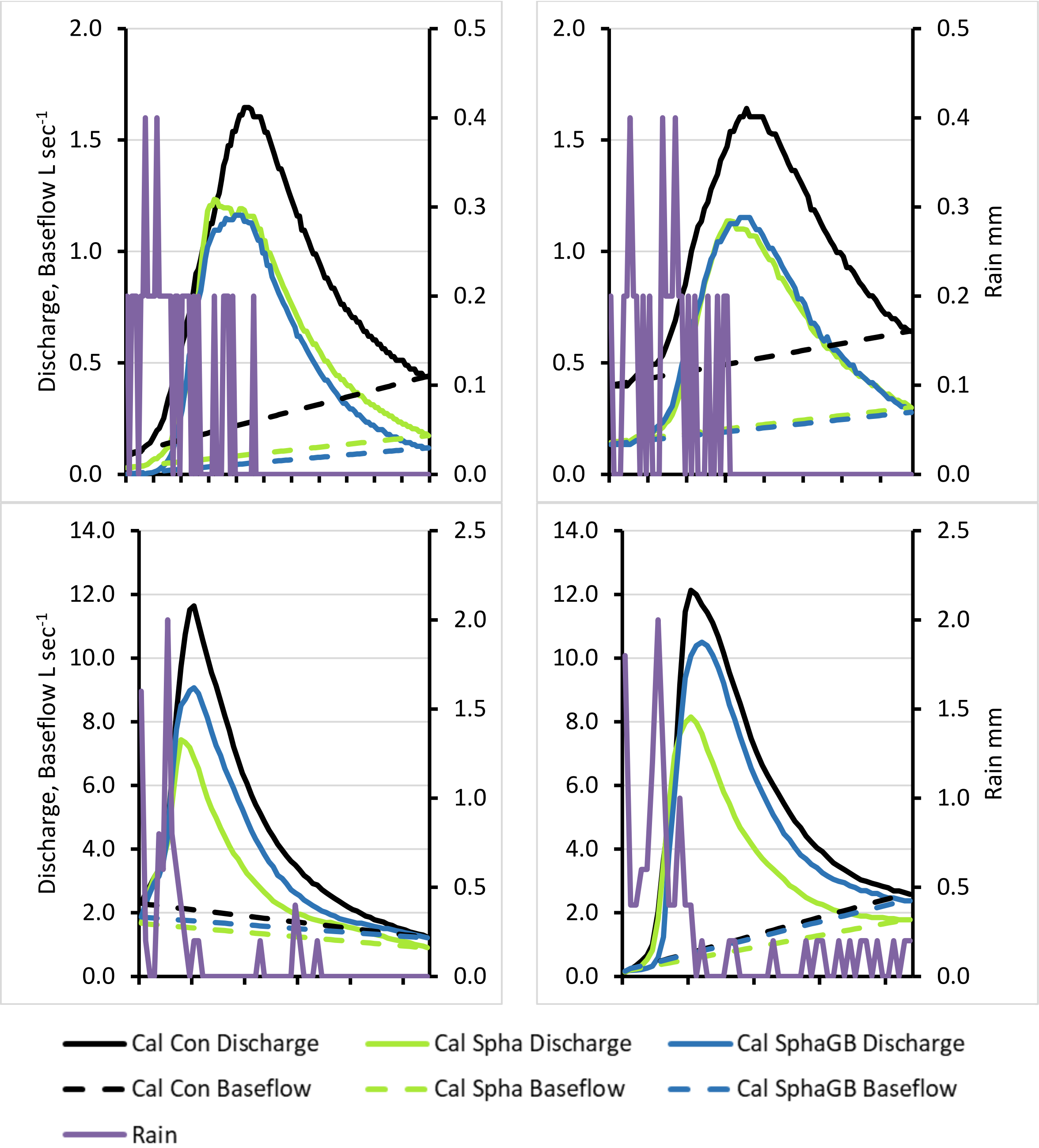

Figure 2: example storm hydrographs from the *Calluna* site. X-axis tick marks indicate hours since the beginning of the storm.

Rainfall-runoff co-efficient may be used to infer the in-storm storage capacity of the site. If the co-efficient is 100%, all of the rain that fell on the site was then exported from the catchment via the weir during the storm. Runoff values of less than 100% indicate that the catchment is retaining some of the rainfall volume, and more than 100% indicates that more water has been flushed from the catchment than was input as rain during that storm. Values of over 100% are more likely to occur when there are several high rainfall or storm events consecutively. Increasing the in-storm storage capacity of catchments (i.e. reducing runoff percentage) may have NFM benefits.

The hydrograph shape index (HSI) reflects the intensity of the storm. It is calculated using storm peak discharge volume and total storm discharge volume. A low value HSI indicates low storm peak and/or a very large total volume, whereas a high value HSI indicates a high storm peak and/or a small total volume. If two storms have similar total discharge volumes, but one has a high peak volume and one has a low peak volume, the HSI value of the storm with the high peak value will be higher than the storm with a low peak volume. Decreasing the HSI suggests that the catchment is becoming less 'flashy' and this may be associated with NFM benefits.

Statistical tests were carried out where the box and whisker plots indicated there might be significant differences. Non-parametric, one-way Mann-Whitney U statistics were used to compare the 'before' (BACI year 0) to the 'after' (BACI year 1 and 2 combined) relative metrics (Spha relative to Con, or SphaGB relative to Con).

3.3.3. Gully blocking trial

Discrete high-flow events were identified from the data recorded by the stage loggers. The timing of maximum water stage was recorded at the upper and lower logger locations, and the difference between these times was calculated (referred to as 'lag' time). Lag times were then compared for high flow events during baseline and post-treatment periods.

4. Results

4.1. Bare peat sites

4.1.1. Discharge

This study was a continuation of existing monitoring as reported in Shuttleworth *et al* (2019). The values for the pre-intervention period and first three years following restoration are slightly different to those reported previously, due to gap filling in the rainfall record allowing more hydrographs to be extracted.

4.1.1.1. Baseline data

Prior to restoration, storm hydrographs at the three sites behaved in a similar manner (Table 7): median lag times ranged between 20 and 30 min, median peak storm discharges were between 3.49 and 4.85 $L\,s^{-1}\,ha^{-1}$, median HSI ranged between 0.15 and 0.17, and median *C* values (rainfall-runoff co-efficient) were between 30% and 38%. There were no significant differences in hydrograph metrics at the three sites before treatment (Kruskal Wallis 1-way ANOVA, $p > 0.05$ for all parameters). Figure 3 includes an example hydrograph from the pre-restoration period, illustrating this similar behaviour.

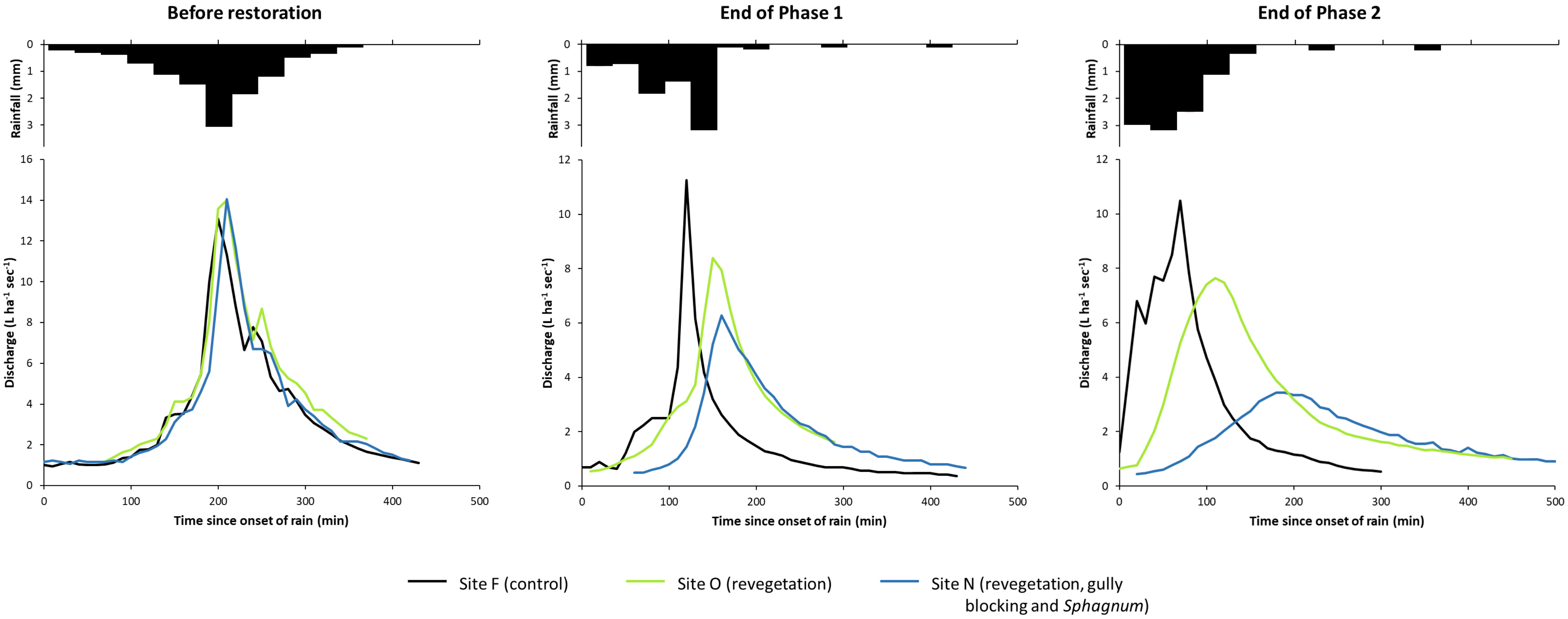

Figure 3: Examples of storm hydrograph responses at the bare peat sites before restoration, at the end of Phase 1 (2014) and at the end of Phase 2 (2021)

4.1.1.2. Trajectories of change over 10 years

Annual descriptive statistics for the four key hydrograph metrics at the three micro-catchments are summarised in Table 7 for reference, but this section focusses on the relative difference between the treatment and control sites (treatment minus control), before and after restoration. Henceforth, these relative differences are referred to as lag_{rel}, $peakQ_{rel}$, HSI_{rel}, and C_{rel}. The relative differences between the treatment and control sites are presented in Table 8 and Figure 4. In Figure 4, the data have been normalised so that the relative values for the pre-restoration period equal zero for ease of interpretation. Positive values on the y-axis indicate that the metric of interest has increased at the treatment site compared to the pre-restoration baseline, while negative values indicate that that the metric of interest has decreased at the treatment site compared to the pre-restoration baseline. All parameters are discussed in terms of their median value.

The restoration works had an immediate effect on three out of the four metrics at both treatment sites. Lag_{rel} increased and both $peakQ_{rel}$ and HSI_{rel} were reduced immediately following restoration. C_{rel} showed no clear directional trends following restoration. At site O (revegetation), the break point analysis showed that there were no subsequent directional trends after the initial step changes following revegetation. At site N, there were no directional trends for the first five years after the step changes following the initial phase of restoration (revegetation and gully blocking). Following the second phase of restoration (*Sphagnum* planting), gradual changes were evident in lag_{rel} and $peakQ_{rel}$ throughout the last five years of monitoring, but there was no further change in HSI_{rel}.

Table 7: Annual summary statistics for the four key hydrograph metrics at the bare peat sites

		2010-11	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
	Years post-rest.	0	1	2	3	4	5	6	7	8	9	10
	n	33	26	28	18	14	23	31	18	31	17	19
Site F												
Lag (min)	Median	30	25	5	7	15	25	25	35	15	25	25
	Maximum	335	105	145	165	150	185	335	145	125	420	75
	Minimum	5	5	5	0	5	5	5	5	5	5	5
	Q1	15	15	5	5	5	15	15	15	15	15	15
	Q3	35	69	15	15	31	45	50	54	32	55	35
Peak Storm Discharge (L s^{-1} ha^{-1})	Median	3.49	4.95	4.45	7.03	8.41	7.12	4.22	4.89	4.97	5.75	5.76
	Maximum	30.76	37.77	72.73	19.21	21.34	20.66	22.71	18.75	71.10	44.54	27.96
	Minimum	0.00	1.25	0.64	0.25	1.44	0.53	0.57	0.90	0.70	2.11	2.25
	Q1	1.89	4.47	2.74	3.07	6.02	4.61	2.03	2.51	2.85	4.04	4.20
	Q3	8.23	11.14	10.97	12.31	13.39	11.80	8.47	10.10	19.90	9.59	10.84
HSI	Median	0.15	0.17	0.20	0.25	0.16	0.15	0.15	0.10	0.12	0.16	0.13
	Maximum	0.69	0.57	0.92	1.07	0.59	0.64	0.55	0.42	0.52	0.49	0.36
	Minimum	0.05	0.07	0.06	0.07	0.07	0.07	0.03	0.03	0.04	0.04	0.06
	Q1	0.10	0.13	0.15	0.14	0.12	0.10	0.10	0.07	0.09	0.09	0.10
	Q3	0.21	0.28	0.38	0.42	0.26	0.19	0.20	0.18	0.26	0.25	0.18
Rainfall-Runoff Coefficient (%)	Median	34.6	39.3	29.2	29.7	43.8	57.6	42.9	48.4	43.0	47.6	38.6
	Maximum	78.3	70.7	56.3	74.4	68.0	81.7	158.8	101.6	105.1	92.7	119.5
	Minimum	8.1	9.7	2.7	0.3	17.7	4.1	6.6	19.7	4.4	9.8	8.9
	Q1	18.6	31.0	21.8	18.2	37.7	36.8	23.6	29.2	29.8	40.5	26.6
	Q3	54.5	49.4	40.0	49.9	57.6	62.2	78.0	60.8	59.2	63.4	46.9
Site O												
Lag (min)	Median	20	55	25	35	30	45	65	55	65	50	55
	Maximum	330	115	185	240	155	435	475	195	275	470	135
	Minimum	0	5	5	15	15	15	15	25	25	25	25
	Q1	15	25	15	25	25	30	42	45	40	40	33
	Q3	45	95	28	63	63	60	113	85	89	85	80
Peak Storm Discharge (L s^{-1} ha^{-1})	Median	4.85	4.31	4.15	5.88	5.21	4.84	3.27	3.51	3.54	2.83	6.74
	Maximum	40.27	33.94	63.90	17.34	21.63	14.55	15.24	9.95	46.56	15.14	17.21
	Minimum	0.67	1.49	0.14	1.10	0.45	0.41	0.37	0.72	0.55	1.00	1.35
	Q1	2.89	2.55	2.52	3.28	2.83	2.88	1.37	2.20	1.73	1.44	4.28
	Q3	11.79	6.51	6.76	9.94	7.64	7.02	4.92	4.79	8.94	4.39	8.87
HSI	Median	0.16	0.13	0.16	0.17	0.13	0.11	0.08	0.08	0.09	0.11	0.09
	Maximum	0.68	0.74	0.44	0.37	0.24	0.23	0.33	0.26	0.46	0.25	0.15
	Minimum	0.04	0.06	0.05	0.06	0.06	0.05	0.02	0.04	0.03	0.03	0.05
	Q1	0.11	0.11	0.11	0.11	0.09	0.09	0.06	0.06	0.06	0.09	0.08
	Q3	0.23	0.20	0.21	0.23	0.21	0.12	0.13	0.10	0.16	0.13	0.12
Rainfall-Runoff Coefficient (%)	Median	38.4	37.1	37.7	45.0	50.0	39.9	50.6	47.9	43.7	32.2	58.4
	Maximum	109.9	66.9	63.5	83.1	85.3	63.5	159.2	63.2	73.5	79.0	100.2
	Minimum	9.0	13.4	1.3	6.2	4.4	7.2	7.3	16.4	8.5	12.7	22.7
	Q1	22.9	28.4	25.5	36.0	30.0	35.8	31.4	33.9	33.5	22.2	36.6
	Q3	59.2	43.7	51.3	60.3	57.9	47.4	59.8	50.6	63.7	43.9	75.8
Site N												
Lag (min)	Median	30	82	65	70	65	95	125	145	115	115	195
	Maximum	405	315	325	235	335	275	475	445	405	495	435
	Minimum	5	5	5	10	15	35	25	65	15	25	25
	Q1	15	45	33	36	56	70	80	105	60	45	100
	Q3	35	125	135	153	115	135	203	280	213	235	265
Peak Storm Discharge (L s^{-1} ha^{-1})	Median	4.29	3.07	1.77	3.99	3.82	4.13	1.96	2.64	3.30	1.57	2.24
	Maximum	26.42	29.63	35.98	15.66	21.31	11.30	10.99	5.93	38.63	13.68	14.46
	Minimum	0.43	0.08	0.04	0.13	0.12	0.02	0.05	0.46	0.01	0.07	0.24
	Q1	2.39	2.14	0.60	1.44	1.72	2.55	1.05	0.82	1.20	0.68	0.77
	Q3	13.30	6.11	5.70	6.27	7.12	6.52	3.58	3.83	8.14	3.10	4.40
HSI	Median	0.17	0.11	0.11	0.13	0.10	0.08	0.07	0.06	0.05	0.06	0.06
	Maximum	0.68	0.36	0.56	0.39	0.60	0.16	0.17	0.10	0.39	0.20	0.11
	Minimum	0.06	0.06	0.05	0.06	0.03	0.02	0.02	0.02	0.03	0.03	0.03
	Q1	0.12	0.09	0.08	0.08	0.07	0.06	0.05	0.04	0.04	0.04	0.04
	Q3	0.23	0.14	0.15	0.19	0.11	0.12	0.09	0.07	0.14	0.09	0.08
Rainfall-Runoff Coefficient (%)	Median	29.5	34.6	27.3	35.4	44.8	41.8	37.9	37.5	39.8	29.9	22.1
	Maximum	64.9	66.3	66.1	69.7	94.0	78.3	103.8	95.5	74.0	65.0	69.3
	Minimum	3.3	0.4	0.2	0.4	0.3	0.1	0.9	14.3	0.0	0.7	2.8
	Q1	19.2	28.1	8.9	20.1	33.2	29.2	30.5	28.3	29.6	20.5	12.0
	Q3	50.1	44.9	43.7	42.4	60.7	54.0	49.6	50.7	57.7	43.0	40.1

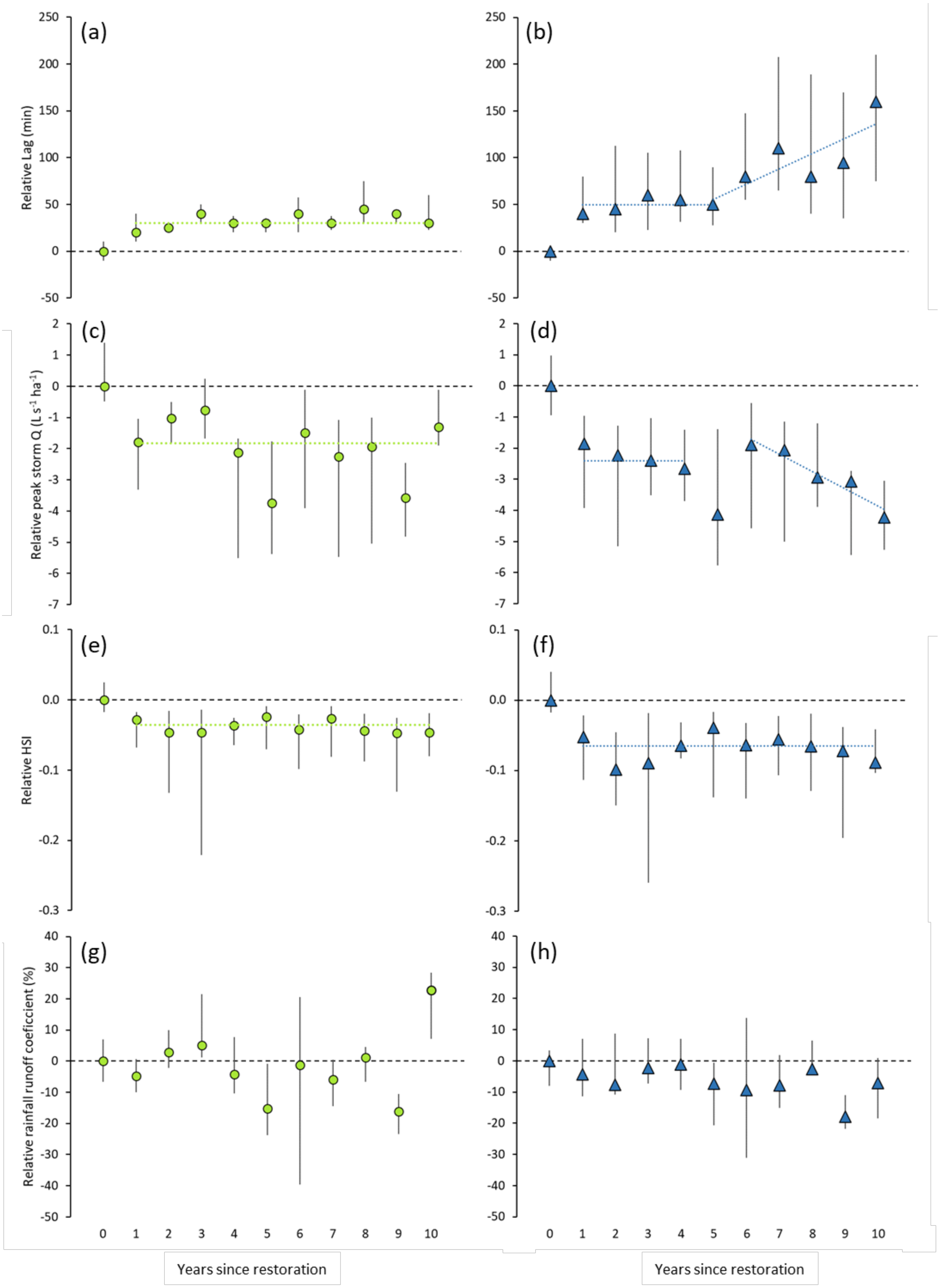

Figure 4: Annual median relative differences between the bare peat treatment and control sites for key hydrography metrics: lag time (a and b), peak discharge (c and d), Hydrograph Shape Index (e and f), and percent runoff (g and h). Green markers represent site O (revegetation) and blue markers represent site N (revegetation, gully blocking and *Sphagnum* planting). Statistically significant step changes and trajectories are marked as dotted lines

4.1.1.2.1. Step changes following the initial phase of restoration

At site O, as there were no directional trends in any of the metrics following initial step changes, average values were derived for the entire post-treatment period. The step changes at site N were considered in light of the break point analysis (see above). As a result, average values were derived for the first five years post-treatment for lag_{rel}, the first four years post-treatment for $peakQ_{rel}$ and for the whole post-treatment period for HSI_{rel} and C_{rel}.

4.1.1.2.1.1. Peak discharge

At site O, before restoration, median $peakQ_{rel}$ was 0.52 L s^{-1} ha^{-1} (119% of that at the control site). Following treatment, $peakQ_{rel}$ ranged between -3.21 and -0.24 L s^{-1} ha^{-1} annually, with a median value of -1.3 L s^{-1} ha^{-1} (75% of that at the control site). This represents a statistically significant decrease in $peakQ_{rel}$ of 1.82 L s^{-1} ha^{-1} (Figure 4 c), or a 45 *pp* decrease in peakQ relative to the control ($p < 0.001$, Mann-Whitney U).

At site N, before treatment, median $peakQ_{rel}$ was 0.04 L s^{-1} ha^{-1} (106% of that at the control site). For the first four years following treatment, $peakQ_{rel}$ ranged between -4.19 and -1.81 L s^{-1} ha^{-1} annually, with a median value of -2.27 L s^{-1} ha^{-1} (56% of that at the control site). This represents a statistically significant decrease in $peakQ_{rel}$ of 2.31 L s^{-1} ha^{-1} (Figure 4 d), or a 50 *pp* decrease in peakQ relative to the control ($p < 0.001$, Mann-Whitney U). Installing gully blocks in addition to revegetation as part of the bare peat treatment decreased $peakQ_{rel}$ by an additional 0.49 L s^{-1} ha^{-1} (i.e. peakQ decreased by a further 5 *pp* relative to the control).

4.1.1.2.1.2. Lag time

At site O, before treatment, median lag_{rel} was −10 min (lag was 67% of that at the control site). Following treatment, lag_{rel} ranged between 10 and 30 min annually (Table 8) with a median value of 20 min (lag was 250% of that at the control site). This represents a statistically significant increase in lag_{rel} of 30 min (Figure 4 a), or a 183 percentage point (*pp*) increase in lag relative to the control ($p < 0.001$, Mann-Whitney U).

At site N, before treatment, median lag_{rel} was 0 min (lag was equal to or 100% of that at the control site). For the first five years following treatment, lag_{rel} ranged between 30 and 60 min, with a median value of 50 min (lag was 500% of that at the control site). This represents a statistically significant increase in lag_{rel} of 50 min (Figure 4 b), or a 400 *pp* increase in lag relative to the control ($p < 0.001$, Mann-Whitney U). Installing gully blocks in addition to revegetation as part of the bare peat treatment increased lag_{rel} by a further 20 min (i.e. lag increased by an extra 217 *pp* relative to the control).

4.1.1.2.1.3. Runoff co-efficient

At site O, C_{rel} varied substantially from year to year, with no evidence of a step change or directional trend. Before treatment, median C_{rel} was 1.6% and following treatment, C_{rel} ranged between -14.6% and 24.3% annually, placing the pre-treatment baseline within the range of the post-treatment period (Figure 4 g).

At site N there was little variation in C_{rel} from year to year, with no evidence of a step change post-treatment ($p = 0.263$, Mann-Whitney U). However, it is worth noting that all of the median annual C_{rel} values post-treatment were consistently lower than the median for the pre-treatment period. Before treatment, C_{rel} was -1.4% and following treatment, C_{rel} ranged between -19.2% and -2.5% annually, with an average of -6.35% for the whole post-treatment period (Figure 4 h). Results suggest that gully blocking may have moderated and reduced the volume of runoff (*C*) compared to revegetation alone, although this is not statistically significant.

4.1.1.2.1.4. Hydrograph shape index

At site O, before treatment, median HSI_{rel} was 0.006 (104% of that at the control site). Following treatment, HSI_{rel} ranged between -0.018 and -0.042 annually, with a median value of -0.033 (72% of that at the control site). This represents a statistically significant decrease in HSI_{rel} of 0.04 (Figure 4 e), or a 32 *pp* decrease in HSI relative to the control ($p < 0.001$, Mann-Whitney U).

At site N, before treatment, median HSI_{rel} was 0.003 (110% of that at the control site). Following treatment, HSI_{rel} ranged between -0.096 and -0.037 annually with a median value of -0.062 (52% of that at the control site). This represents a statistically significant decrease in HSI_{rel} of 0.065 (Figure 4 f), or a 58 *pp* decrease in HSI relative to the control ($p < 0.001$, Mann-Whitney U). Installing gully blocks in addition to revegetation as part of the bare peat treatment decreased HSI_{rel} by an additional 0.026 (i.e. HSI decreased by a further 26 *pp* relative to the control).

Table 8: Annual summary statistics for relative hydrograph metrics (treatment – control) at the bare peat sites

		2010-11	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
	Years post-rest.	0	1	2	3	4	5	6	7	8	9	10
	n	33	26	28	18	14	23	31	18	31	17	19
Site O												
Relative Lag (min)	Median	-10	10	15	30	20	20	30	20	35	30	20
	Maximum	40	90	50	40	40	40	40	40	40	40	40
	Minimum	-40	-10	-10	0	-5	-10	-30	-15	-20	0	-30
	Q1	-20	0	10	20	10	10	10	13	20	20	13
	Q3	0	30	20	40	28	25	48	28	65	30	50
Relative Peak Storm Discharge (L s^{-1} ha^{-1})	Median	0.52	-1.26	-0.50	-0.24	-1.60	-3.21	-0.97	-1.73	-1.43	-3.06	-0.78
	Maximum	30.48	1.16	2.17	2.14	3.23	1.21	5.43	0.91	21.02	-1.08	3.72
	Minimum	-2.23	-19.26	-18.04	-10.01	-16.63	-14.56	-12.52	-8.80	-33.53	-29.40	-15.18
	Q1	0.03	-2.79	-1.31	-1.16	-4.99	-4.85	-3.39	-4.95	-4.52	-4.29	-1.38
	Q3	1.91	-0.52	0.01	0.75	-1.15	-1.26	0.40	-0.56	-0.49	-1.93	0.40
Relative HSI	Median	0.01	-0.02	-0.04	-0.04	-0.03	-0.02	-0.04	-0.02	-0.04	-0.04	-0.04
	Maximum	0.09	0.32	0.03	0.01	0.00	0.02	0.08	0.02	0.08	-0.01	0.01
	Minimum	-0.06	-0.19	-0.48	-0.89	-0.35	-0.52	-0.22	-0.20	-0.23	-0.35	-0.22
	Q1	-0.01	-0.06	-0.13	-0.22	-0.06	-0.06	-0.09	-0.08	-0.08	-0.12	-0.07
	Q3	0.03	-0.01	-0.01	-0.01	-0.02	0.00	-0.01	0.00	-0.01	-0.02	-0.01
Relative Rainfall-Runoff Coefficient (%)	Median	1.6	-3.2	4.4	6.7	-2.6	-13.6	0.4	-4.4	2.8	-14.6	24.3
	Maximum	58.0	13.4	25.9	55.3	27.0	11.1	75.0	31.2	43.3	8.9	40.6
	Minimum	-24.3	-31.3	-9.3	-6.4	-38.4	-33.1	-96.5	-52.8	-67.8	-44.4	-19.2
	Q1	-5.0	-8.4	-0.6	2.8	-8.9	-22.2	-38.0	-12.9	-5.0	-21.8	8.7
	Q3	8.5	2.2	11.6	23.0	9.3	0.6	22.1	2.0	6.1	-8.9	30.0
Site N												
Relative Lag (min)	Median	0	40	45	60	55	50	80	110	80	95	160
	Maximum	70	270	320	70	70	70	70	70	70	70	70
	Minimum	-30	-40	-10	10	10	10	10	40	-10	-20	0
	Q1	-10	30	20	23	31	28	55	65	40	35	75
	Q3	0	80	112	105	108	90	148	208	189	170	210
Relative Peak Storm Discharge (L s^{-1} ha^{-1})	Median	0.04	-1.81	-2.18	-2.36	-2.62	-4.08	-1.86	-2.03	-2.90	-3.02	-4.19
	Maximum	23.35	0.91	0.80	23.35	23.35	23.35	23.35	23.35	23.35	23.35	23.35
	Minimum	-4.34	-25.70	-36.75	-11.70	-19.20	-14.67	-16.19	-16.03	-40.50	-30.86	-20.57
	Q1	-0.90	-3.88	-5.11	-3.46	-3.66	-5.73	-4.53	-4.96	-3.85	-5.39	-5.22
	Q3	1.02	-0.92	-1.24	-0.99	-1.37	-1.35	-0.51	-1.11	-1.15	-2.69	-3.00
Relative HSI	Median	0.00	-0.05	-0.10	-0.09	-0.06	-0.04	-0.06	-0.05	-0.06	-0.07	-0.09
	Maximum	0.25	0.02	0.01	0.04	0.01	0.02	0.00	0.00	0.01	-0.01	-0.01
	Minimum	-0.10	-0.35	-0.55	-0.68	-0.52	-0.50	-0.38	-0.33	-0.25	-0.41	-0.28
	Q1	-0.02	-0.11	-0.15	-0.26	-0.08	-0.14	-0.14	-0.10	-0.13	-0.19	-0.10
	Q3	0.04	-0.02	-0.04	-0.02	-0.03	-0.01	-0.03	-0.02	-0.02	-0.04	-0.04
Relative Rainfall-Runoff Coefficient (%)	Median	-1.4	-5.8	-9.1	-3.6	-2.5	-8.7	-10.6	-9.2	-4.0	-19.2	-8.6
	Maximum	15.0	26.4	29.6	20.6	34.9	21.2	46.9	36.8	21.0	7.8	22.7
	Minimum	-34.6	-37.3	-26.9	-25.7	-35.1	-28.6	-98.8	-42.5	-62.5	-50.4	-83.3
	Q1	-9.4	-12.8	-12.1	-8.7	-10.7	-22.1	-32.4	-16.5	-6.1	-23.1	-19.7
	Q3	2.0	5.8	7.4	5.8	5.7	-2.0	12.4	0.5	5.1	-12.4	-0.5

4.1.1.2.2. Gradual changes following *Sphagnum* planting

Breakpoint analysis showed that gradual changes were evident in peakQ_{rel} and lag$_{rel}$ following the application of *Sphagnum* at site N (Figure 4 b and d). *Sphagnum* mosses were planted four years after the initial treatment (revegetation and gully blocking), but the impact was not evident until the *Sphagnum* had started to establish meaningful (~15%) cover across the catchment and flow pathways. By the end of monitoring (2021), *Sphagnum* cover across the catchment (as monitored in vegetation quadrats on undulating ground) was ~25%; cover in the flow pathway network was ~75%.

4.1.1.2.2.1. Peak discharge

There was a break point in peak$Q_{rel,}$ around five years post-treatment, although year 5 post-treatment behaved differently to the preceding four years and the subsequent directional change. From year 6 onwards, peakQ_{rel} decreased linearly at a rate of 0.57 $L\,s^{-1}\,ha^{-1}$ ($R^2 = 0.921$, $p = 0.010$). By the end of the monitoring period (six years after *Sphagnum* planting), median peakQ_{rel} was -4.19 $L\,s^{-1}\,ha^{-1}$ (39% of that at the control site) representing a 17 *pp* decrease compared to phase 1 of treatment and 67 *pp* decrease compared to the pre-treatment period.

4.1.1.2.2.2. Lag time

There was a clear break point in lag$_{rel,}$ five years post-treatment, after which lag$_{rel}$ steadily increased linearly at a rate of 16.1 min yr^{-1} ($R^2 = 0.6589$, $p = 0.0498$). By the end of the monitoring period, median lag$_{rel}$ was 160 min (lag was 780% of that at the control site), representing a 280 *pp* increase compared to phase 1 of treatment and a 680 *pp* increase compared to the pre-treatment period.

4.1.1.3. Impact of restoration on extreme storm events

Figure 5 shows the difference between observed stormflow metrics at the treatment catchments and estimates of how the treatment catchments would have behaved had no intervention taken place for three time periods: pre-intervention (year 0/2010–11), the end of the first phase of restoration (year 3/2014), and the end of the monitoring period (year 10/2021). The pre-intervention values have been included to show the natural variation between the control and treatment sites for context. In each graph, the *x*-axes show the magnitude of the observed metric at the control catchment (F) to give an idea of storm size and flashiness, and the *y*-axes show the magnitude of the difference between the observed metric at the treatment catchments and the no-intervention estimates, hereafter simply referred to as deviations. Positive values on the *y*-axes indicate that the observed metric of interest was greater than the no-intervention estimate, and negative values indicate the metric of interest was lower than the no-intervention estimate.

At both treatment sites, there were no apparent trends between the observed values at site F and the deviations for lag and *C*. A simple *t*-test was therefore used to assess differences between the two phases of restoration. Peak storm discharge and HSI displayed significant trends in the relationship between observed values and deviations at both of the treatment sites. A general linear model (GLM) was therefore the most appropriate method of assessing difference between the two phases of restoration. For a full justification of the statistical approach, see the Methodology section of this chapter.

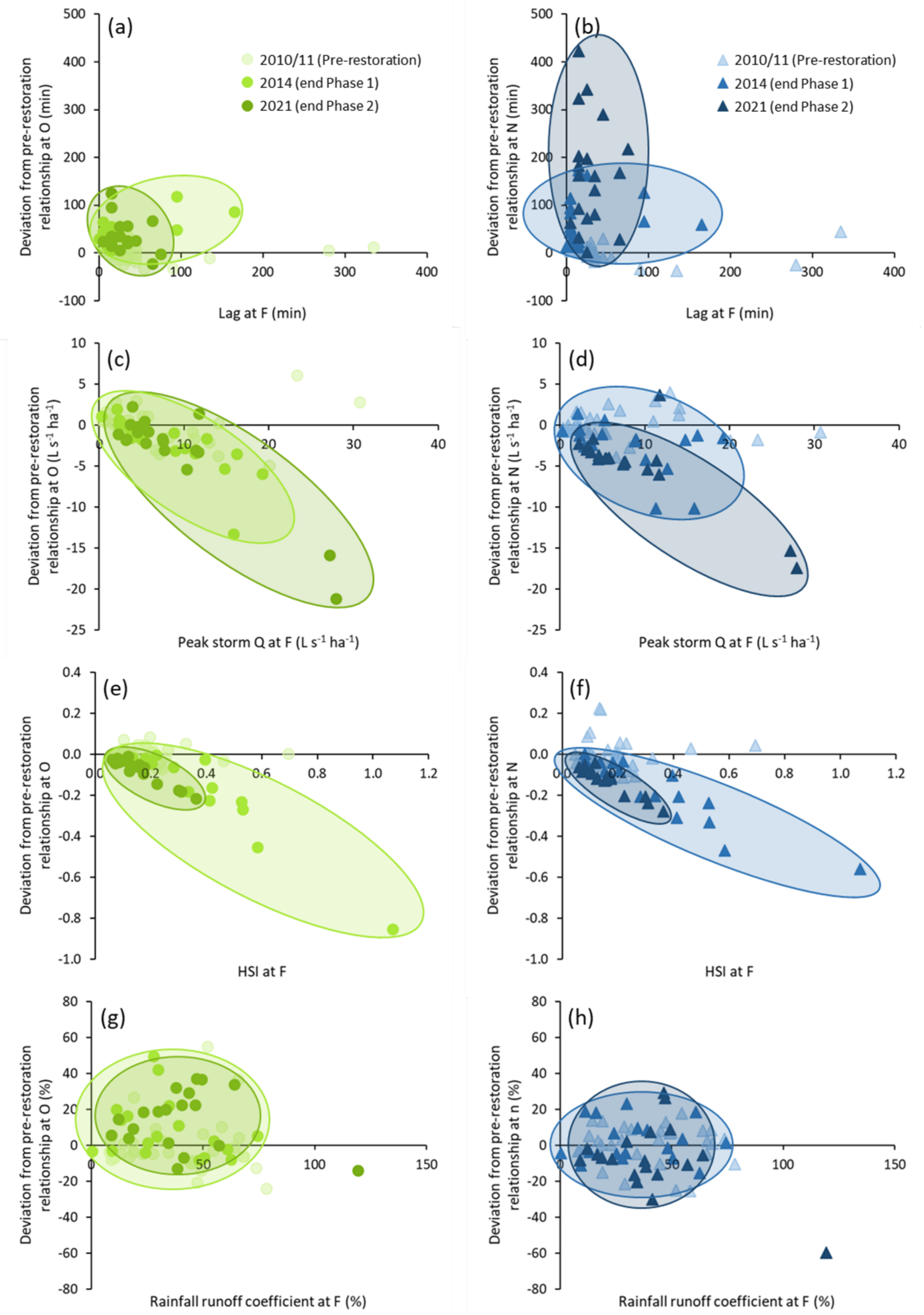

Figure 5: Difference between observed stormflow metrics and estimates of how the bare peat treatment catchments would have behaved had no intervention taken place (lag time (a and b), peak discharge (c and d), Hydrograph Shape Index (e and f), and percent runoff (g and h)) across the full range of observed storm conditions, including 'extreme' events. Green markers represent site O (revegetation) and blue markers represent site N (revegetation, gully blocking and Sphagnum planting). Three time periods are presented: pre-intervention (pale coloured markers), the end of the first phase of restoration (mid coloured markers), and the end of the monitoring period (dark coloured markers). Ellipses have been drawn around the post-treatment groups for ease of comparison. The ellipses contain >95% of the data

4.1.1.3.1. Peak discharge

At both treatment sites there was a negative trend between observed values at site F and the deviations for peak discharge (Figure 5 b and f). This suggests that the higher the magnitude of peak flow at F, the greater the reduction in peak flow at the treatment sites. At site O, the GLM showed no difference in the relationships at the end of the two phases of restoration ($p = 0.525$). At site N there was a significant difference ($p = 0.043$), with greater reductions in peaks flow after the second phase of restoration as compared to the end of the first phase of restoration.

The nature of the trends at the two sites also reveals how the different treatment measures have influenced peak flows. For small to medium size storms (peak storm discharges up to 20 $\mathrm{L\,s^{-1}\,ha^{-1}}$ at site F) there were greater reductions in peak flow at site N than at site O, but for the two highest magnitude events (~28 $\mathrm{L\,s^{-1}\,ha^{-1}}$ at site F) there was little difference in the magnitude of the reduction at the two treatment sites.

4.1.1.3.2. Lag time

The smaller the time value on the x-axis, the shorter the lag time and the flashier/more reactive the storm event was at the control site (F). Almost all of the deviations were positive (Figure 5 a and e), indicating lag times were longer post-treatment than if there had been no intervention. At site O, the *t*-test showed no difference between the deviations at the end of the two phases of restoration ($p = 0.987$), with values ranging from 5 to 118 min in 2014 and -22 to 125 min in 2021. For the flashiest storms, where lag times at F were close to 0 min, the deviations were up to 65 min.

At site N there was a significant difference between the two phases of restoration ($p = 0.002$), with the upper range of the deviations much extended in 2021 compared to 2014 (max 423 and 173 min respectively). Again, these effects were sustained for the flashiest flows at F, with deviations up to 114 min in 2014 and 423 min in 2021.

4.1.1.3.3. Runoff co-efficient

There was no change in behaviour in C at either of the sites (Figure 5 d and h). For the storm that was most productive of runoff (120% at site F) there was a reduction in C at both of the treatment sites, but as there was only one event of this type no conclusions can be drawn from this observation.

4.1.1.3.4. Hydrograph shape index

There was a negative trend between observed HSI values at F and the deviations for both of the treatment sites (Figure 5 c and g), i.e., the more flashy the hydrograph at F (as indicated by a higher HSI), the greater the reduction in flashiness at the treatment sites. For both treatments sites the GLM showed that there was a significant difference in these relationships at the end of the two phases of restoration ($p = 0.018$ at site O and $p = 0.004$ at site N), with greater reductions in HSI at the end of the second phase of restoration. However, it should be noted that these changes were extremely subtle as indicated by the overlapping ellipses in the figure.

Again, the nature of the trends at the two sites reveals how the different treatment measures have influenced HSI/flashiness. For less flashy/reactive storms (HSI values up to ~0.5 at site F) there were greater reductions in HSI at site N than at O, but this is not sustained for the most reactive event (HSI = 1.1 at site F) where there was a greater reduction in HSI at site O.

4.2. Species dominated sites

4.2.1. Overland flow

4.2.1.1. *Calluna* dominated site: *Sphagnum* planting (Spha)

There were substantially fewer usable paired events in the before compared to the after-treatment year for the *Calluna* control and *Sphagnum* treated plots from the mini-catchments (Table 9; Figure 6). Increased rainfall in the after-treatment year is a likely factor. Pairing events was challenging, but was carried out when it was clear that both records were reacting to the same rainfall event. The continuous and manual water table records (see Water Table chapter of this report) show that the *Sphagnum* treated plots compared to the control plots had substantially deeper water tables throughout the monitoring year leading to complacency in the water table to lower magnitude storms. The comparatively deep-water tables evident even in winter are likely to have contributed to reduced saturation-excess overland flow, as rainfall has been able to infiltrate more readily.

Change in median relative (treatment minus control) start and peak lag from paired storms from before to after treatment year is (Table 9; Figure 6) from 8 to -5 and from -8 to -10 respectively. Given a sampling resolution of 5 minutes the change is negligible. Relative start and peak lag lower quartiles shifted to more negative values as distributions moved, indicating comparatively more events with treated plots reacting relatively more quickly. Mann-Whitney U tests reveal that neither change in start or peak lag were significant (Figure 7) at the 95% level ($p \leq 0.05$). Paired storm events here were not equally distributed between seasons (Table 10; Figure 7 a–b) as in the before treatment year events were from spring and summer whereas in the after-treatment year they were from autumn and winter. This may in part explain why distributions have altered as the comparatively lower water tables at the *Sphagnum* treated plots were extenuated in spring and especially summer months leading to slower start and peak and lag times if overland flow is in part influenced by the potential for water to infiltrate versus runoff.

Unpaired events (any event meeting selection criteria regardless of whether can be assigned to same storm across control and treated plots) have been pooled into before and after treatment years (Table 11; Figure 8). These can give a broad albeit less powerful impression of how control and treatment plots have changed. Caution is required as the distribution and number of events between treatment and year can vary greatly. Values displayed are actual times not relative values as these are not paired events. Distribution of peak and start lags and median values have reduced at both control and *Sphagnum* treated plots from before to after treatment years. However, whereas peak lags have reduced only marginally start lags have reduced substantially with changes in median values from 175 to 110 and from 173 to 105 minutes at control and treatment respectively. These reductions are similar between control and treated plots suggesting no effect of treatment itself.

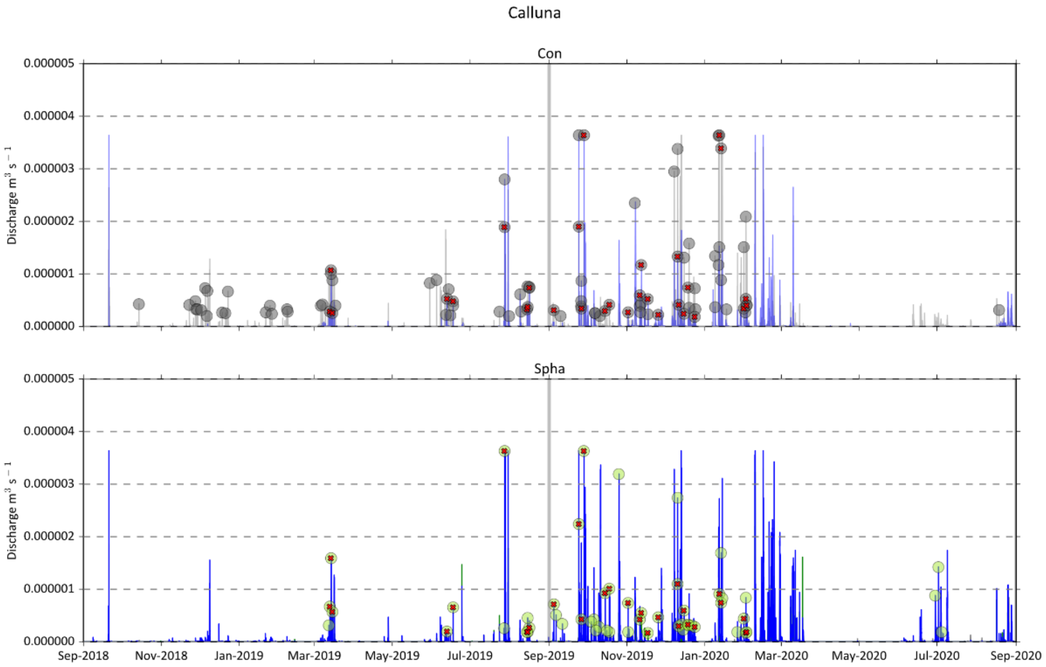

Figure 6: Time series of tipping bucket overland flow data from the *Calluna* control (Con) and *Sphagnum* (Spha) treated intensive plots.
All three discharge records from Con and Spha are plotted together (blue, green and grey). Large circles indicate storm events that were suitable for analysis from Con and Spha (the peak discharge attained is plotted against date). Circles with red crosses indicate the substantially fewer events that are reacting to the same storm and can be analysed as being 'paired'. The vertical grey line divides year 0 and 1 (pre and post treatment).

Table 9: Cal.spha: Descriptive statistics for relative start and peak lags to rainfall from paired storm events for overland flow (tipping buckets) for years 0 and 1 (before and after treatment) of project.

		Year	
		0	1
Start lag (mins)	Count	9	21
	Mean	4	-30
	Stdev	62	93
	Min	-140	-360
	LQ	-5	-58
	Median	8	-5
	UQ	40	8
	Max	63	125
Peak lag (mins)	Count	9	21
	Mean	-1	-15
	Stdev	21	28
	Min	-25	-108
	LQ	-10	-28
	Median	-8	-10
	UQ	-5	-3
	Max	38	43

Table 10: Cal.spha: Descriptive statistics for relative start and peak lags to rainfall from paired storm events for overland flow (tipping buckets) for seasons within years 0 and 1 (before and after treatment) of project.

	Year	Season	Count	Mean	Stdev	Min	LQ	Median	UQ	Max
Start lag (mins)	0	SPR	3	23	43	-25	6	38	48	58
	0	SUM	6	-5	71	-140	-3	6	32	63
	1	AUT	11	-20	121	-360	-8	3	16	125
	1	WIN	10	-41	53	-158	-69	-23	-5	18
Peak lag (mins)	0	SPR	3	21	23	-5	13	30	34	38
	0	SUM	6	-12	7	-25	-10	-10	-8	-8
	1	AUT	11	-15	38	-108	-25	-5	0	43
	1	WIN	10	-16	14	-40	-24	-13	-5	0

Table 11: Cal.spha: Descriptive statistics for relative start and peak lags to rainfall from all storm events chosen (events met selection criteria but not necessarily paired between treatments) for overland flow (tipping buckets) for seasons within years 0 and 1 (before and after treatment) of project.

Treatment		Con		Spha	
Year		0	1	0	1
Start lag (mins)	Count	44	53	12	43
	Mean	200	132	200	136
	Stdev	171	110	116	146
	Min	-25	15	30	5
	LQ	90	60	114	48
	Median	175	110	173	105
	UQ	269	165	294	160
	Max	930	525	390	880
Peak lag (mins)	Count	44	53	12	43
	Mean	69	51	39	44
	Stdev	67	50	31	53
	Min	-5	-25	0	-35
	LQ	25	15	20	10
	Median	40	30	25	20
	UQ	98	100	53	78
	Max	285	165	115	200

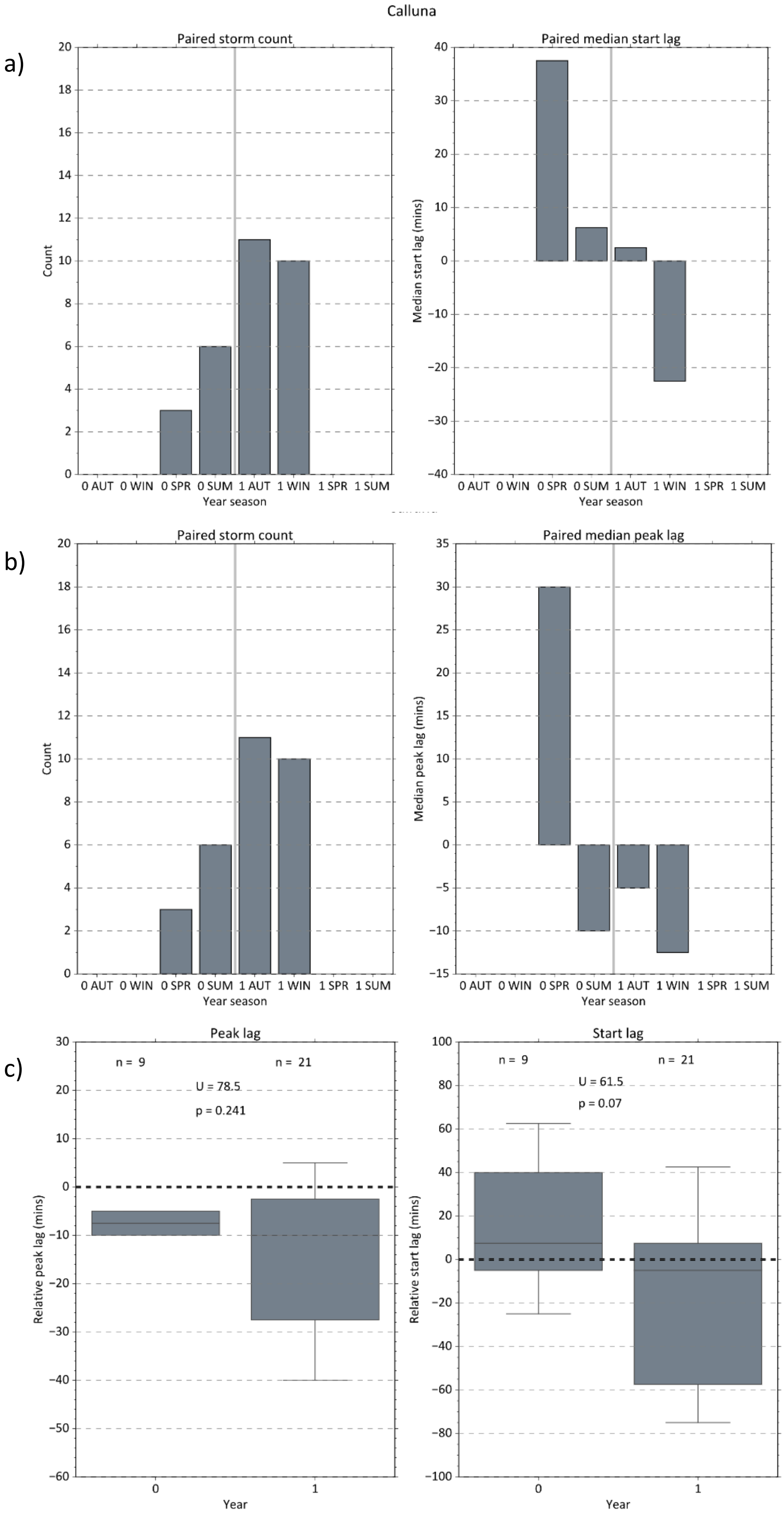

Figure 7: a-b): Cal.spha: Seasonal distribution of paired storm events between treatments. a) median start lag; b) median peak lag. C): Relative (treatment minus control) median start and peak lags to rainfall for each project year. Mann-Whitney U significance tests are displayed for differences between year 0 and 1

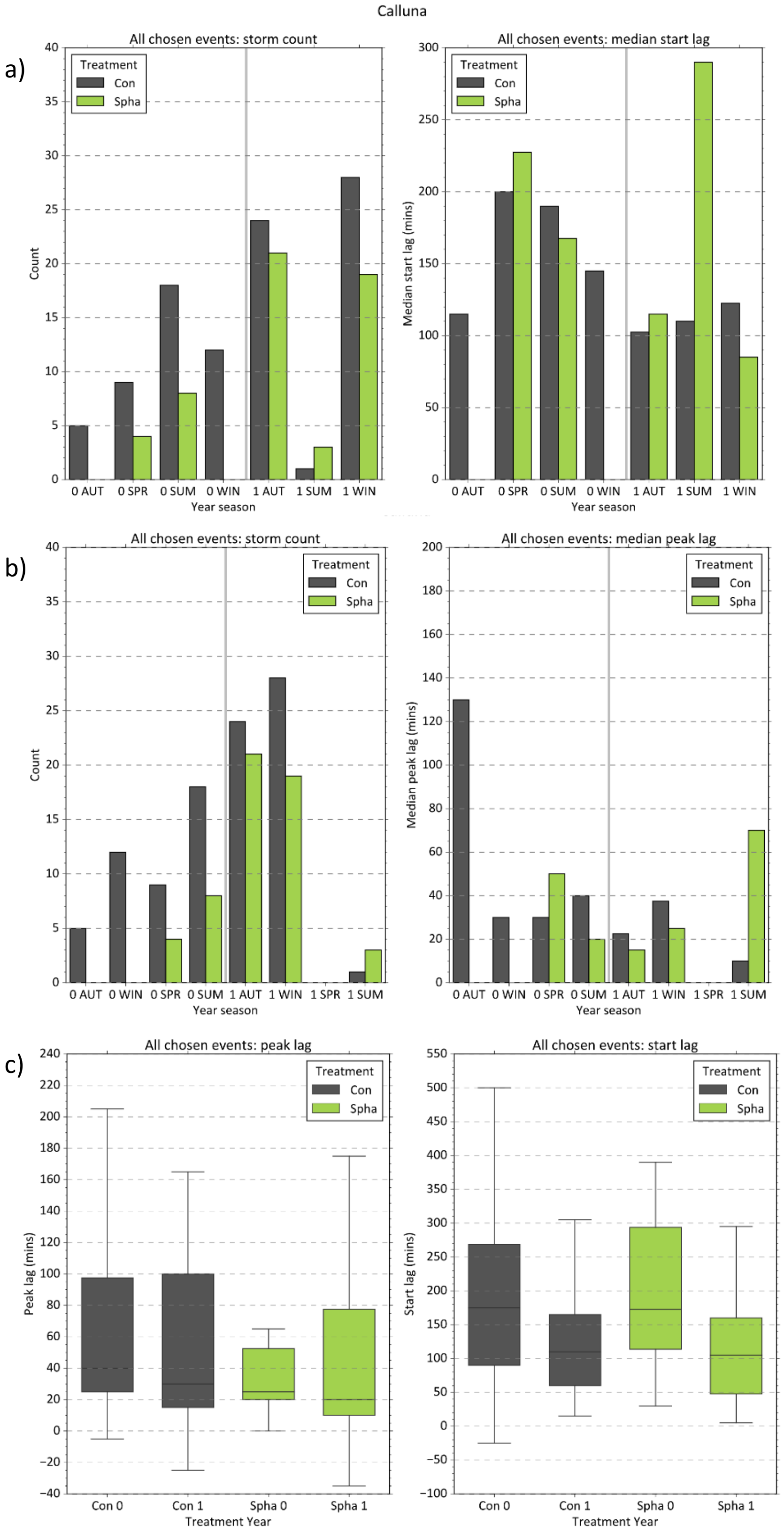

Figure 8: Cal.spha: Seasonal distribution of all events that provided suitable hydrographs from each treatment.
Median lag between a) rainfall start and hydrograph start and b) rainfall peak and hydrograph peak. Data are expressed within project years as boxplots for each treatment in c). These are all events and are not temporally paired across each treatment.

4.2.1.2. *Calluna* dominated site: *Sphagnum* planting and gully-blocking (SphaGB)

As for the *Sphagnum* treated plots in the *Sphagnum* only treated mini catchments there were fewer chosen paired events in the before-treatment compared to the after-treatment year (Table 12; Figure 9), a likely consequence of elevated rainfall in the after-treatment year, as detailed in the introductory chapter of this report. No substantial change was evident in relative (treatment minus control) median peak lag values from before to after treatment years (Table 12; Figure 10) and although there was a change in distribution in a negative direction this was not significant (Mann Whitney-U, Figure 10). There was however a substantial change in relative median start lag values from -98 to -18 (Table 12) as start lag reduced at control and increased at treatment. Examination of unpaired events (Table 14; Figure 11) reveals the same pattern with no substantial change in peak lag times but start lag times reduced at the control and increased at the treated site. Seasonal distribution of paired and unpaired events was relatively equal in the before-treatment year but was skewed to autumn and winter seasons in the after-treatment year (Table 13; Figure 10; Figure 11). However, the opposite trends in start lags are unlikely to be related to unequal seasonal representation.

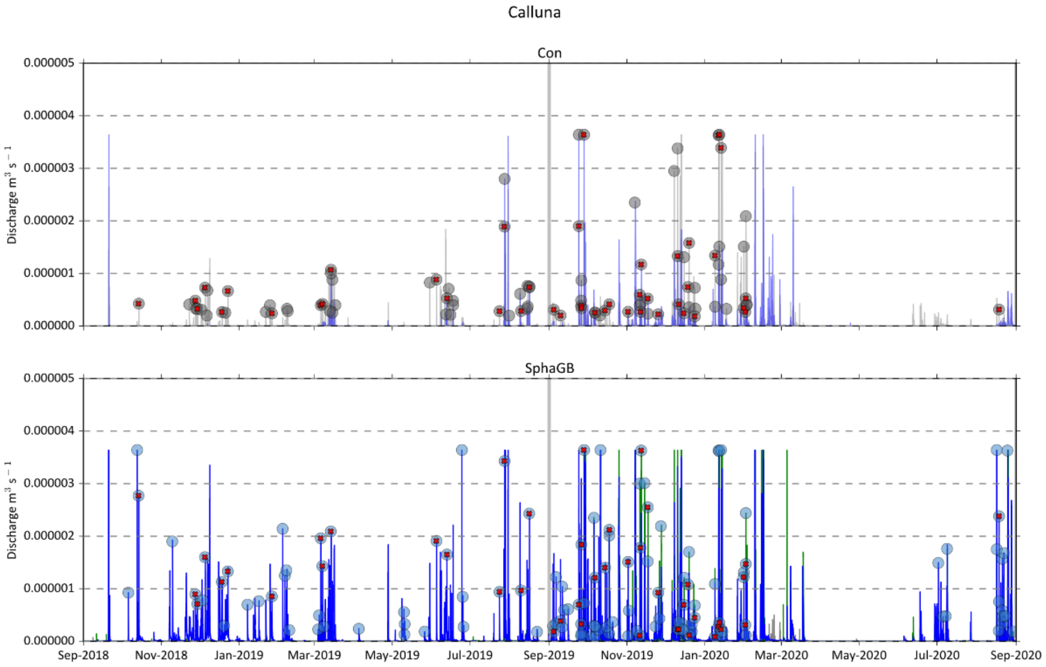

Figure 9: Time series of tipping bucket overland flow data from the *Calluna* control (Con) and *Sphagnum and gully blocked* (SphaGB) treated intensive plots.
All 3 discharge records from Con and SphaGB are plotted together (blue, green and grey). Large circles indicate storm events that were suitable for analysis from Con and SphaGB (the peak discharge attained is plotted against date). Circles with red crosses indicate the substantially fewer events that are reacting to the same storm and can be analysed as being 'paired'. The vertical grey line divides year 0 and 1 (pre and post treatment).

Table 12: Cal.SphaGB: Descriptive statistics for relative start and peak lags to rainfall from paired storm events for overland flow (tipping buckets) for years 0 and 1 (before and after treatment) of project.

		Year	
		0	1
Start lag (mins)	Count	16	29
	Mean	-134	-17
	Stdev	108	56
	Min	-390	-118
	LQ	-173	-40
	Median	-98	-18
	UQ	-76	0
	Max	-5	130
Peak lag (mins)	Count	16	29
	Mean	-27	-14
	Stdev	48	20
	Min	-180	-80
	LQ	-35	-20
	Median	-8	-8
	UQ	-2	0
	Max	10	12

Table 13: Cal.SphaGB: Descriptive statistics for relative start and peak lags to rainfall from paired storm events for overland flow (tipping buckets) for seasons within years 0 and 1 (before and after treatment) of project.

	Year	Season	Count	Mean	Stdev	Min	LQ	Median	UQ	Max
Start lag (mins)	0	AUT	3	-193	170	-390	-243	-95	-95	-95
	0	SPR	3	-158	126	-303	-196	-90	-85	-80
	0	SUM	6	-80	68	-183	-111	-83	-24	-5
	0	WIN	4	-155	99	-280	-198	-150	-108	-40
	1	AUT	15	15	51	-45	-13	0	14	130
	1	SUM	1	-3		-3	-3	-3	-3	-3
	1	WIN	13	-55	37	-118	-73	-40	-28	-3
Peak lag (mins)	0	AUT	3	-33	23	-55	-45	-35	-23	-10
	0	SPR	3	-13	20	-35	-23	-10	-3	5
	0	SUM	6	-18	32	-80	-20	-5	-3	10
	0	WIN	4	-45	90	-180	-49	-3	1	5
	1	AUT	15	-7	12	-38	-10	-8	0	12
	1	SUM	1	0		0	0	0	0	0
	1	WIN	13	-23	25	-80	-28	-18	-5	5

Table 14: Cal.SphaGB: Descriptive statistics for relative start and peak lags to rainfall from all storm events chosen (events met selection criteria but not necessarily paired between treatments) for overland flow (tipping buckets) for seasons within years 0 and 1 (before and after treatment) of project.

Treatment		Con		SphaGB	
Year		0	1	0	1
Start lag (mins)	Count	44	53	39	93
	Mean	200	132	96	113
	Stdev	171	110	162	124
	Min	-25	15	-20	-50
	LQ	90	60	10	30
	Median	175	110	35	75
	UQ	269	165	123	145
	Max	930	525	865	660
Peak lag (mins)	Count	44	53	39	93
	Mean	69	51	116	46
	Stdev	67	50	148	50
	Min	-5	-25	5	-35
	LQ	25	15	20	10
	Median	40	30	55	25
	UQ	98	100	168	80
	Max	285	165	760	205

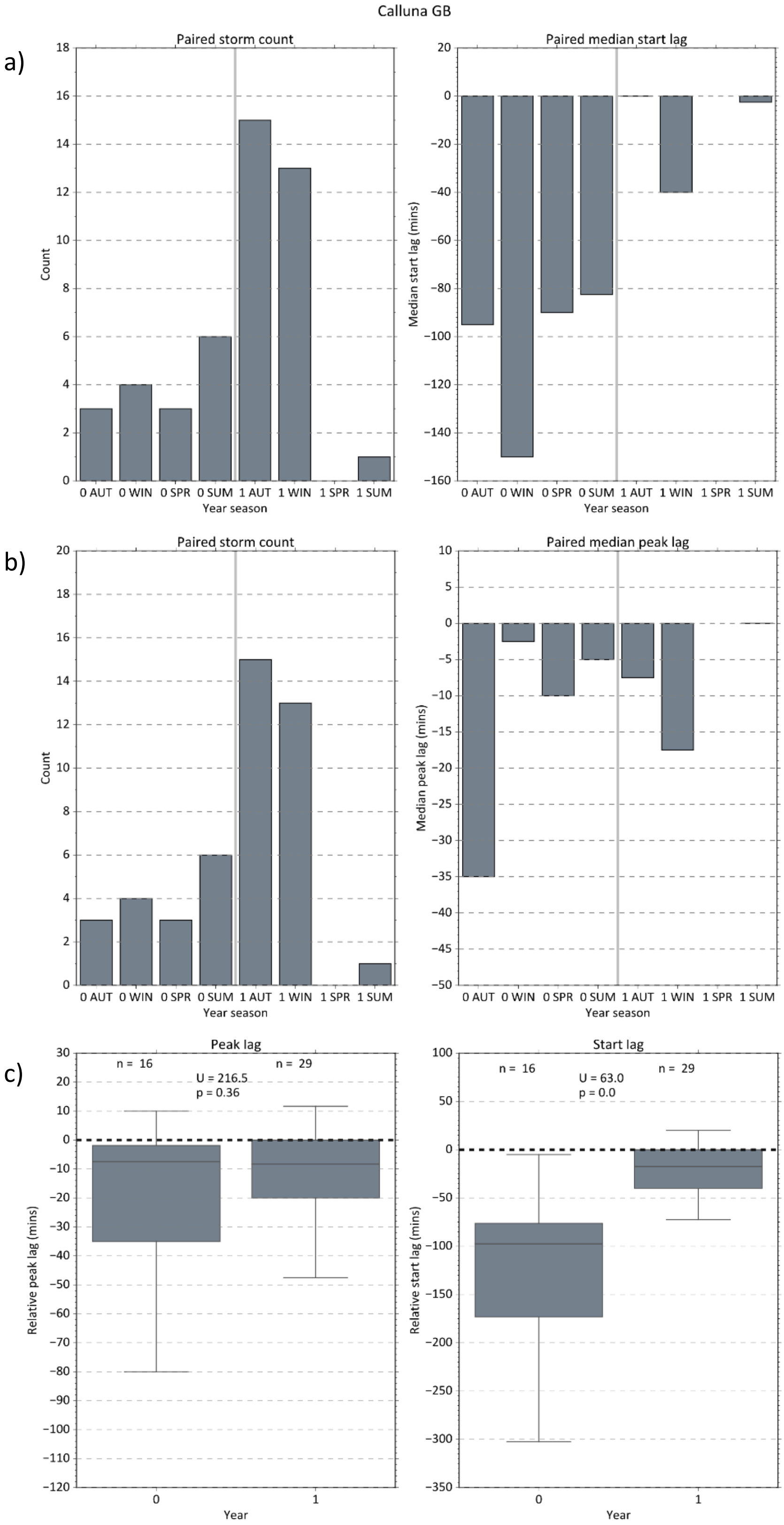

Figure 10: Cal.SphaGB: a–b): Seasonal distribution of paired storm events between treatments. a) median start lag; b) median peak lag. c): Relative (treatment minus control) median start and peak lags to rainfall for each project year. Mann-Whitney U significance tests are displayed for differences between year 0 and 1.

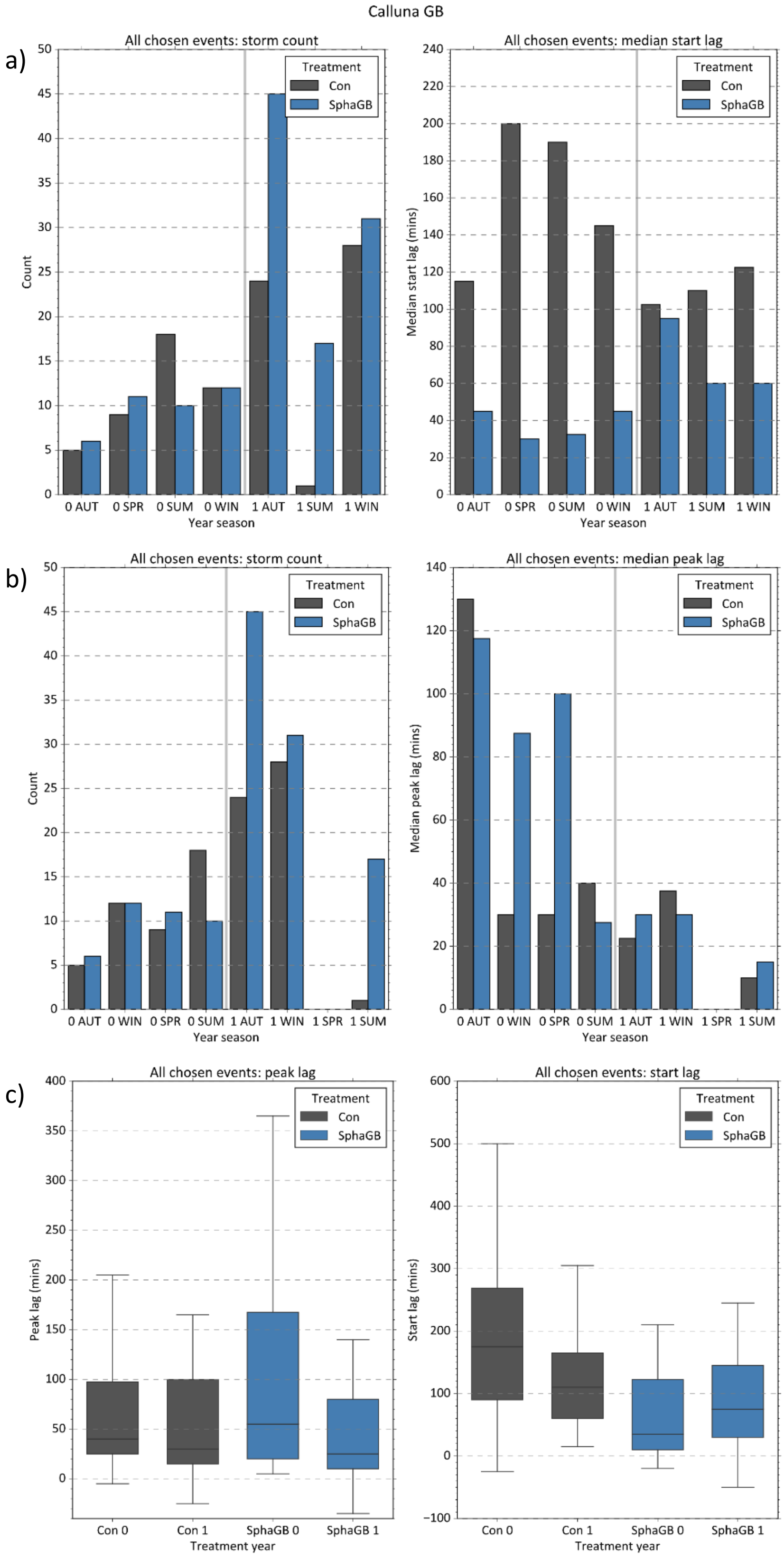

Figure 11: Cal.SphaGB: Seasonal distribution of all events that provided suitable hydrographs from each treatment.
Median lag between a) rainfall start and hydrograph start and b) rainfall peak and hydrograph peak. Data are expressed within project years as boxplots for each treatment in c). These are all events and are not temporally paired across each treatment.

4.2.1.3. *Eriophorum* dominated site

As for the *Calluna* species dominated plots there were fewer chosen paired events in the before-treatment compared to the after-treatment year (Table 15; Figure 12) due to elevated rainfall in the after-treatment year. There was little change in relative median start or peak lag values from before to after treatment years (Table 15; Figure 13) suggesting that both maintained the same relative behaviour with no clear changes due to treatment. Distribution of relative values also remained relatively static with no significant difference between before and after treatment years (Table 16; Figure 13). There were events from every season in the after-treatment year but none from autumn in the before treatment year (Figure 13). Unpaired events demonstrate a similar reduction in start lag duration for control and *Sphagnum* treated plots from before to after treatment years resulting in a similar relative change (Figure 14). Opposing trends were evident for peak lag duration from before to after treatment periods for control and *Sphagnum* treated plots.

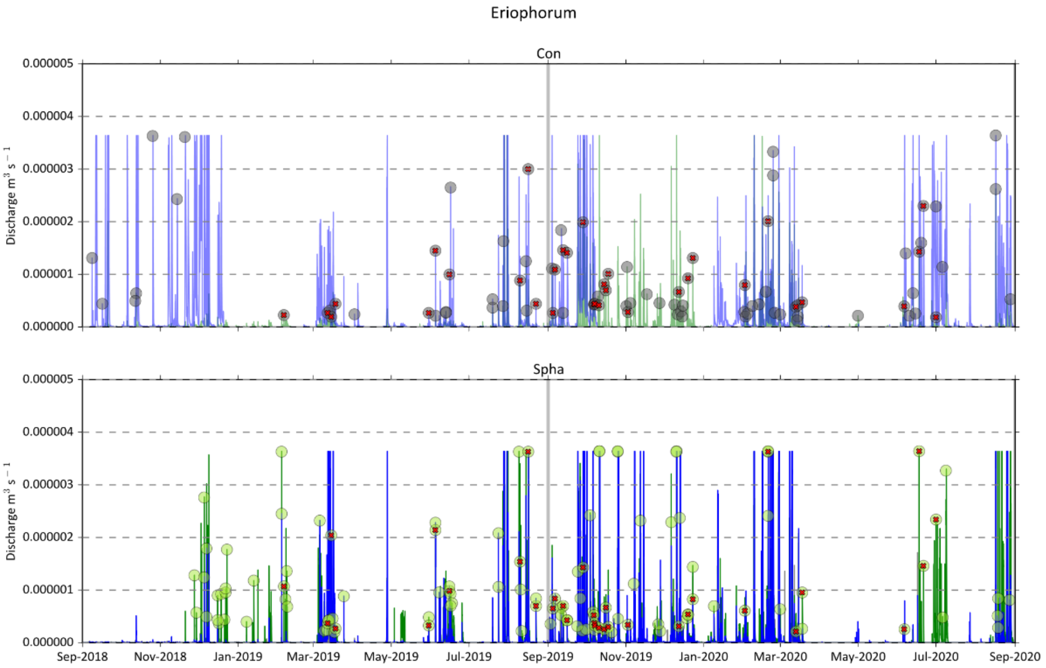

Figure 12: Time series of tipping bucket overland flow data from the *Eriophorum* control (Con) and *Sphagnum* (Spha) treated intensive plots.
All 3 discharge records from Con and Spha are plotted together (blue, green and grey). Large circles indicate storm events that were suitable for analysis from Con and Spha (the peak discharge attained is plotted against date). Circles with red crosses indicate the substantially fewer events that are reacting to the same storm and can be analysed as being 'paired'. The vertical grey line divides year 0 and 1 (pre and post treatment).

Table 15: Eri.Spha: Descriptive statistics for relative start and peak lags to rainfall from paired storm events for overland flow (tipping buckets) for years 0 and 1 (before and after treatment) of project.

		Year	
		0	1
Start lag (mins)	Count	10	24
	Mean	20	35
	Stdev	42	83
	Min	-40	-95
	LQ	-4	-18
	Median	8	3
	UQ	53	73
	Max	85	260
Peak lag (mins)	Count	10	24
	Mean	10	3
	Stdev	26	67
	Min	-10	-218
	LQ	-4	-5
	Median	3	0
	UQ	13	13
	Max	80	110

Table 16: Eri.Spha: Descriptive statistics for relative start and peak lags to rainfall from paired storm events for overland flow (tipping buckets) for seasons within years 0 and 1 (before and after treatment) of project.

	Year	Season	Count	Mean	Stdev	Min	LQ	Median	UQ	Max
Start lag (mins)	0	SPR	4	30	50	-20	-9	28	66	85
	0	SUM	5	1	26	-40	-3	5	10	33
	0	WIN	1	75		75	75	75	75	75
	1	AUT	13	25	79	-95	-30	0	80	170
	1	SPR	2	24	34	0	12	24	36	48
	1	SUM	4	113	121	5	18	94	189	260
	1	WIN	5	4	38	-20	-18	-10	-5	70
Peak lag (mins)	0	SPR	4	19	42	-10	-8	4	31	80
	0	SUM	5	4	9	-5	-3	0	8	18
	0	WIN	1	5		5	5	5	5	5
	1	AUT	13	-11	67	-218	-5	-3	0	80
	1	SPR	2	49	83	-10	19	49	78	108
	1	SUM	4	-23	71	-130	-27	9	13	20
	1	WIN	5	41	55	0	0	3	90	110

Table 17: Eri.Spha: Descriptive statistics for relative start and peak lags to rainfall from all storm events chosen (events met selection criteria but not necessarily paired between treatments) for overland flow (tipping buckets) for seasons within years 0 and 1 (before and after treatment) of project.

Treatment		Con		Spha	
Year		0	1	0	1
Start lag (mins)	Count	29	62	52	63
	Mean	142	64	107	101
	Stdev	210	93	82	119
	Min	-5	-40	-10	-15
	LQ	20	10	40	10
	Median	80	35	98	60
	UQ	145	74	150	150
	Max	1080	420	315	440
Peak lag (mins)	Count	28	62	50	64
	Mean	43	82	68	63
	Stdev	72	130	75	83
	Min	-5	-5	-5	-10
	LQ	10	15	10	10
	Median	15	30	48	28
	UQ	35	85	94	71
	Max	330	610	290	420

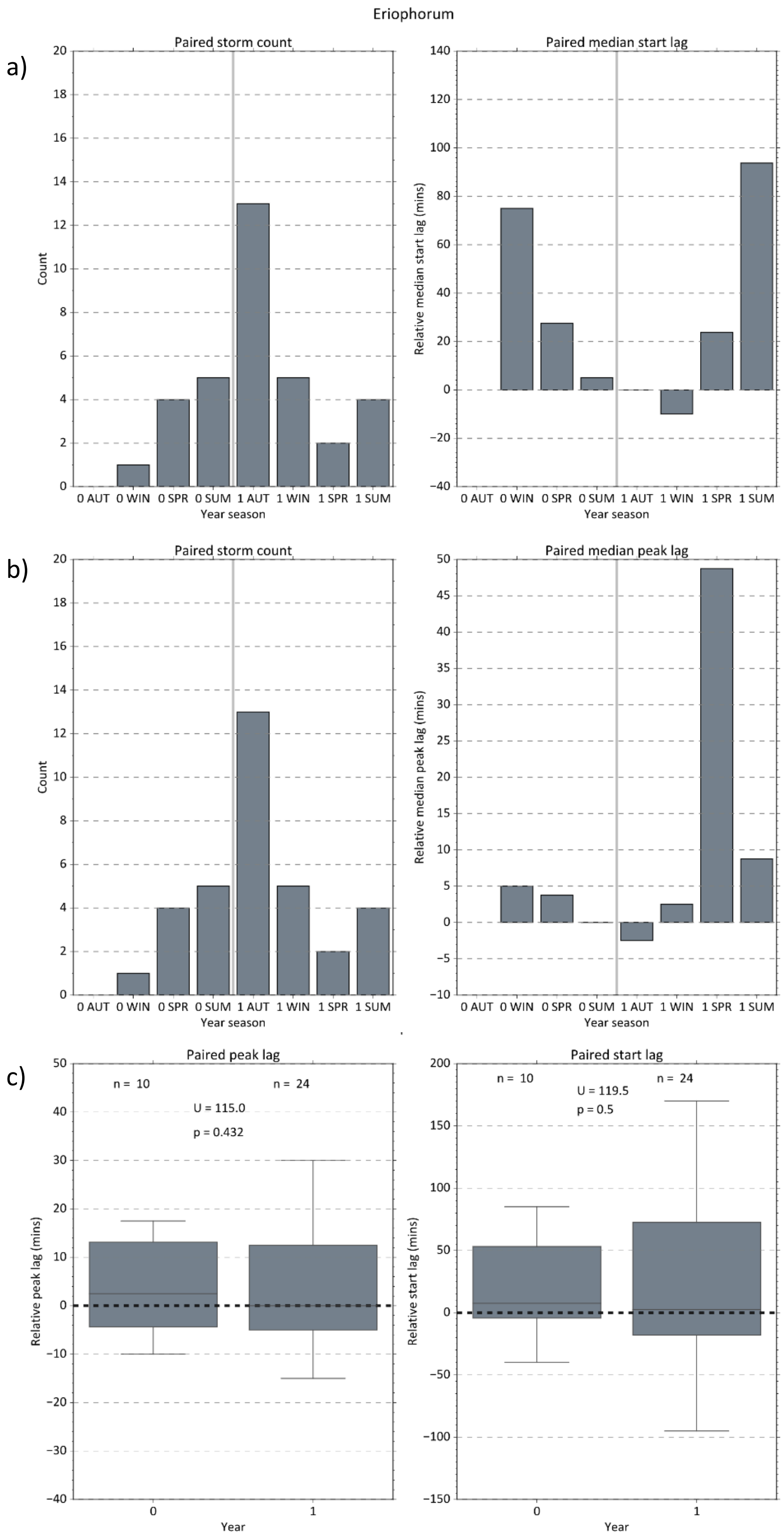

Figure 13: Eri.Spha: Seasonal distribution of paired storm events between treatments.
a) median start lag; b) median peak lag. c): Relative (treatment minus control) median start and peak lags to rainfall for each project year. Mann-Whitney U significance tests are displayed for differences between year 0 and 1

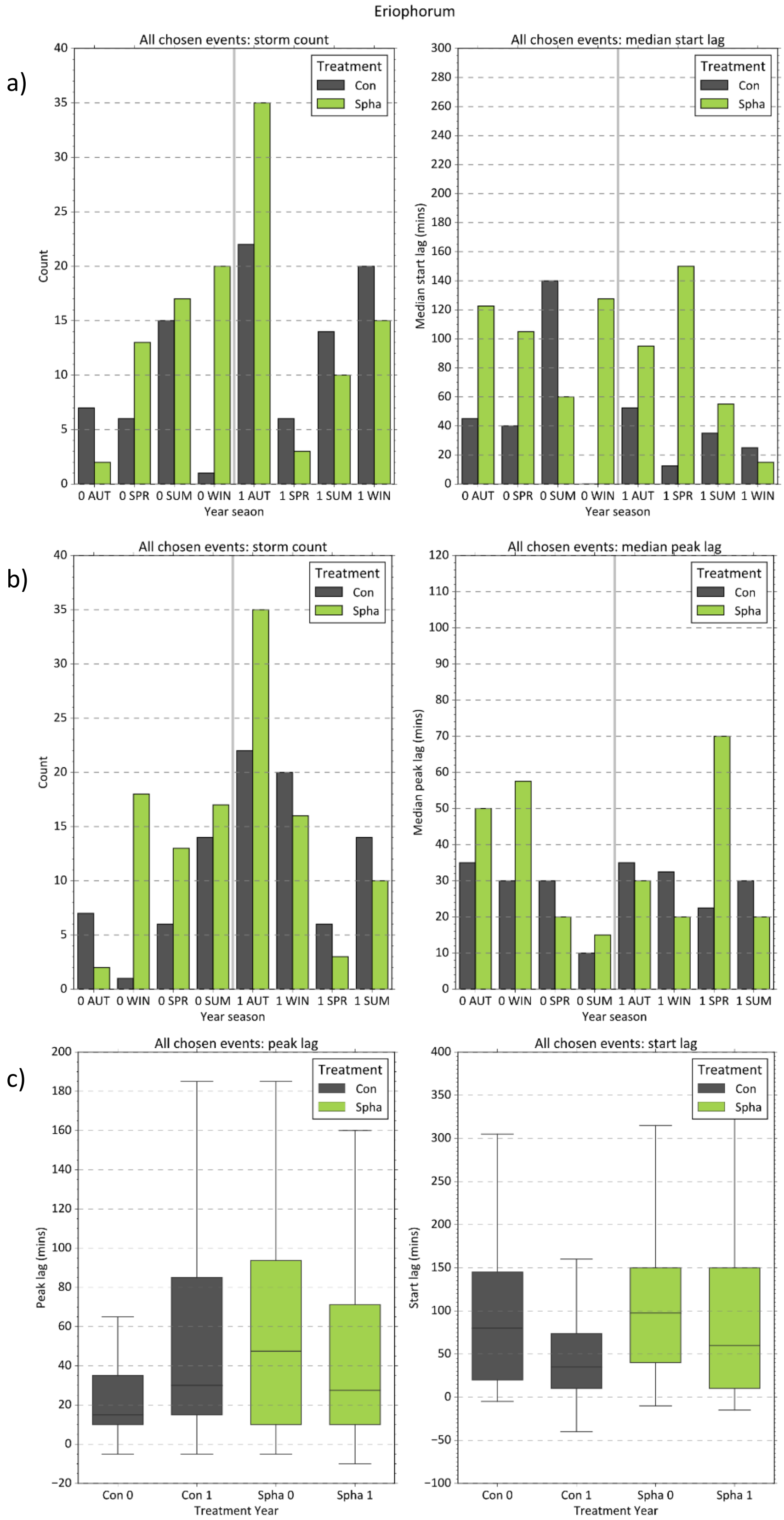

Figure 14: Eri.Spha: Seasonal distribution of all events that provided suitable hydrographs from each treatment.
Median lag between a) rainfall start and hydrograph start and b) rainfall peak and hydrograph peak. Data are expressed within project years as boxplots for each treatment in c). These are all events and are not temporally paired across each treatment

4.2.1.4. *Molinia* dominated site

No data were available from the *Molinia* dominated site due to technical issues with the monitoring equipment.

4.2.2. Discharge

During each BACI year, there were several storm events – the timings of these over the calendar year are shown in Figure 15. Dividing the year into seasons (spring = Mar–May; summer = Jun–Aug; autumn = Sep–Nov; winter = Dec–Feb) showed that the majority of storms at all three sites were in the autumn and winter. Cumulatively, there were only 13 storms in spring (2, 4 and 7 at *Calluna*, *Eriophorum* and *Molinia*, 5% of all storms), compared with 111 in winter (32, 40 and 39 at *Calluna*, *Eriophorum* and *Molinia*, 45% of all storms). 81% of the storms at *Calluna* and *Eriophorum* were in the autumn and winter, compared with 71% at *Molinia*. *Molinia* had the highest proportion of spring and summer storms (8% and 21% respectively). There were no clear changes in the distribution of storm events in year 0, 1 and 2.

There were several high rainfall events during the spring and summer months, however they tended to be low-intensity rainfall over several hours, or where several high rainfall events occurred consecutively, and so these events did not fit the criteria of ‘storms’ for further analysis.

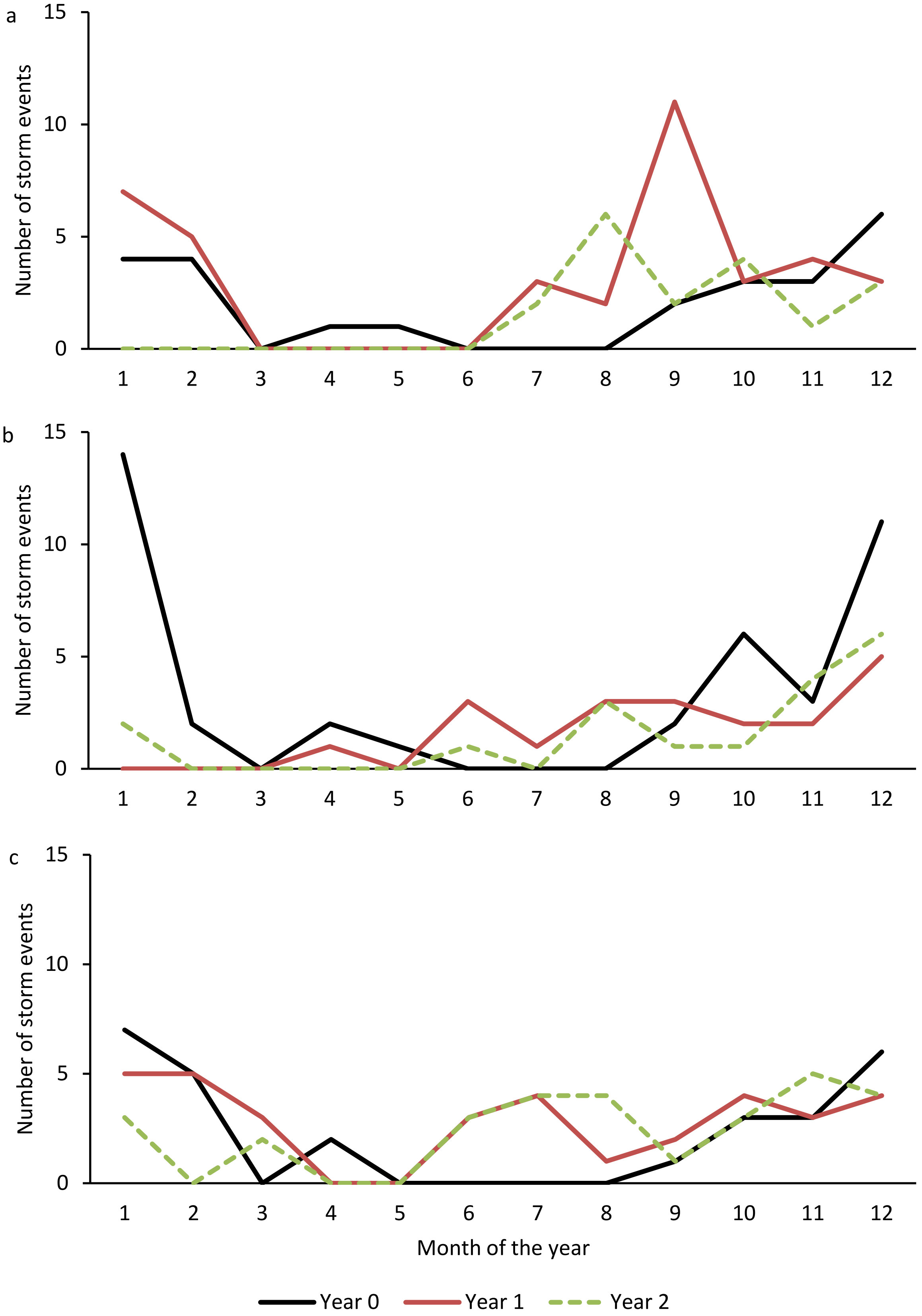

Figure 15: The storm event distribution across the calendar year (January = month 1, December = month 12) at: a) *Calluna*; b) *Eriophorum*; and c) *Molinia* sites.

The metrics calculated for each storm were:

- peak storm discharge (peakQ)
- lag time between peak rainfall and peak flow (lag);
- rainfall runoff coefficient (*C*); the proportion of the rainfall over the catchment that was discharged via the weir
- Hydrograph Shape Index (HSI) (the ratio of peak storm discharge to total storm discharge, a measure of hydrograph intensity whereby high numbers indicate flashy hydrographs and low numbers indicate more attenuated flow)

For each metric at each site, the minimum, lower quartile, median, mean, upper quartile and maximum of are presented in a table, followed by a box plot of the *Sphagnum* site (and *Sphagnum* and gully blocked site at *Calluna*) data relative to the Control site.

A summary of the main findings for each metric at each site is presented in Table 18. It should be noted that all effect sizes were small, variable and within error, so while some results are showing the beginning of a desirable trend, the effect of *Sphagnum* and/or gully blocking on storm hydrology metrics is small so far.

Table 18: Summary of the main findings for each metric, relative to the Control catchment in each vegetation type.
NS = not statistically significant. Note: all effect sizes were small and within error.

After planting/blocking	peakQ	Lag	*C*	HSI
Calluna Spha	↓ NS	↑ $p < 0.01$	↓ $p < 0.01$	- NS
Calluna SphaGB	↓ NS	↑ $p < 0.01$	↓ $p < 0.01$	- NS
Eriophorum Spha	↓ 0.01	↑ NS	↓ NS	↓ NS
Molinia Spha	↑ NS	↓ NS	- NS	↓ NS

4.2.2.1. *Calluna* dominated site

Over the three years, the total rain in the storms ranged from 4 to 42 mm. The mean total rainfall during the storms in years 0, 1 and 2 were 7.1, 9.4 and 8.8 mm. The duration of storms ranged from 3.3 to 29.4 hours. The mean duration of storms in years 0, 1 and 2 were 11.5, 9.7 and 12.5 hours.

4.2.2.1.1. Peak discharge

Peak discharge at all three mini-catchments was lowest in BACI year 0, highest in year 1 and intermediate in year 2 (Table 19). The relative peak discharge from *Sphagnum* site was lower in year 1 and 2 than in year 0 (Figure 16). These results suggest it is possible that planting *Sphagnum* lowered the peak discharge during storm events. However, the decrease in peak discharge was not statistically significant when comparing before and after *Sphagnum* planting (Mann-Whitney U, p = 0.42).

Relative to the peak discharge at the Control site, the peak discharge at the *Sphagnum* plus gully-blocking site was lower after planting (Figure 16). These results suggest it is possible that planting *Sphagnum* and blocking the drainage gully lowered the peak discharge during storm events. Relative to the Control site, the peak discharge at the *Sphagnum* plus gully blocking site was decreasing each year (Mann-Whitney U, not significant, p = 0.13), suggesting that if the experiment continued, the impact of the *Sphagnum* and gully blocking may become more pronounced over time.

Table 19: The minimum, lower quartile, median, mean, upper quartile and maximum peak discharge (in L sec^{-1} ha^{-1}) for all storms in each *Calluna* mini-catchment in each BACI year.

BACI year	Mini-catchment	Minimum	Lower Quartile	Median	Mean	Upper Quartile	Maximum
0	Con	0.2	1.1	2.3	2.4	3.4	5.5
0	Spha	0.5	1.5	2.8	3.1	4.4	7.7
0	SphaGB	0.3	1.0	2.1	2.7	4.0	6.9
1	Con	0.6	2.0	3.5	5.2	7.6	16.9
1	Spha	0.6	2.3	4.4	5.7	7.8	16.9
1	SphaGB	0.6	2.0	3.6	5.4	7.7	17.8
2	Con	0.6	1.3	2.9	3.7	6.1	12.1
2	Spha	0.9	1.7	3.7	4.4	6.5	13.1
2	SphaGB	0.4	1.0	2.4	3.6	6.1	12.8

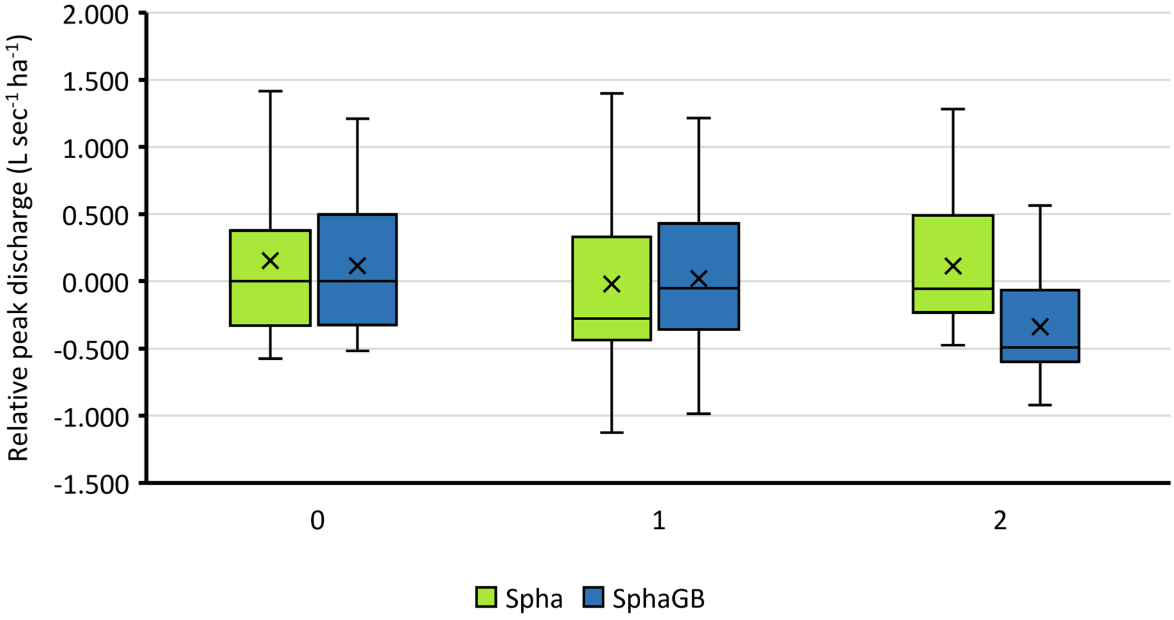

Figure 16: *Calluna* Peak discharge (relative to the Con mini-catchment) for Spha and SphaGB in each BACI year.
Year 0 median value has been normalised to zero to show change since treatment.

Comparing the *Sphagnum* site with the *Sphagnum* plus gully-blocking site showed the impact of gully blocking on the peak discharge. The two sites showed a similar trend – during approximately half of the storms (36 out of 80) the *Sphagnum* site peak discharge was higher than the *Sphagnum* plus gully blocking peak discharge. These results suggest that the blocking of the drainage gully did not lower the peak discharge any more than just planting *Sphagnum* on the site.

As shown in Figure 16, there was a wide range of peak discharge values, and only two years of data post-intervention, so that while these results are showing the beginning of a positive trend, the effect of *Sphagnum* and gully blocking on peak discharge is small so far.

4.2.2.1.2. Lag time

Peak lag time varied between years in the three mini-catchments. It was longest in year 0, then similar in year 1 and 2 (Table 20).

Relative to lag times at the Control site, lag times at the *Sphagnum* site were longer after planting – (Figure 17). This suggests it is possible that planting *Sphagnum* increased lag times during storms. There were significant increases in Spha relative lag times (median ~18 minutes) comparing before and after *Sphagnum* planting (Mann-Whitney U, $p < 0.01$). However, as *Sphagnum* cover only increased by ~5% during the monitoring period it is unlikely that this change alone would have caused the increase in lag times.

Relative to lag times at the Control site, lag times at the *Sphagnum* plus gully blocking site were longer in year 1 and 2 (Figure 17), indicating that planting *Sphagnum* and blocking the gully may have increased the amount of time between the onset of heavy rain and the peak of the storm flow. The relative lag times increased each year. There were significant increases in SphaGB relative lag times (median ~30 minutes) comparing before and after *Sphagnum* planting and gully blocking (Mann-Whitney U, $p < 0.01$). These results suggest that both *Sphagnum* planting and gully blocking can increase the lag times in the first two years after intervention. Blocking the gully had a larger impact on the lag times than planting *Sphagnum* alone, which had only increased by ~5% during the monitoring period.

Table 20: The minimum, lower quartile, median, mean, upper quartile and maximum lag time (in minutes) for all storms in each *Calluna* mini-catchment in each BACI year

BACI year	Mini-catchment	Minimum	Lower Quartile	Median	Mean	Upper Quartile	Maximum
0	Con	77.5	175.0	217.5	245.83	312.5	507.5
0	Spha	67.5	145.0	197.5	220.21	285.0	477.5
0	SphaGB	77.5	160.0	205.0	226.04	287.5	497.5
1	Con	27.5	72.5	140.0	163.42	207.5	567.5
1	Spha	17.5	62.5	137.5	151.18	187.5	532.5
1	SphaGB	27.5	82.5	175.0	177.50	227.5	582.5
2	Con	57.5	92.5	127.5	179.44	242.5	667.5
2	Spha	37.5	77.5	130.0	161.11	232.5	407.5
2	SphaGB	67.5	107.5	150.0	192.50	252.5	442.5

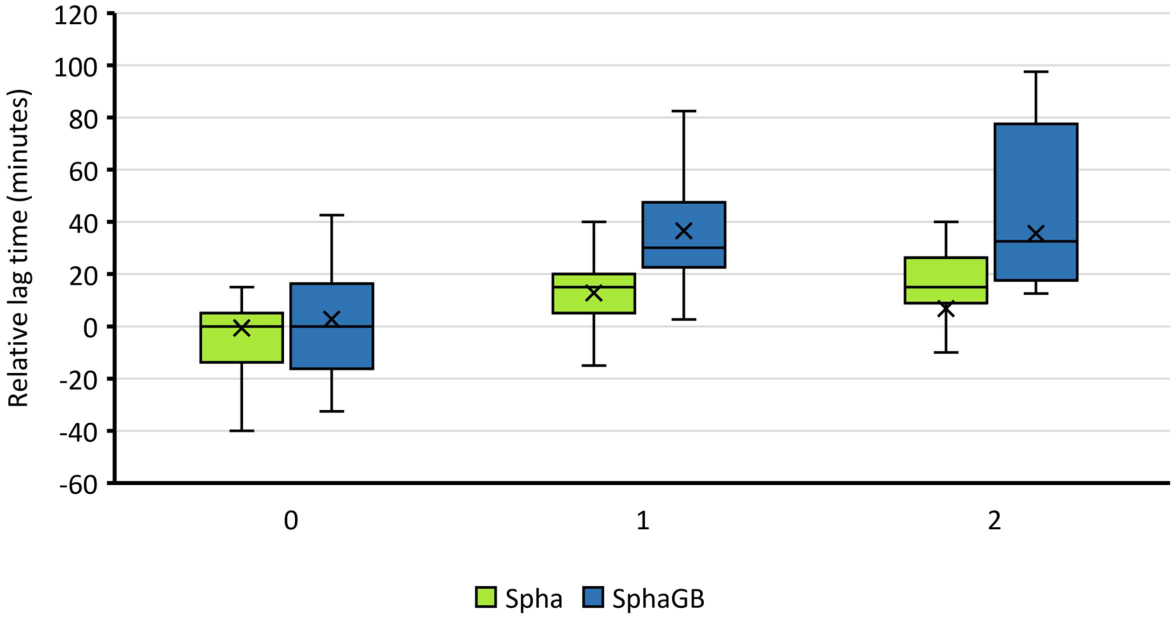

Figure 17: *Calluna* Lag time (relative to the Con mini-catchment) for Spha and SphaGB each BACI year. Year 0 median value has been normalised to zero to show change since treatment.

4.2.2.1.3. Runoff co-efficient

The majority of storms resulted in runoff percentages below 100% at the Control and *Sphagnum* plus gully blocked weirs in years 0, 1 and 2. The mean runoff from the Control site was lowest in year 0, then similar in year 1 and 2 (Table 21). In years 1 and 2, the mean (and median) runoff from the *Sphagnum* weir was higher than 100%, indicating that the *Sphagnum* catchment was losing more water than was input as rain during the storm. The cause of this is unknown but could be related to catchment size error or snowmelt, therefore these results should be treated with caution.

Relative to the runoff percentage at the Control site, the runoff percentage at the *Sphagnum* site was lower after planting (Figure 18). The runoff percentage decreased each year, indicating that planting *Sphagnum* may have caused the runoff to decrease. Planting *Sphagnum* appears to have increased the holding capacity of the *Sphagnum* catchment at times of heavy rain. There was a significant decrease in runoff percentage between the *Sphagnum* relative to Control before and after *Sphagnum* planting (Mann-Whitney U, $p < 0.01$).

Relative to the runoff percentage at the Control site, the runoff percentage at the *Sphagnum* plus gully blocked site decreased (Figure 18; Mann-Whitney U comparing before and after intervention, $p < 0.01$). This suggests that planting *Sphagnum* and blocking the drainage gully increased the water holding capacity of the catchment at times of heavy rain. As there was only a small change seen in holding capacity in the *Sphagnum* only catchment, it is likely that the majority of the increased holding capacity of the SphaGB catchment was due to the installation of gully blocks.

Table 21: Minimum, lower quartile, median, mean, upper quartile and maximum runoff (percent) for all storms in each *Calluna* mini-catchment in each BACI year

BACI year	Mini-catchment	Minimum	Lower Quartile	Median	Mean	Upper Quartile	Maximum
0	Con	14	48	73	73	90	209
0	Spha	31	68	87	93	110	273
0	SphaGB	16	55	80	85	114	254
1	Con	22	58	93	94	120	167
1	Spha	43	75	106	103	135	164
1	SphaGB	25	64	91	91	122	167
2	Con	35	62	89	92	117	175
2	Spha	50	69	105	106	133	212
2	SphaGB	28	44	81	79	96	166

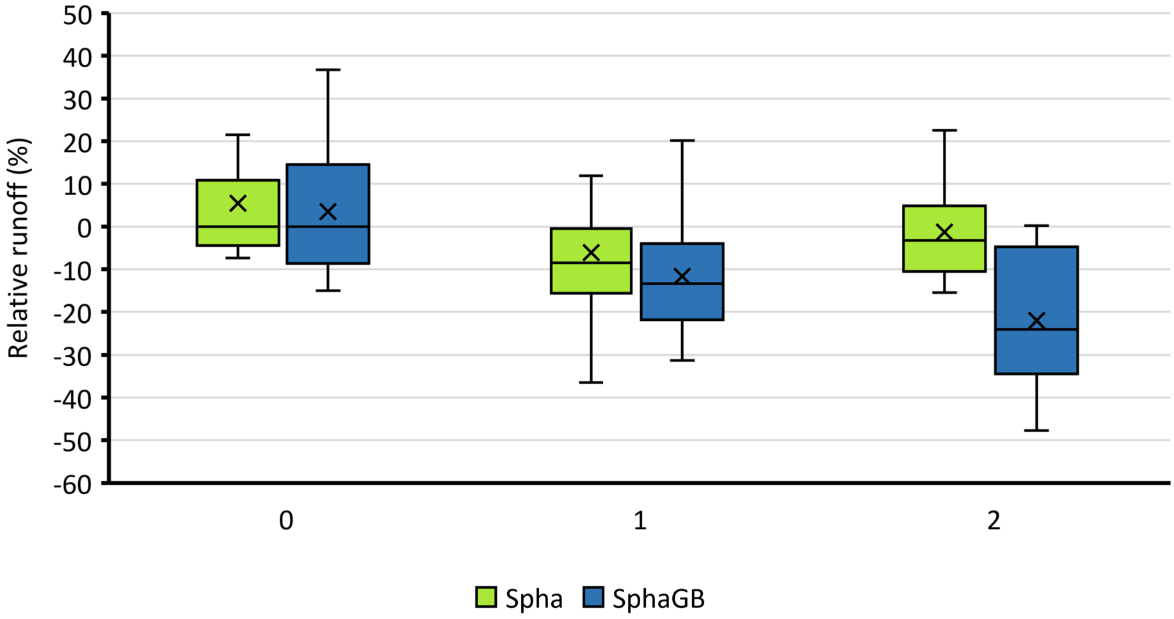

Figure 18: *Calluna* Runoff % (relative to the Con mini-catchment) for Spha and SphaGB each BACI year. Year 0 median value has been normalised to zero to show change since treatment.

4.2.2.1.4. HSI

Mean HSI values were higher in year 1 than year 0 and 2 at all three weirs (Table 22).
Relative to the HSI values at the Control site, the HSI values at the *Sphagnum* site were not significantly different (Figure 19), indicating that during the monitoring period planting *Sphagnum* did not appear to lower the storm peak volume in the *Sphagnum* catchment (Mann-Whitney U test, $p = 0.85$).

Relative to the HSI values at the Control site, the HSI values at the *Sphagnum* plus gully blocked site were not significantly different (Figure 19), showing that during the monitoring period planting *Sphagnum* and blocking the gullies did not lower the storm peak volume (Mann Whitney U, p = 0.13).

Table 22: Minimum, lower quartile, median, mean, upper quartile and maximum hydrograph shape index value for all storms in each *Calluna* mini-catchment in each BACI year

BACI year	Mini-catchment	Minimum	Lower Quartile	Median	Mean	Upper Quartile	Maximum
0	Con	0.022	0.036	0.045	0.047	0.057	0.082
0	Spha	0.037	0.065	0.080	0.082	0.096	0.129
0	SphaGB	0.034	0.054	0.068	0.064	0.075	0.097
1	Con	0.030	0.043	0.054	0.062	0.080	0.128
1	Spha	0.043	0.071	0.086	0.100	0.122	0.220
1	SphaGB	0.039	0.059	0.073	0.083	0.105	0.168
2	Con	0.012	0.043	0.050	0.051	0.066	0.093
2	Spha	0.018	0.067	0.078	0.084	0.106	0.161
2	SphaGB	0.015	0.054	0.069	0.073	0.086	0.156

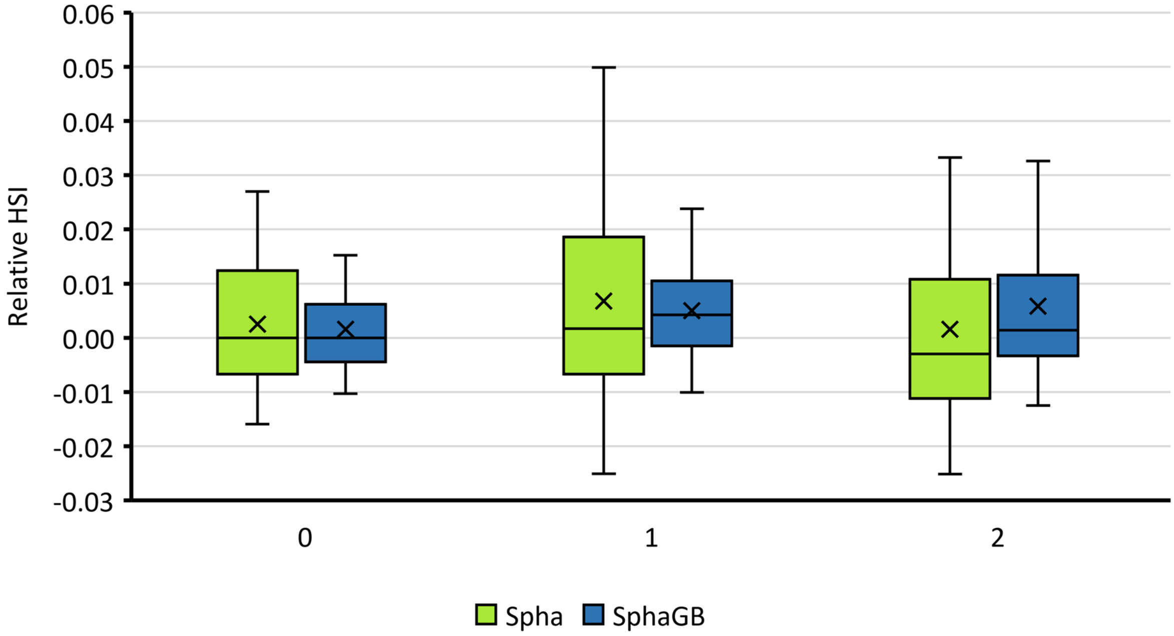

Figure 19: *Calluna* Hydrograph shape index (relative to the Con mini-catchment) for Spha and SphaGB each BACI year. Year 0 median value has been normalised to zero to show change since treatment.

4.2.2.2. *Eriophorum* dominated site

Over the three years, the total rain in the storms analysed ranged from 4 to 19 mm. The mean total rainfall during the storms in years 0, 1 and 2 were 7.5, 7.7 and 8.7 mm. The duration of storms ranged from 3.5 to 25.3 hours. The mean duration of storms in years 0, 1 and 2 were 11.6, 10.9 and 14 hours.

4.2.2.2.1. Peak discharge

Mean peak discharge was higher at the *Sphagnum* catchment weir than the Control catchment weir in all three years (Table 23). There were only 3 storms where peak discharge was higher at the Control weir than the *Sphagnum* weir.

Relative to the peak discharge at the Control site, peak discharge at the *Sphagnum* site decreased in year 1 and 2 (Figure 20). This result suggests that planting *Sphagnum* may have significantly decreased peak discharge in the first two years after planting (Mann Whitney U, $p < 0.05$). *Sphagnum* cover in the catchment was ~10% by Year 2 – while it is possible that this change in surface cover caused the apparent reduction in peak discharge, it is unlikely that it was the sole cause. Further monitoring is required to establish whether the reduction in peak discharge is maintained in future years.

Table 23: Minimum, lower quartile, median, mean, upper quartile and maximum peak discharge (in L sec^{-1} ha^{-1}) for all storms in each *Eriophorum* mini-catchment in each BACI year

BACI year	Mini-catchment	Minimum	Lower Quartile	Median	Mean	Upper Quartile	Maximum
0	Con	0.7	2.6	3.4	4.4	4.6	11.9
0	Spha	1.2	2.7	4.2	4.9	6.2	14.2
1	Con	1.3	2.7	4.3	4.9	6.2	13.6
1	Spha	0.9	3.1	4.3	5.1	6.1	14.3
2	Con	1.6	2.9	4.0	4.8	6.7	11.6
2	Spha	1.4	2.8	3.7	4.9	6.7	12.9

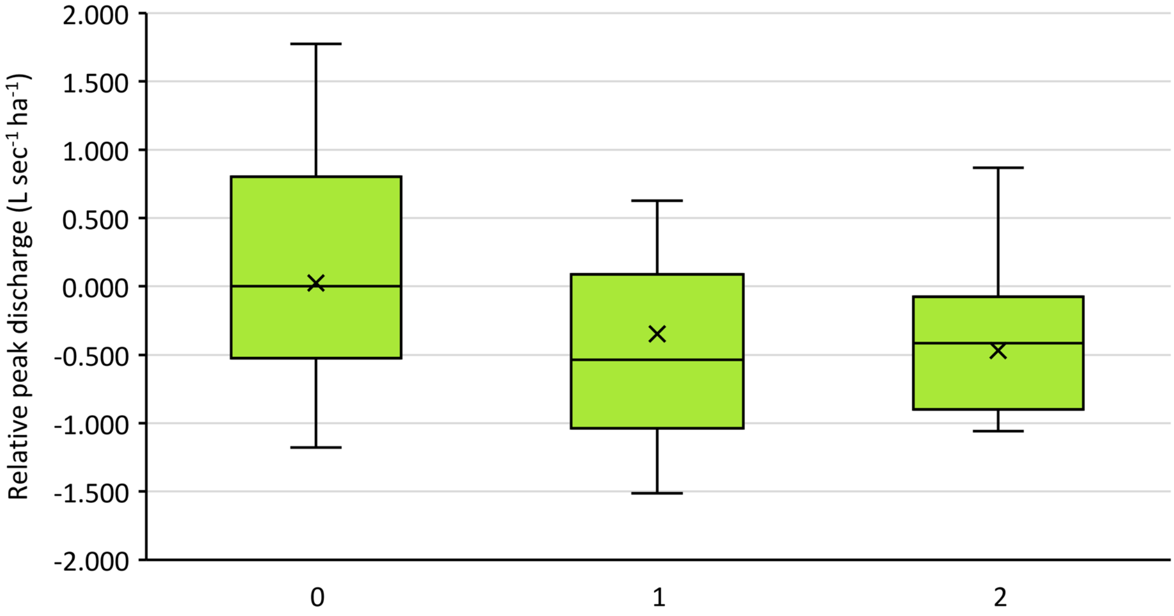

Figure 20: *Eriophorum* Peak discharge (relative to the Con mini-catchment) for Spha each BACI year. Year 0 median value has been normalised to zero to show change since treatment.

4.2.2.2.2. Lag time

Mean lag time was longer at the *Sphagnum* catchment weir (3.7 hours) than the Control catchment weir (3 hours) in all three years (Table 24). There were only 8 storms where the lag time was longer at the Control catchment than at the *Sphagnum* site.

Relative to lag time at the Control site, lag time at the *Sphagnum* site was similar in year 1 and higher in year 2 (Figure 21). The increase in year 2 was small, but could show the start of a positive trend. Further monitoring is required to establish whether this apparent change is maintained.

Table 24: Minimum, lower quartile, median, mean, upper quartile and maximum lag time (in minutes) for all storms in each *Eriophorum* mini-catchment in each BACI year

BACI year	Mini-catchment	Minimum	Lower Quartile	Median	Mean	Upper Quartile	Maximum
0	Con	22.5	107.5	157.5	180.67	252.5	407.5
0	Spha	27.5	147.5	222.5	225.92	302.5	442.5
1	Con	27.5	57.5	147.5	187.50	230.0	672.5
1	Spha	67.5	92.5	175.0	221.50	280.0	677.5
2	Con	32.5	52.5	122.5	166.67	182.5	567.5
2	Spha	47.5	112.5	167.5	210.56	232.5	612.5

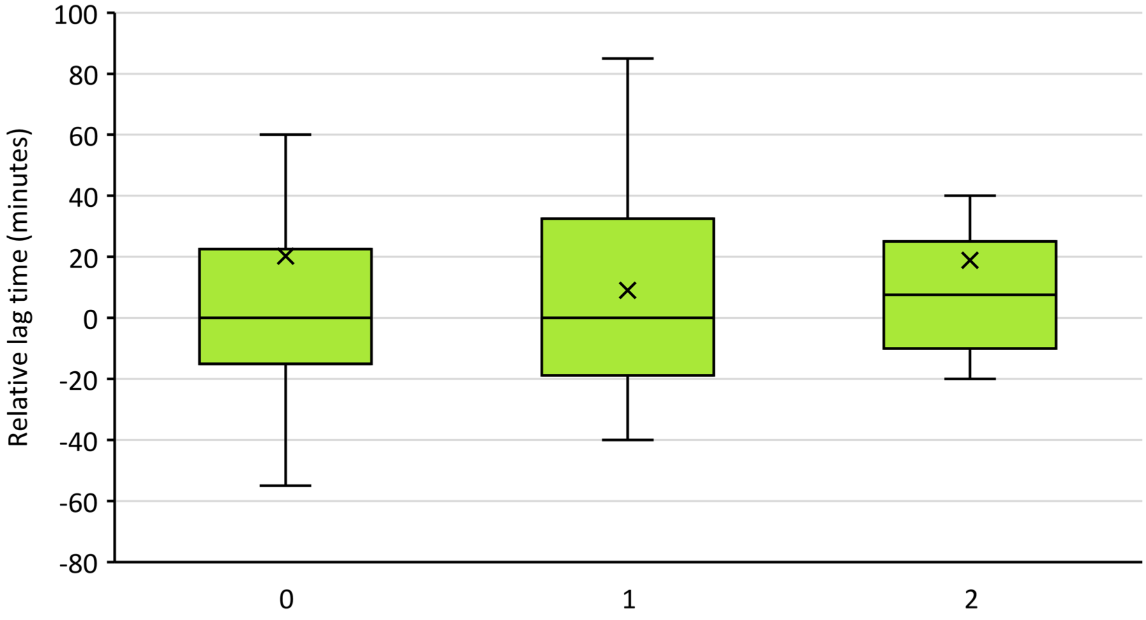

Figure 21: *Eriophorum* Lag time (relative to the Con mini-catchment) for Spha each BACI year. Year 0 median value has been normalised to zero to show change since treatment.

4.2.2.2.3. Runoff co-efficient

The majority of storms resulted in runoff percentages above 100% at the Control and *Sphagnum* weirs in years 0, 1 and 2. The mean runoff from the Control site was lowest in year 1, and similar in year 0 and 2 (Table 25). At both catchment weirs, the mean runoff values were more than 100%, indicating that both catchments were discharging more water than was input as rain during the storm.

The *Eriophorum* rain gauge data were compared to *Calluna* rain gauge data (as the geographically closest site) to determine if the *Eriophorum* rain gauge was consistently under-recording rain during the highest rainfall events and/or during winter – however there was good correlation between the two gauges in all four winter periods and in the whole dataset.

The storms with very high runoff values all occurred during winter, and so it is possible that some of water contributing to the high runoff may have been ice/snow melt. The mean air temperature during these storms was above 5 °C; however the soil temperature was occasionally lower than 5 °C, supporting the hypothesis that the large volumes of runoff were caused by ice/snow melt.

Removing all storms with soil temperatures below 5 °C (37 storms out of 79 total), left mostly spring, summer and autumn storms. Reanalysing the relative storm data of the remaining 42 storms showed that runoff from the *Sphagnum* site was approximately the same as the Control in year 0, and consistently lower than the Control in years 1 and 2. An additional possible cause for rainfall runoff co-efficient values exceeding 100% is catchment size calculation error (if the digital surface model used to map the catchment boundary calculates a catchment size smaller than reality).

Relative to the runoff percentage at the Control site, the runoff percentage at the *Sphagnum* site appeared to reduce after planting (Figure 22), suggesting that planting *Sphagnum* may have increased the holding capacity of the *Sphagnum* catchment at times of heavy rain. This change was not statistically significant however, and this finding should be treated with caution due to the possible errors in runoff co-efficient calculation.

Table 25: Minimum, lower quartile, median, mean, upper quartile and maximum runoff (in percent) for all storms in each *Eriophorum* mini-catchment in each BACI year
Any values significantly above 100 may be erroneous

BACI year	Mini-catchment	Minimum	Lower Quartile	Median	Mean	Upper Quartile	Maximum
0	Con	28	83	97	142	123	837
0	Spha	50	146	184	242	220	1111
1	Con	55	84	107	108	127	161
1	Spha	78	128	194	180	228	305
2	Con	64	95	124	130	142	304
2	Spha	85	150	216	224	240	600

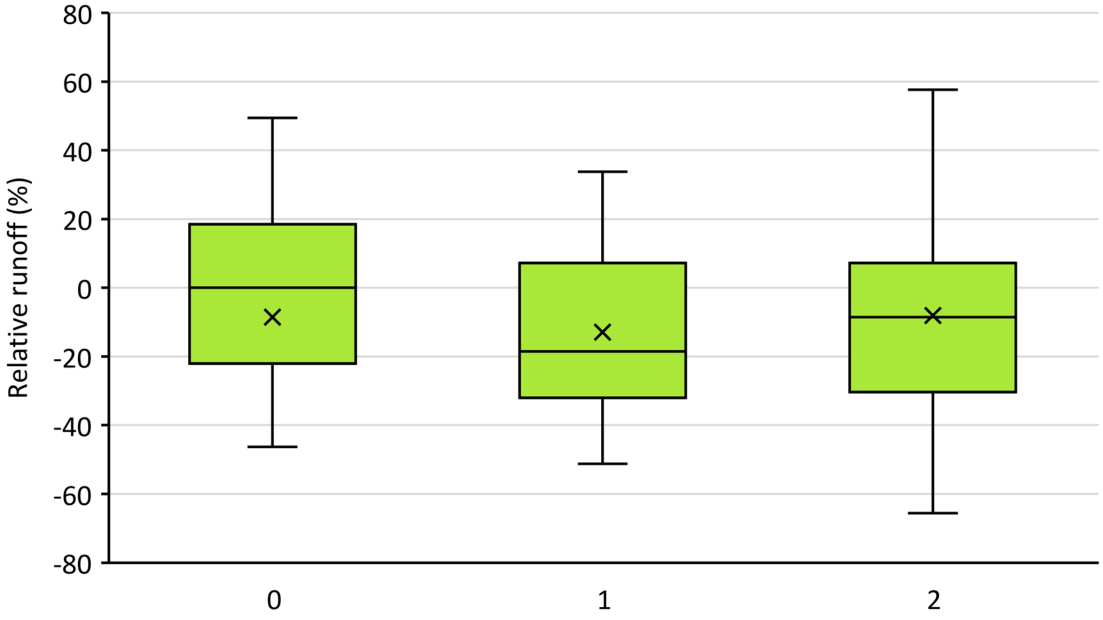

Figure 22: *Eriophorum* Runoff (relative to the Con mini-catchment) for Spha each BACI year. Year 0 median value has been normalised to zero to show change since treatment.

4.2.2.2.4. HSI

Mean HSI values were higher in year 1 than year 0 and 2 at both weirs (Table 26).
Relative to the HSI values at the Control site, no significant change in the HSI values at the *Sphagnum* site were observed after planting (Figure 23), suggesting that planting *Sphagnum* had no observable effect on flashiness of storms within the first two years of planting.

Table 26: Minimum, lower quartile, median, mean, upper quartile and maximum hydrograph shape index value for all storms in each *Eriophorum* mini-catchment in each BACI year

BACI year	Mini-catchment	Minimum	Lower Quartile	Median	Mean	Upper Quartile	Maximum
0	Con	0.025	0.037	0.047	0.048	0.056	0.112
0	Spha	0.015	0.022	0.027	0.028	0.034	0.063
1	Con	0.021	0.039	0.051	0.059	0.074	0.114
1	Spha	0.012	0.022	0.029	0.034	0.042	0.071
2	Con	0.014	0.039	0.047	0.047	0.054	0.067
2	Spha	0.009	0.022	0.025	0.027	0.033	0.045

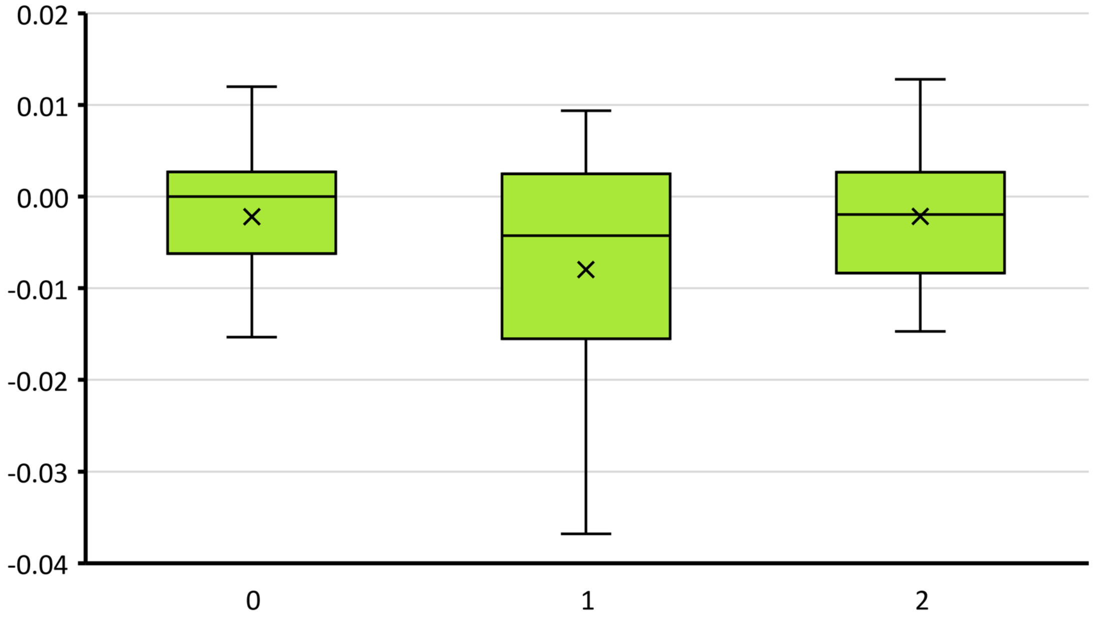

Figure 23: *Eriophorum* Hydrograph shape index (relative to the Con mini-catchment) for Spha each BACI year.
Year 0 median value has been normalised to zero to show change since treatment.

4.2.2.3. *Molinia* dominated site

Over the three years, the total rain in the storms ranged from 4 to 36 mm. The mean total rainfall during the storms in years 0, 1 and 2 were 9.0, 9.7 and 10.9 mm. The duration of storms ranged from 3.4 to 31.7 hours. The mean duration of storms in years 0, 1 and 2 were 12.6, 14.7 and 15.3 hours.

4.2.2.3.1. Peak discharge

Mean peak discharge at the Control weir was similar in all three years (Table 1Table 27).

Relative to peak discharge at the Control site, peak discharge at the *Sphagnum* site did not appear to change significantly after planting (Figure 24). Further monitoring is required to establish whether the future development of *Sphagnum* cover will affect peak discharge.

Table 27: Minimum, lower quartile, median, mean, upper quartile and maximum peak discharge (in L sec^{-1} ha^{-1}) for all storms in each *Molinia* mini-catchment in each BACI year

BACI year	Mini-catchment	Minimum	Lower Quartile	Median	Mean	Upper Quartile	Maximum
0	Con	0.5	1.5	2.8	4.0	6.2	12.0
0	Spha	0.1	0.4	1.0	1.2	1.6	4.9
1	Con	0.5	1.6	2.4	3.5	4.3	12.0
1	Spha	0.2	0.5	0.7	1.1	1.2	4.2
2	Con	0.5	1.6	2.4	3.8	5.0	13.1
2	Spha	0.2	0.5	0.7	1.2	1.4	5.1

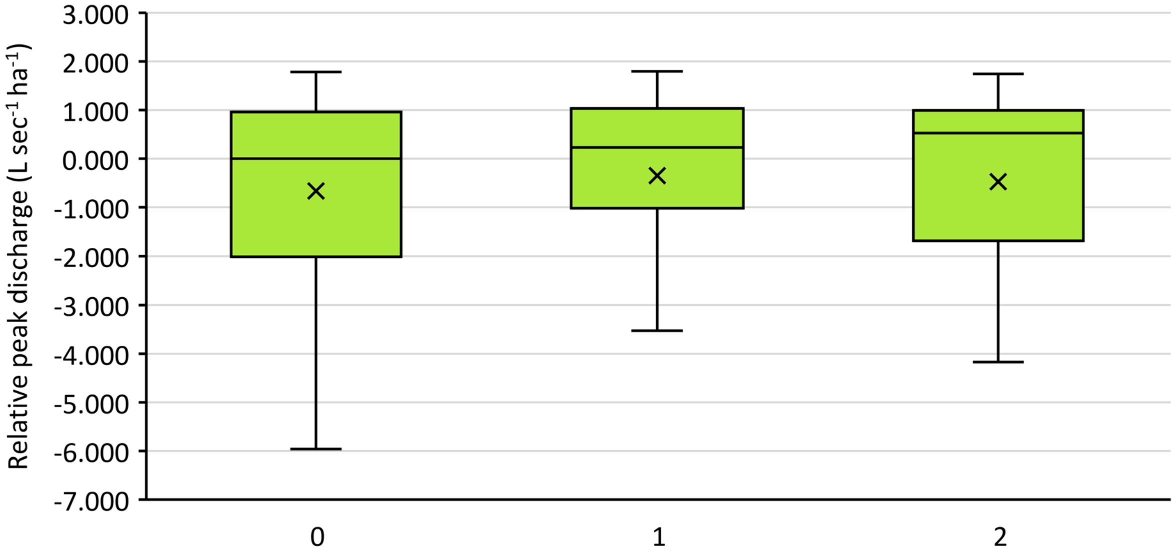

Figure 24: *Molinia* Peak discharge (relative to the Con mini-catchment) for Spha each BACI year. Year 0 median value has been normalised to zero to show change since treatment.

4.2.2.3.2. Lag time

Mean lag time was longer at the *Sphagnum* catchment weir (average 3.7 hours) than the Control catchment weir (average 3.4 hours) in the first year, before *Sphagnum* was planted (Table 28). In years 1 and 2 there were very small differences in mean lag time between the Control and *Sphagnum* sites, however mean lag time decreased each year. Out of 90 storm events, approximately half (40) had a higher mean lag at the *Sphagnum* site than the Control site. Relative to lag times at the Control site, there was no significant change in lag times at the *Sphagnum* site after planting (Figure 25).

Table 28: Minimum, lower quartile, median, mean, upper quartile and maximum lag time (in minutes) for all storms in each *Molinia* mini-catchment in each BACI year

BACI year	Mini-catchment	Minimum	Lower Quartile	Median	Mean	Upper Quartile	Maximum
0	Con	27.5	92.5	197.5	205.46	327.5	487.5
0	Spha	27.5	102.5	212.5	222.13	327.5	527.5
1	Con	27.5	102.5	135.0	189.71	257.5	732.5
1	Spha	12.5	62.5	142.5	187.21	252.5	722.5
2	Con	47.5	97.5	172.5	170.26	202.5	412.5
2	Spha	17.5	97.5	167.5	177.67	192.5	492.5

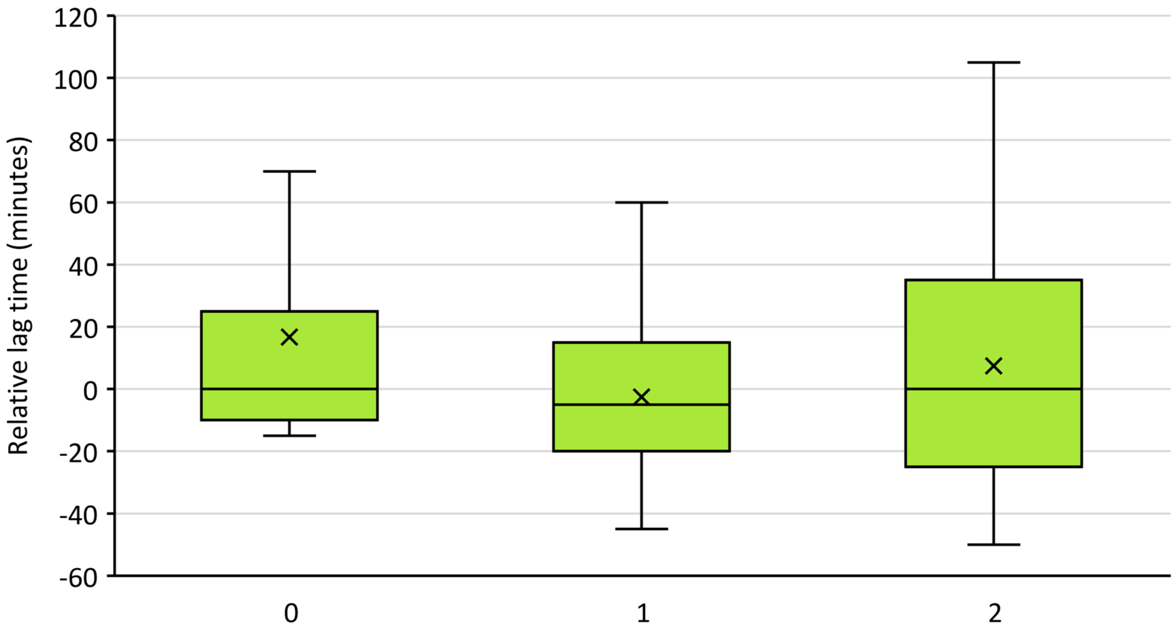

Figure 25: *Molinia* Lag time (relative to the Con mini-catchment) for Spha each BACI year. Year 0 median value has been normalised to zero to show change since treatment.

4.2.2.3.3. Runoff co-efficient

There were clear differences in the runoff between the Control and *Sphagnum* catchments. The mean runoff from the Control site was highest in year 0, then decreased in year 1 and year 2 (Table 29). In all three years, the *Sphagnum* catchment mean runoff was around 30%, suggesting either that the catchment was storing a significant proportion of the rainfall during storm events or that there was an error in catchment size estimation (an overestimation of catchment size would result in an underestimation in runoff %). There was no event where the runoff percentage was higher in the *Sphagnum* catchment than the Control site.

Relative to the runoff percentage at the Control site, the runoff percentage at the *Sphagnum* site was similar before and after planting. There was no clear trajectory in the relative runoff percentage after intervention (Figure 26).

Table 29: Minimum, lower quartile, median, mean, upper quartile and maximum runoff (in percent) for all storms in each *Molinia* mini-catchment in each BACI year

BACI year	Mini-catchment	Minimum	Lower Quartile	Median	Mean	Upper Quartile	Maximum
0	Con	24	53	95	108	151	245
0	Spha	4	17	27	32	45	87
1	Con	19	67	91	100	114	296
1	Spha	2	19	25	31	34	107
2	Con	22	66	85	97	127	182
2	Spha	6	18	26	30	39	70

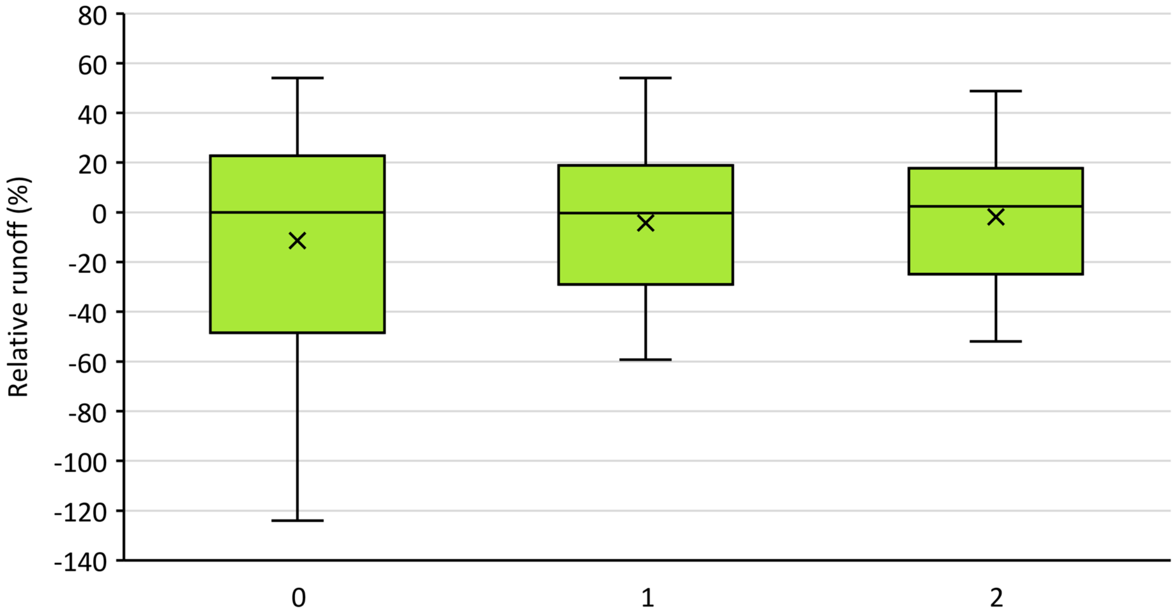

Figure 26: *Molinia* runoff (relative to the Con mini-catchment) for Spha each BACI year. Year 0 median value has been normalised to zero to show change since treatment.

4.2.2.3.4. HSI

HSI values were similar at both weirs during year 0 (Table 30). In year 1 and year 2, the HSI values were lower than in year 0, and lower at the *Sphagnum* site than the Control site.

Relative to the HSI values at the Control site, the HSI values at the *Sphagnum* site showed no change after planting (Figure 27).

Table 30: Minimum, lower quartile, median, mean, upper quartile and maximum hydrograph shape index value for all storms in each *Molinia* mini-catchment in each BACI year

BACI year	Mini-catchment	Minimum	Lower Quartile	Median	Mean	Upper Quartile	Maximum
0	Con	0.015	0.018	0.026	0.029	0.039	0.071
0	Spha	0.006	0.008	0.012	0.013	0.017	0.033
1	Con	0.012	0.019	0.027	0.028	0.033	0.049
1	Spha	0.006	0.008	0.011	0.012	0.014	0.025
2	Con	0.013	0.019	0.024	0.024	0.029	0.041
2	Spha	0.006	0.008	0.009	0.010	0.012	0.018

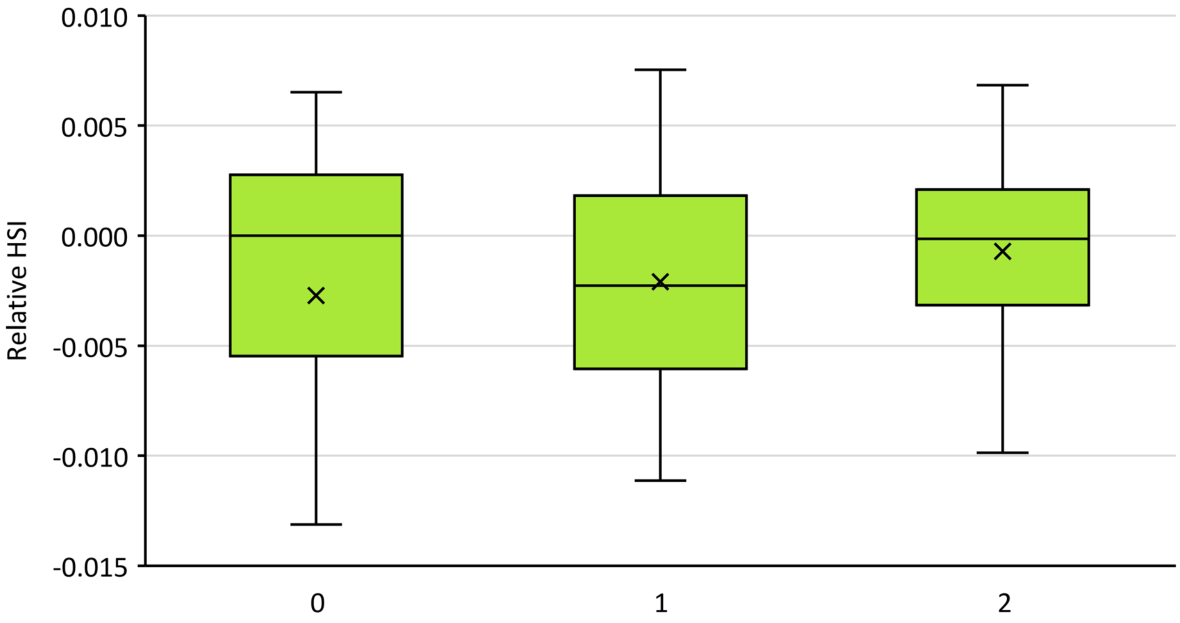

Figure 27: *Molinia* Hydrograph shape index (relative to the Con mini-catchment) for Spha in each BACI year.
Year 0 median value has been normalised to zero to show change since treatment.

4.3. Gully blocking trial

Median lag time (difference in timing of peak stage at upper and lower dam locations) in the pre-treatment period was -9.5 minutes (n=10), suggesting that peak stage in heavy rain events occurred at the lower location earlier than at the upper location Figure 28. This could be due to differences in gully profile – the gully is narrower and therefore more constricted at the downstream location than at the upper location. Stage may therefore be more responsive to changes in discharge than at the upper (wider location).

A significant difference in lag times was observed between baseline and post-treatment periods (Mann-Whitney U: 659, standardised test statistic 2.75, p=0.006), with median lag time increasing from -9.5 to +9 minutes, resulting in an overall increase in lag time of 18.5 minutes. No significant difference was observed between lag times between the 20mm and 30mm slot periods, although median lag time increased from 6 minutes (20mm slots) to 10 minutes (30mm slots). There was no control site or replication in this trial so these data are for illustrative purposes only.

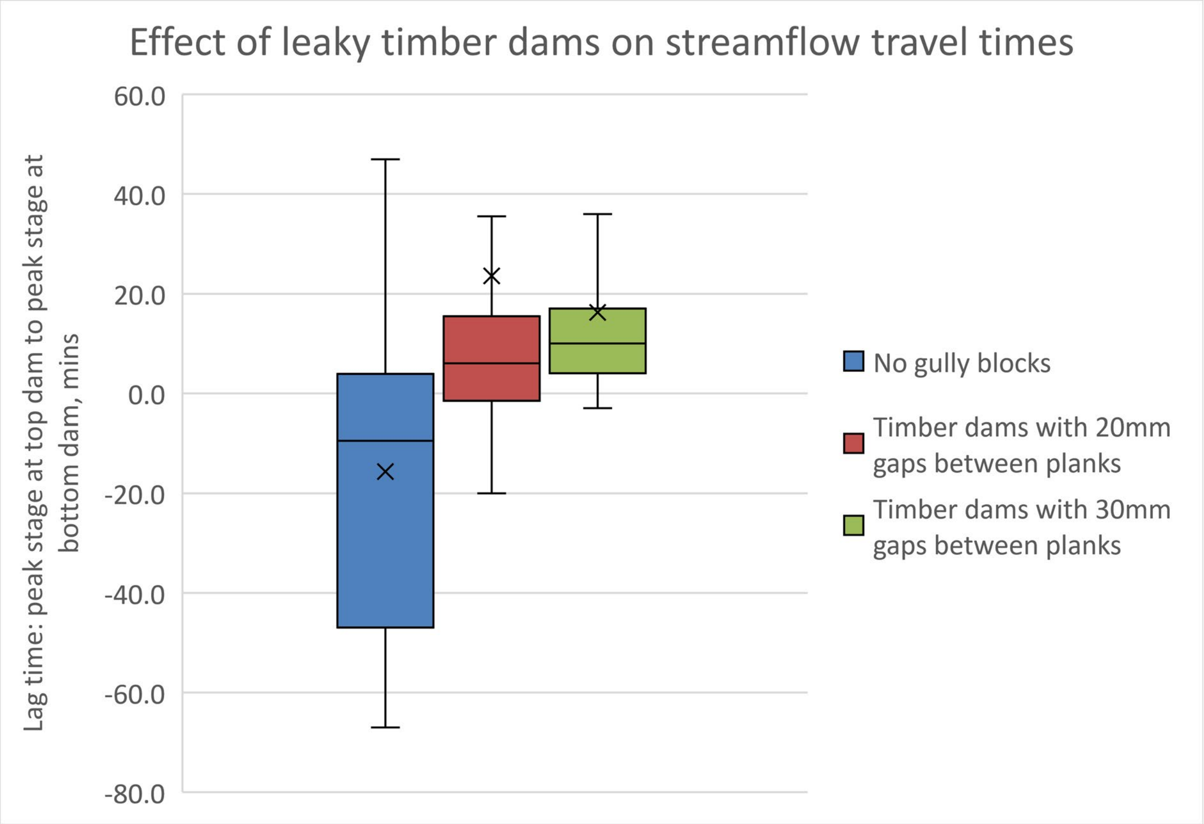

Figure 28: effect of leaky timber dams on streamflow travel times

5. Discussion

5.1. Bare peat

5.1.1. Trajectories of change over 10 years

Restoration has had a pronounced effect on the hydrology of treatment sites, producing marked changes in stormflow behaviour.

5.1.1.1. Initial step-changes

Restoration by revegetation had an immediate and significant impact on storm hydrograph characteristics, increasing lag times by 183 percentage points (*pp*), and decreasing peak storm discharge by 45 *pp* and HSI by 32 *pp*. Gully blocking enhanced the benefits of revegetation, with lag times increased by a further 217 *pp*, and peak storm discharge and HSI reduced by an additional 5 and 26 *pp* respectively, relative to the control. However, neither of the treatments had any impact on the proportion of storm event rainfall that became storm discharge (*C*). This is in keeping with previously published work on the sites detailed in Shuttleworth *et al* (2019), although it should be noted that the changes differ slightly here due to gap filling in the rainfall data and a longer monitoring period allowing a larger population of storms to be analysed.

These step changes are consistent with an increase in surface roughness provided by the nurse crop, slowing the flow of runoff across the hillslope (cf. Holden *et al*, 2008, Pan and Shangguan, 2006). Grayson *et al* (2010) observed similar changes in hydrograph behaviour at a naturally revegetated peatland site in the North Pennines. Goudarzi *et al* (2021) link this flow attenuation to a thickening of overland flow, which they conceptualise as an increase in ‘kinematic’ or within-storm storage (i.e. the amount of surface water in motion which is not yet delivered to the outlet, at any given point in time). Gully blocking enhanced the impacts of revegetation on peak discharge and lag time, but the lack of change in runoff coefficient indicates that there was no significant gain in storage through ponding behind gully blocks (cf. Evans *et al*, 2005). The additional changes in stormflow hydrographs associated with gully blocking were rather driven by the introduction of large-scale roughness elements to the channel (Shuttleworth *et al*, 2019). Goudarzi *et al* (2021) also highlight the importance of gully blocking in increasing kinematic storage as significant in providing the further benefits of peak flow reduction and lag increase compared to revegetation alone.

After the initial step changes, no further changes in any of the metrics were observed at the site that was restored by revegetation alone (site O). This is surprising given the profound changes in vegetation detailed in the Diversity chapter of this report. One might assume that as species richness develops through time, further roughness benefits would be evident. For example, modelling work by Holden *et al* (2008) found that overland flow was slower over *Sphagnum* compared to *Eriophorum,* and experimental work by Bond *et al* (2020) showed that overland flow velocities varied greatly over different vegetation types in upland grasslands. However, our results show that any impact of denser vegetation cover (with no *Sphagnum* present) developing through time is marginal compared to the initial transition from a smooth bare peat surface to a rough nurse crop cover and natural inter-annual variation in rainfall.

5.1.1.2. New trajectories of change following *Sphagnum* planting

Similar to site O, no further changes were observed at the re-vegetated and gully blocked site (site N) during the first phase of restoration following the initial step changes. However, gradual improvements in lag time and peak discharge were evident following the application of *Sphagnum*. There was a slight delay between the *Sphagnum* planting in 2015 and the onset of these gradual changes in storm flow, so it appears that *Sphagnum* cover needs to develop to at least 10% on hillslopes or 15% in flow lines before it starts to meaningfully attenuate flow. By 2021, *Sphagnum* cover at site N was 25% in the fixed quadrat locations (hillslopes/undulating ground) and 85% across the whole flow pathway network in the catchment. In addition to this lateral increase in ground cover, the *Sphagnum* layer increased in density and vertical height, in places reaching up to ~30cm above the peat surface. The combined extent and depth of the *Sphagnum* cover within the flow pathways and across the hillslopes has increased the hydraulic roughness of the surface over/through which overland storm flow must pass in order to convert to discharge at the catchment outlet (for illustration see Figure 29). For further detail on vegetation change and *Sphagnum* spread see the Diversity chapter of this report.

Lag time began to increase from 2016 onwards, and by the end of the monitoring period in 2021 lag was 280 percentage points longer than during phase one. Peak storm discharge began to decrease from 2017 onwards and by the end of the monitoring period was 17 percentage points less than during phase one. This is consistent with modelling work on the impact of *Sphagnum* on overland flow velocities by Holden *et al* (2008), discussed above, and Gao *et al* (2016) who showed that high density *Sphagnum* ground cover should significantly slow flow and reduce peak discharges by up to 13.4% if concentrated in riparian zones. It is unclear why there should be an offset between the starting point of the trajectories for lag and peak storm discharge. Peak storm discharge was anomalously low at both of the treatment sites in 2016, to the point it was significantly different to the magnitude of the initial step change at site N and is likely driven by synoptic hydrometeorology as discussed in Shuttleworth *et al* (2019). Without this anomaly, the trajectories may well have started at the same time.

There is still uncertainty as to whether the trajectory of change at site N can be attributed solely to the spread of *Sphagnum* cover or if there is some contribution from the natural maturation of gully blocks as they age. The Protect-NFM project (NE/R004560/1, protectnfm.com) monitored three additional mini-catchments on Kinder Edge that were re-vegetated and gully blocked at the same time as site N but then were not subject to further intervention. Preliminary findings suggest that the level of runoff attenuation at these catchments was less than at site N, supporting the finding from this study that *Sphagnum* has additional benefits beyond revegetation and gully blocking, but without any pre-treatment data from these additional catchments it is difficult to draw any firm conclusions. Further monitoring is also required to assess the end point of the *Sphagnum* trajectory at site N, and whether a trajectory of change is detectable at the re-vegetated site (site O) as the vegetation further matures over longer time scales, particularly if *Sphagnum* returns as the site becomes wetter (see the Water Table, Soil Moisture and Overland Flow Generation chapter of this report) and *Sphagnum* abundance increases in the surrounding area. Anecdotally, a small number of *Sphagnum* patches were observed in flow pathways at O in 2022. The cause of establishment of these patches is unknown but it could be from *Sphagnum* spores/fragments translocated from nearby areas of abundance by wind, humans or non-human animals.

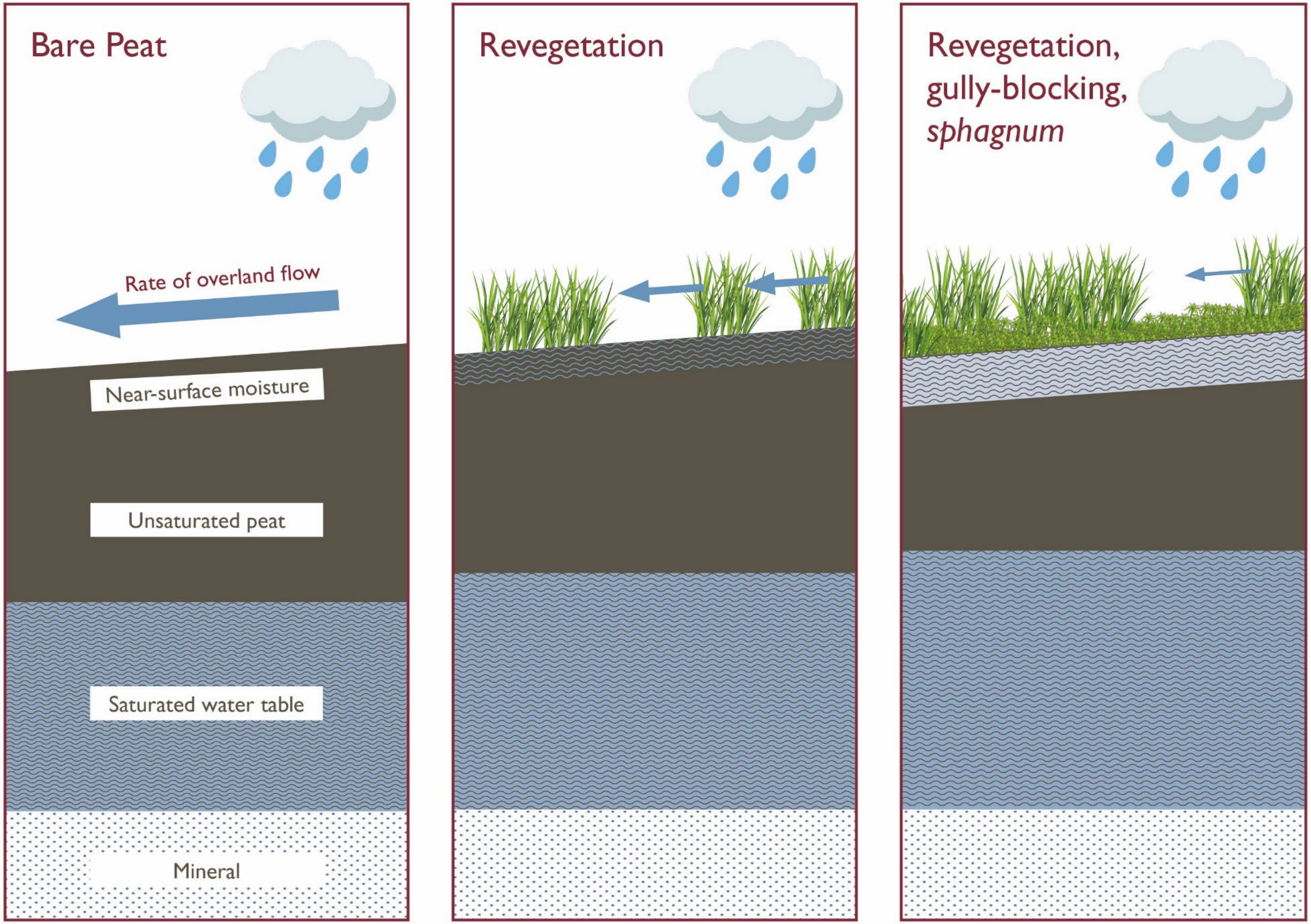

Figure 29: Schematic illustration of hydrological effects of revegetation and *Sphagnum* planting.
New vegetation protects the peat surface from drying out, leading to saturated water table rise and increase in near-surface soil moisture; vegetation also creates a rough surface, reducing overland flow velocity. Sphagnum enhances these effects, increasing saturated water table rise, near-surface soil moisture and surface roughness, further reducing overland flow velocity

5.1.2. Impact of restoration on extreme storm events

5.1.2.1. Lag time

The clearest evidence of sustained impacts of restoration across different types of events can be seen in lag times. At site O (revegetation only), lag times could be up to an hour longer than at the control site when the quickest/flashiest flows were observed at the control site. Gully blocking provided additional benefits during these ‘quick’ events, with lag times reaching nearly three hours longer at site N compared to the control during the first phase of restoration. *Sphagnum* provided further benefits at site N, with lag times up to seven hours longer than at the control during flashy flow at the control site.

5.1.2.2. Peak discharge

The impacts of the treatment interventions were also evident in high magnitude events, where the highest peak flows were observed at the control site. Here the reductions in peak flow scaled with storm size, so the higher the peak flow observed at the control site, the greater the reduction in peak flow at the treatment sites. However, unlike for lag there were no additional reductions in peak storm discharge from gully blocking and *Sphagnum* (as compared to revegetation alone) during the highest flows, with their additional benefits only evident in smaller to medium sized events. During the highest magnitude events with sustained heavy rainfall, any additional benefits to kinematic (within storm) storage provided by the gully blocks and *Sphagnum* were overwhelmed by the sheer volume of water flowing through the system (Goudarzi *et al* 2021). Nevertheless, it is important to note that at both treatment sites the biggest reductions in peak flows were observed in the highest magnitude events.

Overland flow and flow depths are relatively shallow in headwaters compared to larger catchments, meaning that roughness effects can persist in high magnitude storm events (Shuttleworth *et al*, 2019; Goudarzi *et al* 2021). Changes to hydrograph behaviour post-treatment were still evident during the largest and flashiest storms, indicating that the changes in runoff delivery were maintained in the more extreme, flood relevant events. This is an important finding in terms of natural flood management (NFM), as the observed hydrological impacts of treatment in peatland headwaters have the potential to alter downstream stormflow behaviour and reduce flood risk and severity.

5.1.3. Implications for restoration, land management and NFM

These findings have implications beyond simply revegetating areas of bare peat. *Sphagnum* mosses are regarded as ‘keystone’ species in peatlands (Rochefort, 2000, Gorham and Rochefort, 2003) due to their role in bog building, carbon sequestration, and maintaining high water tables and acidic conditions, and their reintroduction is becoming a priority in blanket peat restoration initiatives. As many areas of bare peat have been stabilised through effective restoration initiatives over the last two decades, the focus of peatland restoration is now shifting towards rehabilitating vegetated peatlands that nevertheless remain in Unfavourable-Recovering condition, much like the work on reintroducing *Sphagnum* to species dominated sites detailed in this report. The results from the bare peat sites show that widespread *Sphagnum* reintroduction has the potential to make a major contribution to NFM, especially if strategically targeted in riparian zones as suggested by Gao *et al* (2016).

5.1.3.1. NFM vs rewetting?

Crucially, this study has shown that the NFM benefits of runoff attenuation are not in conflict with one of the other key goals of peatland restoration: rewetting. Water tables at these sites are steadily rising towards the surface, and the bog is slowly rewetting (as discussed in the Water Table, Soil Moisture and Overland Flow Generation chapter of this report). Modelling work by Ballard *et al.*

(2012) and Lane and Milledge (2013) on the impacts of grip blocking suggested that rewetting peatland catchments could lead to a loss of storage capacity during storm events and lead to flashier, higher magnitude flows. However, this study has provided further evidence that surface roughness is the key driver of flow attenuation following restoration of bare peat (cf Shuttleworth *et al*, 2019; Goudarzi *et al* 2021), meaning any changes in subsurface storage will have a negligible impact on runoff.

5.1.3.2. NFM benefits for the wider catchment

The significant and sustained post-treatment changes in runoff observed at the restored bare peat sites have reduced flood risk at the headwater scale. These effects will propagate downstream, with the potential to reduce flood risk at the larger catchment scale in communities at risk of flooding. These downstream effects will depend on four important factors relating to spatial and temporal scales:

1) the extent of peat cover in the catchment (Allott *et al*., 2019);
2) the area bare peat available for restoration relative to the size of the catchment (Milledge *et al*, 2015);
3) the position of restoration works in the landscape (Gao *et al*, 2016); and
4) the nature of the local geography and associated hydrograph synchronisation effects as changes to hydrograph behaviour in multiple small headwater catchments contribute to the wider catchment hydrograph (Pattison *et al*, 2014, Metcalfe *et al*, 2018).

This final point is an important consideration that has not yet been mentioned in this discussion. As bare peat restoration attenuates runoff from headwater sub-catchments it will change the timing that peak flow from different tributaries coincides in the main channel. Should these peak flows be ‘de-synchronised’, tributary peak flows will reach the main channel at different times and reduce overall peak in discharge and therefore flood risk (Blanc et al, 2012). However, there is also a chance that the converse could happen – that the timing of peak flow from previously unsynchronised tributaries could coincide and amplify peak flow downstream, and there is evidence that a moorland improvement scheme designed to delay runoff in the Allen Water (Scotland) may have partially synchronised sub-catchment peak flows (Nutt and Perfect, 2011). However, as blanket peats are typically located in the extreme upper reaches of catchment networks, the increase in lag times following bare peat restoration would generally be expected to reduce peak flows downstream (Shuttleworth *et al*., 2019). To avoid any unintentional deleterious effects, catchment-scale models can be used to test different spatial patterns of NFM interventions in the landscape and their impact on peak flow from tributaries throughout a stream network before future restoration works take place. Goudarzi *et al* (in preparation) estimated that, if the restoration techniques used at site N were applied to the 1,520 ha of suitable peatland in the Glossop catchment (4,000 ha), peak storm flows in 5–100 year return period events may be reduced by 5–12% in “long-blunt events” and 6–24% in “short-sharp events.” This has important implications for designing flood management strategies at the catchment scale.

It should be noted that the findings in this report are based on single catchments – there was no replication of either treatment. Therefore, while the initial step changes and ensuing trajectories presented here were statistically significant, confidence in these results would be improved by repeating these treatments at comparable sites.

5.2. Species dominated sites

5.2.1. Overland flow

Intensively *Sphagnum* planted ‘run-off plots’ within the mini-catchments were used to assess any impacts of dense *Sphagnum* cover on overland flow related storm behaviour at the plot scale. The only clear significant change observed was in the *Calluna* SphaGB mini catchment, where start lag times significantly increased relative to the control. Peak lags here and both peak and start lag times elsewhere demonstrate no significant change. Planting of *Sphagnum* is the only implemented change that has occurred at these locations and therefore is likely to be the primary cause of any changes seen. Changing the vegetation on blanket moorlands and therefore the surface roughness has the potential to alter overland flow response and travel from the slopes to the stream network (Holden *et al*., 2008; Grayson *et al*., 2010). *Sphagnum* has been shown to exhibit a rougher surface reducing overland flow velocities (Holden *et al*., 2008) especially compared to unvegetated surfaces. *Sphagnum* cover one year after planting increased from 0 to 28% at the *Eriophorum* mini catchment intensive plots but has thus far resulted in no significant change in lag times. At the non-gully blocked *Calluna* mini catchment the intensively planted sites displayed an increase from 0 to 18% and again showed no significant changes in lag times. The gully blocked *Calluna* catchment intensive plots although attaining the levels of *Sphagnum* cover exhibited at the other species dominated plots (0 to 26%) did demonstrate a significant change in start lags times alone with relatively longer lag times at the treated plots. Generally, however, up until September 2020 intensive *Sphagnum* planting had shown little if any effect on lag times related to overland flow. This is not surprising and should not be seen as a negative result as the *Sphagnum* is unlikely to have grown to have produced any depth of layer which is likely to have a substantial effect on slowing overland flow velocities and increasing lags. One year post planting is not a sufficient time to robustly judge effects of *Sphagnum* planting on overland flow.

5.2.2. Discharge

Sphagnum was planted across the rest of the treatment mini-catchments, but at lower densities than in the intensive run-off plots, to assess any impacts of *Sphagnum* planting at the headwater catchment scale. The lower planting density (although still higher than current standard restoration planting densities) and short time-scale of the study mean that observable effects of the *Sphagnum* planting were less likely at the headwater catchment scale than at the intensive run-off plot scale. This study found that in the first two years after *Sphagnum* planting and/or gully blocking, there were small but statistically significant changes in storm peak discharge, lag times and/or runoff on *Calluna* and *Eriophorum* dominated sites. Smaller apparent changes were observed at the *Molinia* site, but these were not statistically significant. If the trends observed after two years at these sites are genuine and continue in future years, peak discharge has started to decrease and lag times have started to increase. There were no clear changes to rainfall runoff co-efficient (except a possible small reduction at the *Calluna* site, suggesting a possible increase in catchment holding capacity) or Hydrograph Shape Index (HSI). It should be noted that for the majority of results, the effect size was small, variable and within error, so that while some results are showing the beginning of a trend, the effect of *Sphagnum* and/or gully blocking on storm hydrology metrics is small so far. It is unsurprising that the results obtained so far show small and variable changes given the low percentage cover of *Sphagnum* during the monitoring period.

The impact on hydrology of introducing *Sphagnum* to already vegetated areas of blanket bog has not been widely studied. *Sphagnum* alone has been shown to slow flow in drainage ditches, and to retard overland flow (Holden *et al*., 2008). Planting *Sphagnum* will increase surface roughness. Increasing surface roughness has been shown to have a greater impact on peak flows in rivers than blocking drains (Gao *et al*., 2017). Models have been used to show the impact on storm hydrographs of revegetating areas of bare peat – simulations showed that revegetating bare areas with *Eriophorum* did not delay peak discharge times, whereas revegetating the riparian areas with *Sphagnum* produced lower flow peaks and delayed the hydrograph peak in both low and high rainfall events. Rougher surfaces reduced flood peaks (Gao *et al*., 2017). Planting *Sphagnum* has been shown to reduce the peak discharge at both *Calluna* sites (Table 19, Figure 16). Data from vegetation surveys showed that *Sphagnum* established at all sites following planting. This will likely have resulted in increased surface roughness, with potential for reductions in peak discharge, increased lag times, decreased runoff and decreased ‘flashiness’ during storm events.

Blocking drainage gullies to raise water tables is a common method of peatland restoration. Pools of water can form behind the gully blocks. The hydrology of these artificial peatland pools have been compared to natural pools: during storm events, the artificial pools had larger changes in water level, shorter lag times and shorter recession rates than natural pools (Holden *et al* 2018). During the year, the natural pools overflowed 9 times and artificial pools overflowed 54 times, showing the artificial pools had higher runoff rates and lower holding capacity than the natural pools (Holden *et al* 2018). Studies of forest-to-bog restoration (felling forests, blocking drains on blanket bog) showed that peak discharge during storm events was higher in intact bog than afforested or restored sites, and lag times were longer at afforested and restoration sites than the intact site. Hydrograph intensity (similar to HSI) was high at the intact and restored sites (Howson *et al* 2021). Building gully blocks may physically hold back some of the water that falls during storm events. This was observable in lag-time data from the *Sphagnum* + gully blocking mini-catchment at the *Calluna* site in this study, where lag times were longer than at the Control and *Sphagnum*-only mini-catchments. There were no clear changes to peak discharge associated with the gully blocks, although there was an apparent reduction in peak discharge in the second year (not statistically significant) – further monitoring is required to establish whether this becomes a significant change as the gully blocks mature.

5.3. Gully blocking trial

The gully blocking trial was designed as a pilot study. As such, monitoring was light-touch only and did not include an untreated control gully, a rain gauge or a means of converting water stage height to stream discharge. Therefore, results should be considered as illustrative only. The installation of a series of six leaky timber dams along a 40m stretch in one gully appeared to delay peak stage at the bottom dam by 18.5 minutes ($p=0.006$). Measurements of the timber dams and gully dimensions suggested that, if all dams were holding water to the top, the six dams would generate a total of ~33m^3 of temporary storage capacity. While at least some of this available capacity appeared to be activated during high flow events, there is uncertainty in the exact attenuating effect on streamflow due to the lack of a control gully and the pre-existing variability in streamflow characteristics in the studied gully.

6. Conclusions

6.1. Bare peat sites

Restoration of heavily degraded blanket bog with deeply incised gullies and extensive areas of bare peat has led to significant changes to streamflow behaviour in storm events with important implications for natural flood management at the larger catchment scale.

A range of metrics were analysed: peak discharge, lag time, hydrograph shape index (HSI) and rainfall runoff co-efficient; all were calculated relative to values observed at the untreated control site. In the first four years following initial treatment, revegetation of bare peat areas led to a 45 percentage point (*pp*) decrease in peak discharge, a 183 *pp* increase in lag times and a 32 *pp* decrease in hydrograph shape index (HSI); the proportion of rainfall exiting the catchment as storm flow was unchanged. Adding gully blocking to the suite of restoration treatments enhanced the benefits of restoration, with peak discharge reduced by an additional 5 *pp*, lag times increased by an additional 217 *pp* and HSI reduced by an additional 26 *pp*. the rainfall runoff co-efficient was also unchanged at this site.

In the ensuing six years, no further changes were observed as a result of initial revegetation of bare peat, although the initial benefits were maintained.

By contrast, following the planting of *Sphagnum* mosses four years after initial revegetation and gully-blocking, the initial benefits were observed to increase significantly year-on-year to the end of the monitoring period, as a result of the continued growth of *Sphagnum* in the flow pathways and across the catchment. By the end of the monitoring period (ten years following initial treatment and six years following *Sphagnum* planting), peak discharge was reduced by 65 *pp*, lag times increased by 680 *pp*; HSI and rainfall runoff co-efficient remained the same as following initial treatment.

These findings reveal significant NFM benefits at the headwater catchment scale associated with the development of extensive Sphagnum cover, especially in riparian zones. While revegetation and gully-blocking have important roles to play in providing NFM benefits, the roughness effect of an extensive and thick Sphagnum layer has a significantly greater effect. Modelling suggests that these changes in headwater catchments will results in NFM benefits at the larger catchment scale, including in extreme storm events. Peak flows in flood-relevant events may be reduced by 5–12% in "long-blunt" events and 6–24% in "short-sharp" events (Goudarzi *et al*, in preparation).

Further monitoring is required to determine the future trajectories of change as the vegetation communities continue to diversify at both treatment sites, and as the re-introduced *Sphagnum* continues to grow both laterally and vertically. Climate change may also affect future trajectories. Initial findings (see the Water Table, Soil Moisture and Overland Flow Generation chapter of this report) suggest that extensive *Sphagnum* cover promotes near-surface wetness which may maintain conditions required for successful *Sphagnum* growth. By contrast, lack of extensive *Sphagnum* cover and domination by other, more drybtolerant species may promote drier near-surface conditions, reducing the likelihood of propagation of *Sphagnum* cover, and its associated NFM benefits.

6.2. Species dominated sites

The introduction of *Sphagnum* plugs into mini-catchments dominated by *Calluna*, *Eriophorum* and *Molinia* in 2019 meant that on all three trial sites *Sphagnum* was successfully established and cover began to increase during the course of the monitoring.

With only two (or in the case of the intensively planted 'run-off plots', one) years of post-treatment monitoring analysed, the *Sphagnum* plugs did not have time during the monitoring to obtain a great depth. However, *Sphagnum* cover did increase. The largest increase was observed on the *Eriophorum* dominated site, followed by the *Calluna* and the increase was smallest on the *Molinia* dominated site.

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. A range of metrics were analysed: peak discharge, lag time, hydrograph shape index (HSI) and rainfall runoff co-efficient. In addition overland flow lag times were analysed using measurements taken from intensively planted 'run-off plots'. All metrics were calculated relative to values observed at untreated control sites. Most changes found were small, variable and within error. The directions of change observed are summarised below:

On the *Calluna* dominated site peak discharge decreased – but this was a small change and not statistically significant in either treated catchment. However, the peak lag time increased significantly after treatment in both treatment catchments, more so in the *Sphagnum* and gully-blocked catchment. Both treatment catchments saw a significant decrease in rainfall runoff co-efficient, but no significant changes in HSI were found. The intensively planted run-off plots (SphaGB) showed a significant decrease in run-off start lag time in the one year of post-treatment monitoring.

On the *Eriophorum* dominated site peak discharge showed a statistically significant reduction at the treatment site relative to control in the post treatment years. The peak lag time at the treatment catchment increased relative to control in year 2 post-treatment, but not significantly. Rainfall run-off co-efficient results showed more than 100%, and various confounding factors were investigated. It was concluded that snowmelt was the most likely cause off these results, and once those events were excluded, the treatment catchment showed a small by insignificant decrease in relative run-off.

Similarly HSI results were lower post-treatment, but not significantly so. The intensively planted run-off plots showed no significant change in overland flow in the one year of post-treatment monitoring.

On the *Molinia* dominated site, no significant changes were found in the first years after treatment. Peak discharge was higher at the treatment catchment, but not significantly so. Very small differences were found between peak lag times, with the treatment catchment showing a marginally lower lag time, but again not significantly so. There were quite clear differences between catchments in rainfall run-off co-efficient with the treatment catchment storing a significant proportion of rainfall throughout the monitoring period. This finding reinforces the findings in the Water Table chapter of this report that the catchments are hydrologically dissimilar. However, relative to control there was no clear change seen after treatment. Relative to control the HSI at the treatment catchment was lower (showing a flatter peak storm hydrograph) after planting but it should be noted that both catchments showed different characteristics prior to planting. No useable data was retrieved from the in intensively planted run-off plots on this site.

These findings hint that there are likely to be NFM benefits of introducing *Sphagnum* into sites dominated by a single species once *Sphagnum* has attained a greater depth and increased in lateral growth. The mechanisms and processed identified on the restored bare-peat sites (such as increased surface roughness) are very likely to come into effect if the current trajectory of *Sphagnum* spread on these sites continues. Detailed and reliable baseline and early years results have been gathered though this project and continued monitoring and repeated analysis will be essential to determine the effect of *Sphagnum* introduction as the plants mature.

6.3. Gully blocking trial

The installation of leaky timber dams appeared to attenuate streamflow during heavy rain events by 18.5 minutes, with no significant difference in attenuation between designs using 20 mm and 30 mm slots between planks. These findings were from a pilot study only and therefore require further monitoring for verification. Based on observations in the field, 20 mm slots between planks may be insufficient on sites with a high source of vegetation debris (on this site *Calluna vulgaris*) and/or peat sediment to avoid the slots becoming blocked and therefore failing to release water stored during high flow events over the following hours/days/weeks. This may then reduce the available temporary storage available in subsequent heavy rain events. The slots were increased to 30 mm; these taller slots were also observed to block over time but less quickly and less consistently. It is therefore recommended that leaky timber dams should be installed with slots at least 30 mm high between planks if temporary in-storm storage is a priority. Further work is required to assess optimum slot height in leaky dams: if the slots are too tall the dam may not attenuate any water in all but the most extreme streamflow events.

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