Restoration of Blanket bogs; flood risk reduction and other ecosystem benefits

Annex 5. Flood Risk

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Final report of the Making Space for Water project

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CONTENTS

FIGURES

TABLES

SUMMARY

1) Restoration of peatland headwater catchments has the potential to reduce downstream flood risk through changes in catchment storage and/or storm runoff behaviour. To date, however, there has been little research on stream flow responses to the most common restoration practices of re-vegetation of bare peat and gully blocking.

2) An intensive field monitoring campaign took place over five-years (2010-14), in the form of a before-after-control-impact study of degraded micro-catchments on Kinder Scout with additional data from established reference sites. The monitoring focused on evaluating changes in storm-flow behavior following restoration and assessment of water table conditions and overland flow generation at various stages of the erosion-restoration continuum.

3) Restoration has resulted in statistically significant changes in all but one of the hydrological parameters studied. Catchments became wetter following re-vegetation – water tables rose by 35 mm and overland flow production increased by 18%. Storm-flow lag times in restored catchments increased by up to 267 %, while peak storm discharge and hydrograph shape index decreased by 37% and 38% respectively. There were no statistically significant changes in percentage runoff, indicating limited changes to within-storm catchment storage. Although there appear to be some additional benefits of gully blocking, these are not statistically significant when compared to the impacts of re-vegetation of bare peat alone.

4) The results show that storm water moves through restored catchments more slowly, attenuating flow and storm hydrograph responses. The key hydrological process response to restoration is a reduction in flow velocities associated with increased surface roughness following the establishment of vegetation cover.

5) We conclude that restoration significantly alters peatland storm runoff behaviour, delaying the release of storm-flow from headwater catchments with benefits for downstream flood reduction. The study provides robust empirical data and process analyses to inform and calibrate hydrological models and to quantify the flood risk benefits of restoration at larger catchment scales.

1 INTRODUCTION

The primary objective of the Making Space for Water project was to demonstrate how land management changes (specifically peatland restoration) in the Upper Derwent catchment might impact on flood risk. There has been considerable recent interest in the extent to which blanket peat restoration in headwater systems can help regulate flood flows to downstream areas (e.g. Bain et al. 2011), with studies to date focusing on the impacts of ditch (grip) blocking on storm hydrology and flood risk (e.g. Holden et al. 2004; Ballard et al. 2012; Lane & Milledge 2012). Landscape-scale restoration through the re-vegetation of bare peat and the blocking of erosion gullies is increasingly extensive in the Peak District and other areas of upland Britain (e.g. Anderson et al. 2009) and these types of restoration have the potential to significantly alter hydrological functioning of degraded blanket peat through changes in storm-flow runoff generation processes, runoff pathways and catchment storage. However, despite the large scale implementation, there has been almost no research on stream flow responses to re-vegetation and gully blocking (Parry et al. 2014) and we lack empirical data to both demonstrate the impacts of this restoration on storm-flow behaviour and to inform and calibrate catchment models of flood risk.

We report here on a major, five-year (2010-2014) experiment designed to evaluate the hydrological changes associated with peatland restoration by re-vegetation of bare peat and gully blocking. The main experiment takes the form of a before-after-control-impact (BACI) study of degraded peatland micro-catchments on Kinder Scout in the Peak District National Park (Figure 1), focusing on the monitoring of changes in storm-flow behaviour and other in key hydrological variables. This experiment is supplemented by hydrological data obtained from the monitoring of additional reference sites, in particular an intact blanket peat micro-catchment, a micro-catchment re-vegetated in 2003 (and therefore representing 'late-stage' restoration conditions) and further bare peat and restored sites on the Bleaklow Plateau. These reference data are used for 'space for time' comparisons, assuming that sites with of different erosion/degradation status and restored at different times constitute a time series through the intact-eroded-restored trajectory.

Blanket peatlands are naturally hydrologically 'flashy' systems with stream flow responding rapidly to rainfall events, relatively short hydrograph lag times and high peak flows relative to total storm runoff volumes (Figure 2)(Evans et al. 1999). However, peatland degradation and erosion through loss of vegetation cover or gully development can further increase the flashiness of stream flow response leading to higher storm-flow peaks (e.g. Grayson et al. 2010). There are several potential mechanisms by which degradation and restoration might alter storm-flow runoff characteristics and hence influence hydrograph flashiness and peak flows, but the key factors relate to (i) potential changes in within-storm catchment storage and (ii) potential changes in the overland flow characteristics of the peatland.

In hydrologically intact blanket peat systems storm runoff is dominated by surface or near surface flow and saturation excess overland flow is the dominant runoff pathway in high flow events (Holden & Burt 2003). Water tables are typically close to the ground surface (Evans et al. 1999), so soil water storage is limited and rapid saturation excess overland can be generated in response to significant rainfall events. Severely eroded blanket peats, however, have significantly depressed water tables (Daniels et al. 2008; Allott et al. 2009) potentially creating more soil water storage during rainfall events or increasing subsurface storm-flow pathways relative to intact catchments

(Daniels et al. 2008). The surfaces of eroded and bare peat surfaces are also subject to the development of hydrophobicity (Egglesman et al. 1993; Evans et al. 1999) 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. A further consideration is that depth to water table is an important control on the production of saturation excess overland flow, but water tables are in turn controlled by water balance and evapotranspiration (Rydin & Jeglum 2006). It follows that changes in evaporative flux from peatlands associated with change s in surface cover and vegetation might alter water tables and hence both soil water storage and the prevalence of overland flow generation within storm events.

Restoration by re-vegetation could therefore influence water tables, soil water storage and overland flow generation in a number of ways. If the development of a vegetation layer increases evapotranspiration rates this could result in lower water tables and increased soil water storage capacity, particularly after dry antecedent conditions, resulting in less flashy storm hydrograph response. Alternatively, the development of vegetation cover and root penetration could break up the surface of bare peat areas, increasing infiltration rates, raising water tables and reducing soil water storage, thereby increasing flashiness. In terms of surface cover changes, the establishment of a vegetation cover might also result in increased prevalence of surface depressions between vegetation clumps, increasing surface storage. Importantly, Holden et al. (2008) stress the role of overland flow in controlling storm hydrograph response, more specifically demonstrating the role of surface roughness as a control on overland flow velocity and travel times, and hence on hydrograph response times. They show that overland flow velocity is a function of surface cover type, with velocity on bare peat > *Eriophorum* spp cover > *Sphagnum* spp cover, indicating that the re-establishment of vegetation on bare peat could be important for reducing downstream flood peaks (Holden et al. 2008; Grayson et al. 2010). Gully blocking is also potentially important, creating a series of stone or wooden 'dams', which initially result in the formation of pools within the gully systems. Although such pools can rapidly fill with sediment, while extant they could reduce storm-flows through increased within-storm storage, particularly after dry antecedent conditions. Importantly, gully blocks also create barriers to flow within the gullies, initially from the presence of the blocks but on a longer timescale through sedimentation and associated vegetation growth in gully bottoms (Evans et al. 2005). They could therefore reduce flow velocities within gully systems through increased surface roughness, increasing storm water travel times as expressed through hydrograph lag.

From these considerations it is clear that peatland restoration could alter storm-flow runoff pathways and associated hydrograph response in a number of ways, summarised by four working hypotheses for the process response:

1. *Re-vegetation will increase evapotranspiration rates, lowering water tables and increasing soil water storage*

   Predicted changes: Increased depth to water table, reduced overland flow generation, delayed hydrograph response (increased lag times) in storm events (particularly after dry antecedent conditions) and lower runoff ratios.

2. *Re-vegetation will increase infiltration rates through the reduction of surface peat hydrophobicity and root penetration, increasing water tables and reducing soil water storage.*

   Predicted changes: Decreased depth to water table, increased overland flow generation, reduced hydrograph response times (decreased lag times) and higher runoff ratios.

3. *Re-vegetation and gully blocking will increase within-storm catchment storage due to surface ponding of water within vegetation and in pools behind blocks respectively.*

   Predicted changes: Lower runoff ratios and increases in lag times, particularly for smaller storm events or after dry antecedent conditions.

4. *Re-vegetation and gully blocking will increase surface roughness effects, with peat surface re-vegetation reducing overland flow velocities and gully blocks and associated gully re-vegetation reducing channel velocities.*

   Predicted changes: Delayed hydrograph response (increased lag times) but no change in runoff ratios.

Importantly, these different process changes predict different sets of responses in water tables, overland flow generation, runoff ratios (the proportion of rainfall which generates storm-flow) and the nature of hydrograph responses. The hypotheses can therefore be tested by monitoring key hydrological parameters at the study sites.

The key aims of the study are therefore:

1) To establish the hydrological and runoff characteristics of restored and un-restored peatlands.

2) To evaluate changes in storm-flow behaviour following restoration, in particular the key hydrograph variables of hydrograph lag time and peak storm-flow, in order to establish the impact of restoration on flood risk.

3) To establish the causes of any detected change in storm-flow behaviour by testing hypotheses of process change associated with restoration. This focus on process explanation is required to permit effective up-scaling of restoration effects and the evaluation of downstream flood risk benefits through robust hydrological modelling.

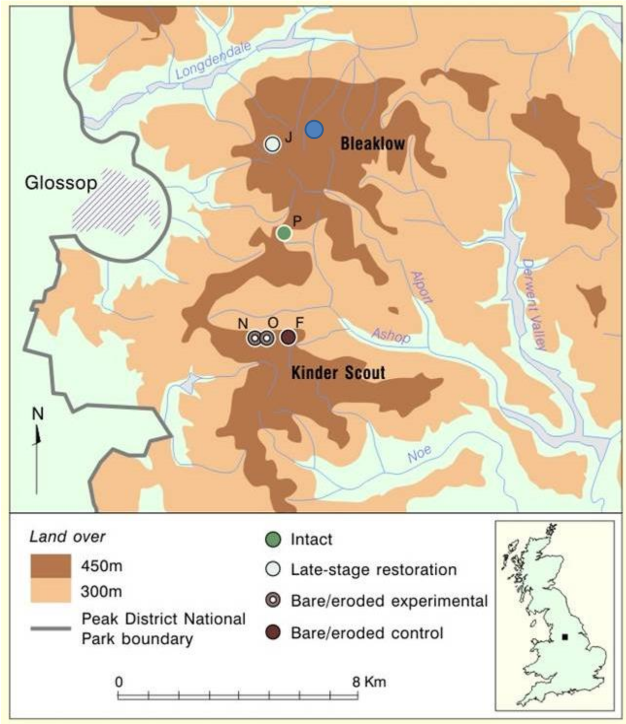


Figure 1: Location of the study catchments. The blue circle represents the location of additional sites used in the water table study.

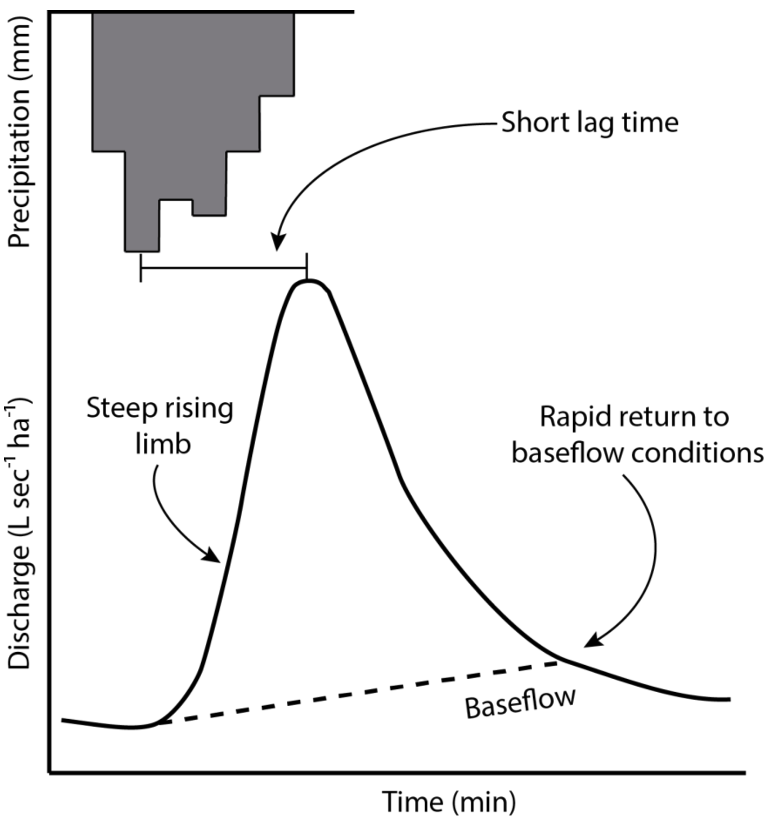


Figure 2: Features of a flashy storm hydrograph, typical of those produced in peatland systems.

2 WATER TABLES

2.1 Introduction

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

Allott et al. (2009) found substantial between-site variation in average water table conditions which was strongly associated with erosion status. Intact sites with no erosion gullies at or proximate to the site have water tables consistently close to the peat surface, while sites with dense erosion gullies are associated with lower water table conditions. Allott et al. (2009) also compared water tables at bare eroding sites and sites restored by re-vegetation, and although there was not enough data to produce significant results, this preliminary study indicated that water tables were higher at the restored sites, suggesting that water tables can be raised by re-vegetation of bare peat.

This section builds on the work of Allott et al. (2009), using water table data from eroding, restored and intact areas of peatland, gathered at a range of spatial and temporal scales, to further our understanding of the influence of re-vegetation on peatland water tables.

2.2 Methodology

2.2.1 Experimental Set-up and Data Collection

Monitoring focussed on the three main study catchments on Kinder Scout (F, N, and O) and the intact control (P) and late stage re-vegetated catchments (J), with additional data derived from bare and late-stage re-vegetated sites on the Bleaklow Plateau. Water tables were measured at weekly intervals as part of three different monitoring programmes: two space-for-time substitution studies based on the Bleaklow sites provide information on water table depths at sites of differing erosion statuses over the same sampling period, and the main study catchments on Kinder were monitored before and after intervention to assess relative changes in water table following restoration by re-vegetation.

The water table depth at each site was determined using dipwells. Allott et al. (2009) showed that multiple randomly located dipwells are required for the reliable quantification of water table conditions at the site scale, and determined that 15 dipwells are required to obtain reliable estimates of site water table conditions at any given time. Accordingly, clusters of 15 dipwells were randomly located within a 30 x 30 m area at each site. Dipwells were constructed and installed to the same specifications outlined in Allott et al. (2009). In brief, each dipwell comprised a 1 m length of polypropylene waste pipe (internal diameter 30 mm) with perforation holes drilled at 100 mm intervals, to allow water levels to equilibrate inside the pipe. Dipwells were driven into pre-prepared boreholes of the same diameter, with approximately 100 mm of pipe protruding above the ground surface.

Manual measurements of water levels in the dipwells were made using purpose-constructed electronic dip-meters. All manual measurements of water table depths were made relative to the ground surface using a 150 mm long plastic collar which fitted closely over the protruding section of dipwell. Throughout each of the three studies, water table depths were measured at each site on the same days. Details of the timing and duration of the sampling campaigns are summarised in Table 1.

2.2.2 Data analysis

A general linear model (GLM) approach based on an analysis of variance (ANOVA) was used to analyse the effect of vegetation on water table depth. A repeated measures design was employed for the space-for-time studies using *site type* (bare, re-vegetated, intact) as the fixed between-subject factor, and *measurement date* as the levels of the within-subject factor. A mixed design was employed for the BACI study which introduced *year* (before and after treatment) as a further within-subject factor. Mauchly's test was used to test for sphericity. In cases where the assumption of sphericity was violated, the Greenhouse–Geisser correction was used to adjust the degrees of freedom.

2.3 Spatial variation in water tables

This section discusses the differences in water tables recorded at bare, late stage re-vegetated (restored in 2003), and intact peatland sites from two field studies. Data for Study 1 were collected at bare (T and S) and late-stage re-vegetated (J and Tu) sites on two days in November 2009 (as part of the Allott et al. (2009) water table project), then at nine weekly intervals between September and December 2011. Data for Study 2 were recorded at the pre-restoration bare Kinder sites (F, N, O) and late stage re-vegetated and intact Bleaklow sites, at nine weekly intervals between September to November 2010 at bare, intact, and late stage re-vegetated sites. The variation in the data is presented in Figure 3, the corresponding summary statistics are presented in Table 2, and the results of the ANOVA are presented in Table 3. Water table values are based on the mean depth to water table measured at each dipwell cluster.

Water tables were deeper and more variable at bare sites than at vegetated sites (both restored and intact). The shallowest water tables were measured at the intact site where the water level was always within 150 mm of the peat surface, while at the bare and re-vegetated sites water tables varied between 198 and 568 mm and 159 to 427 mm respectively.

The observed differences in water table depth at the different sites were statistically significant in both studies ($P = 0.000$). Median water table depth at the bare and re-vegetated sites differed by 90 mm in Study 1 and 102 mm in Study 2. This indicates that c.7-8 years after re-vegetation, water tables are 24 to 30 % closer to the surface than in areas of bare peat. However, water tables do not return to intact, pre-erosion levels as median water table depth at the re-vegetated site in Study 2 was still 166 mm deeper than at the intact site.

Figure 4 shows that water tables at the bare sites were consistently deeper than at vegetated sites (both restored and intact) on any given measurement day, and that the magnitude of this difference varied through time. This is confirmed by the interaction term in the ANOVA which was significant in both studies (Study 1 - $P = 0.000$, Study 2 $P = 0.012$) indicating that the relative difference in water tables at the study sites varied between measurement days. The largest differences were evident when water tables were at their deepest (e.g. 02/11/09 and 06/10/11), while smaller differences can be seen when water tables were closer to the peat's surface (e.g. 06/11/09, 04/11/10 and 13/10/11).

2.4 Changes in water tables following re-vegetation

This section discusses changes in water tables following restoration by re-vegetation at the main study catchments on Kinder Scout (F, N, and O). An initial sampling campaign collected data from the two then-bare sites between September and November 2010 at 11 weekly intervals. Sites N and O were re-vegetated by the application of lime, seed and fertilizer in late July 2011, with subsequent additions of lime and fertilizer in July 2012 and July 2013. Gully blocks were also installed at site N in November 2011 and April 2012, but the dipwell clusters were situated away from gully edges so as not to be affected by localised water table drawdown. Water table data from the two treatment sites can therefore be combined, and will be referred to collectively as the *treatment* site for the rest of this section. Site F will be referred to as the bare *control*. A subsequent sampling campaign collected data from the two sites at 12 weekly intervals between September and December 2014. The variation in the data is presented in Figure 5 and the corresponding summary statistics are presented in Table 4. Water table values are based on the mean depth of water measured at each dipwell cluster.

In 2010, water tables at the two sites varied over a similar range; between 198 and 422 mm, and 204 and 439 mm at the control and treatment sites respectively (Table 4). However, despite experiencing a similar range of water table depths, there is a statistically significant difference in water tables at the two sites throughout the study ($P = 0.000$, Table 5). This is because on the majority of measurement days, water tables were deeper at the control site, both before and after treatment (Figure 6).

Upon first inspection of the 2014 data there appears to have been no change in water table depth at the treatment site following restoration, with water tables still varying over a similar range – between 242 and 428 mm (Table 4). However, there is a statistically significant difference in the way water tables behaved before and after restoration at the two sites ($P = 0.006$; Table 5), as demonstrated by the diverging interaction lines in Figure 5b. Because peatland water table depths are primarily controlled by precipitation and evapotranspiration, a direct comparison of water tables before and after restoration at the treatment site is not appropriate, as differing rainfall and temperature regimes may contribute to the observed distribution of water table depths. While there was very little change in water table depth at the treatment site following restoration, water tables at the bare control site were deeper in 2014 than they were in 2010.

By examining the relative differences in water table depth at the treatment and control sites (Figure 7 and Figure 6), the effect of restoration becomes clear. If restoration were to have had no effect, we would see the same similar relative differences in water table depth before and after restoration, but this is not the case. In 2010, prior to restoration, the relative difference in median water table depth was 27 mm (Table 4), and during periods where water tables were closest to the surface, there was no difference in water table depth at the two sites (Figure 6a). Three years after re-seeding, the relative difference had increased to 59 mm, and a greater difference was maintained on the majority of measurement dates, including days where water tables where shallowest (Figure 6b). This represents a relative decrease in water table depth of 35 mm.

2.5 Key results: Water tables

1. Peatland water tables are highly variable in time as they are controlled by variable rainfall and temperature regimes.
2. Despite this, there are significant differences between water table conditions at sites with different restoration statuses.
3. The highest water tables were found at intact sites where levels were consistently within 150 mm of the peat's surface, while the deepest water tables were measured at bare sites where water table depths can exceed 560 mm.
4. Re-vegetation significantly raises water tables by up to 38 %, but not to levels comparable with intact sites.
5. The observed differences between bare and re-vegetated sites were more pronounced when water tables were at their deepest.
6. Three years after restoration by re-vegetation on Kinder, water tables had risen 35 mm relative to the bare control, while c.7-8 years post-restoration on Bleaklow, relative water table was 90 – 102 mm closer to the surface at re-vegetated sites.

2.6 Figures and Tables

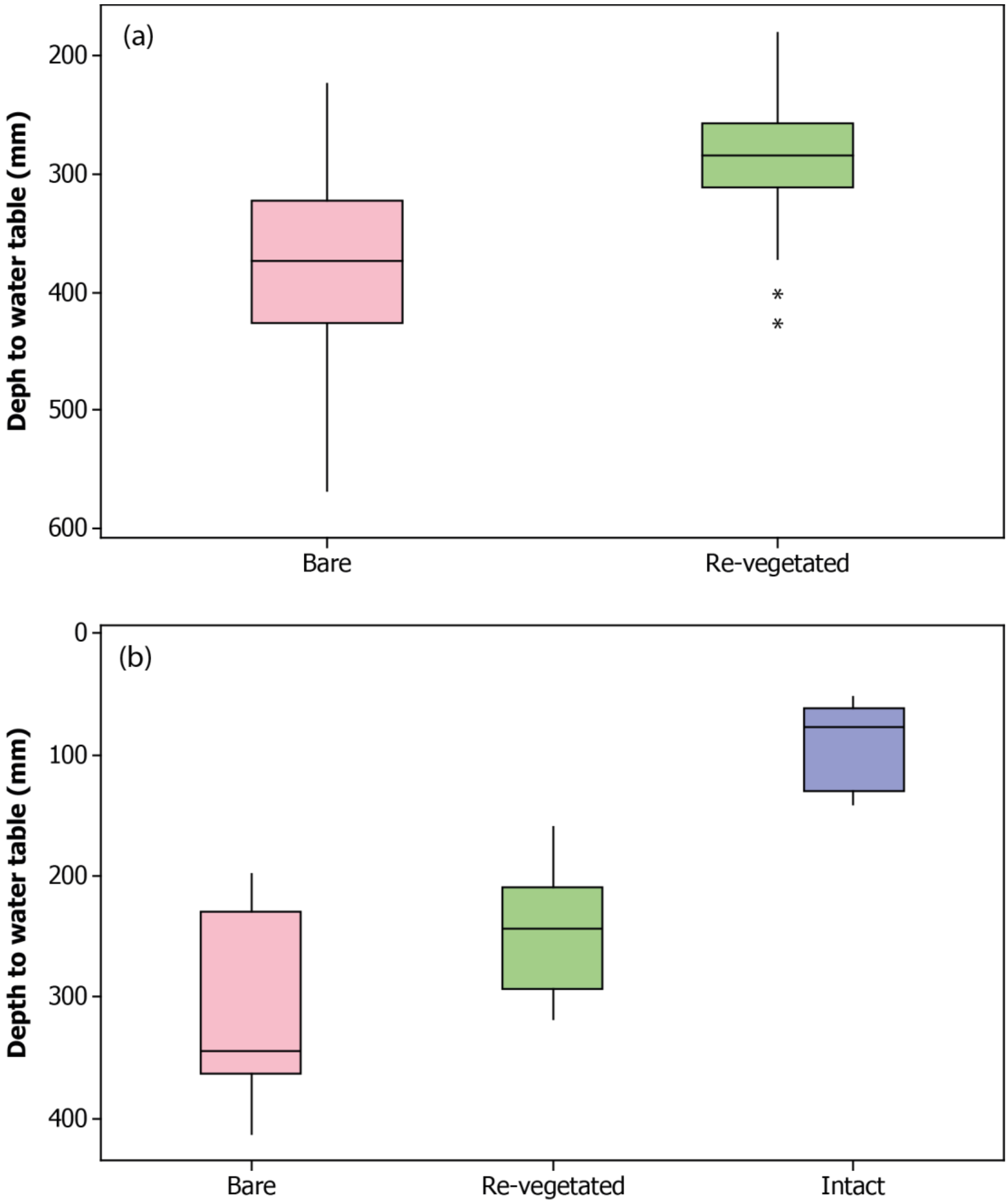


Figure 3: Distribution of water table depths at: (a) bare and late-stage re-vegetated sites in 2009/2011, and (b) bare, late-stage re-vegetated, and intact sites in 2010.

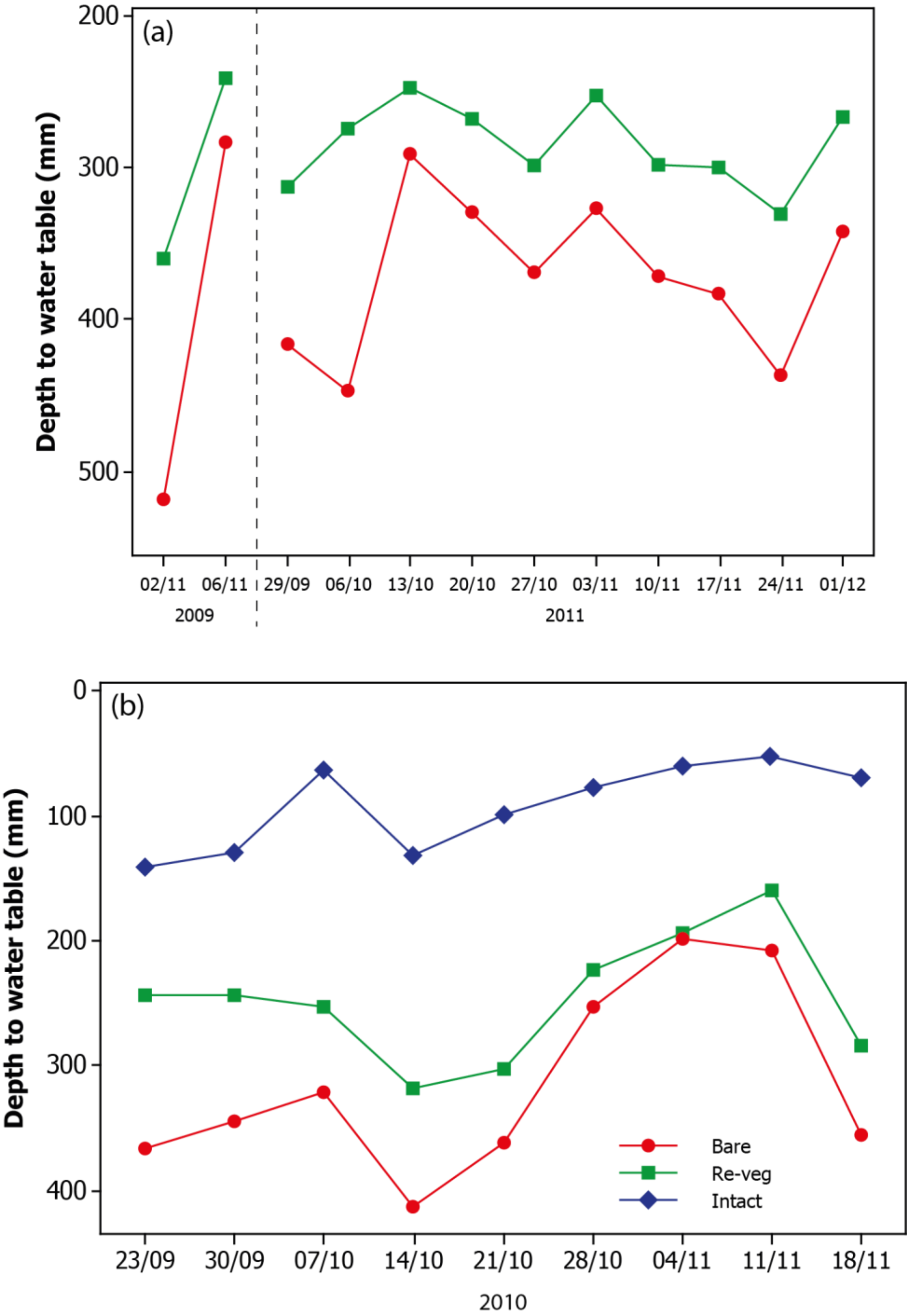


Figure 4: Variation in water table depths through time at: (a) bare and late-stage re-vegetated sites in 2009/2011, and (b) bare, late-stage re-vegetated, and intact sites in 2010.

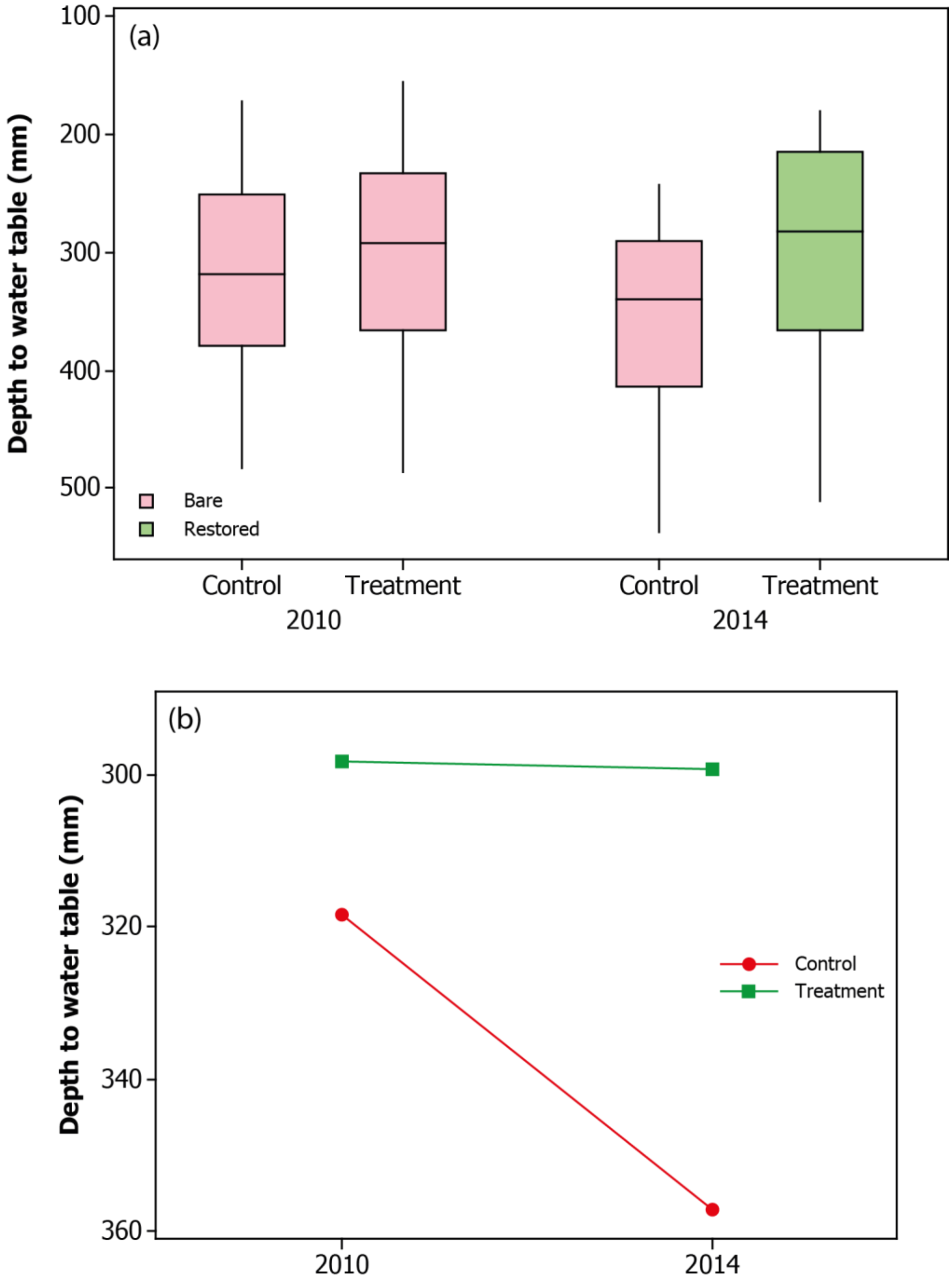


Figure 5: (a) Distribution of water table depths at the treatment and control sites before and after treatment; (b) Interaction plot showing the differences in water table at the treatment and control sites before and after treatment.

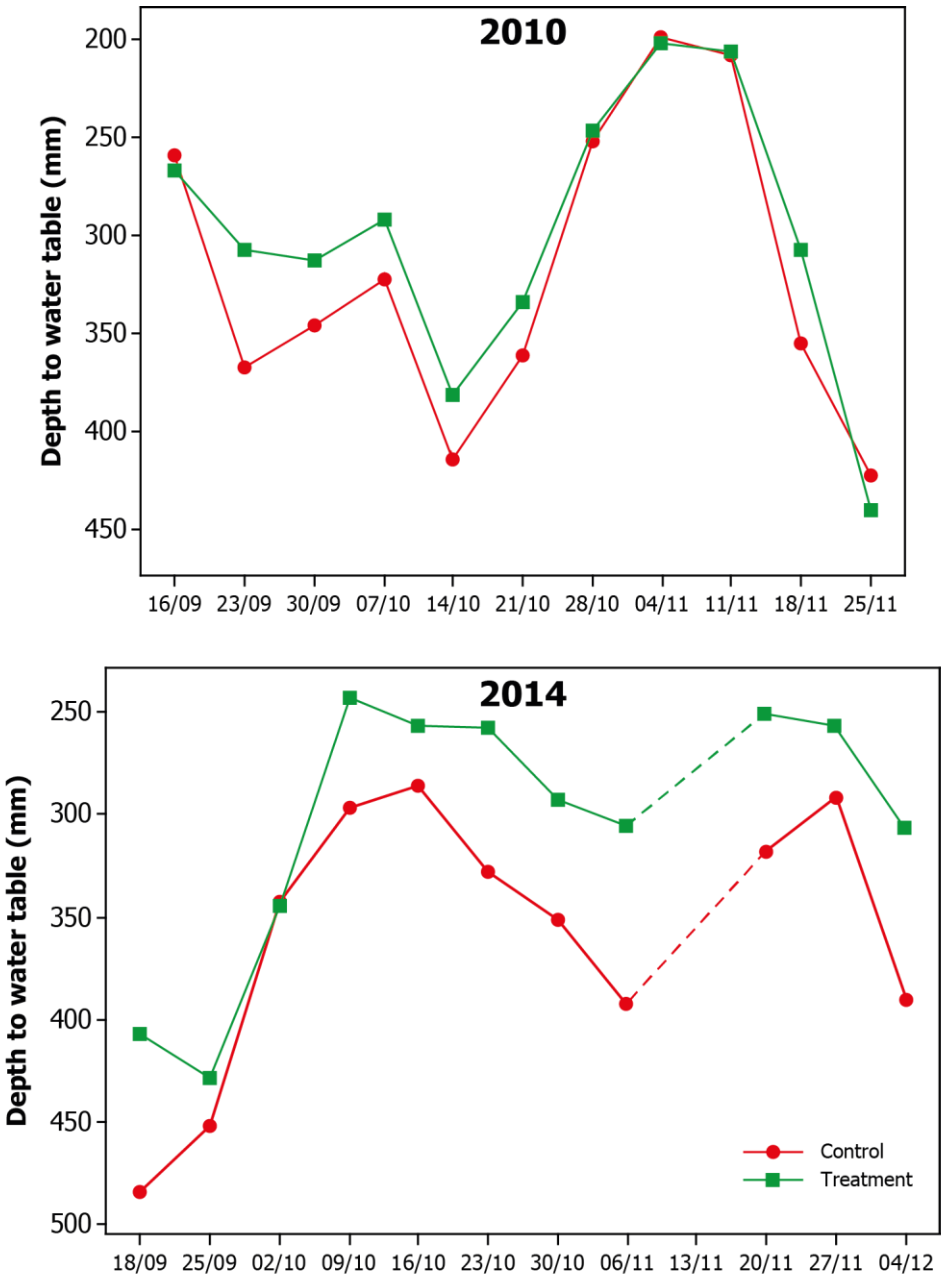


Figure 6: Variation in water table depths through time at the control and treatment sites before (2010) and after (2014) restoration.

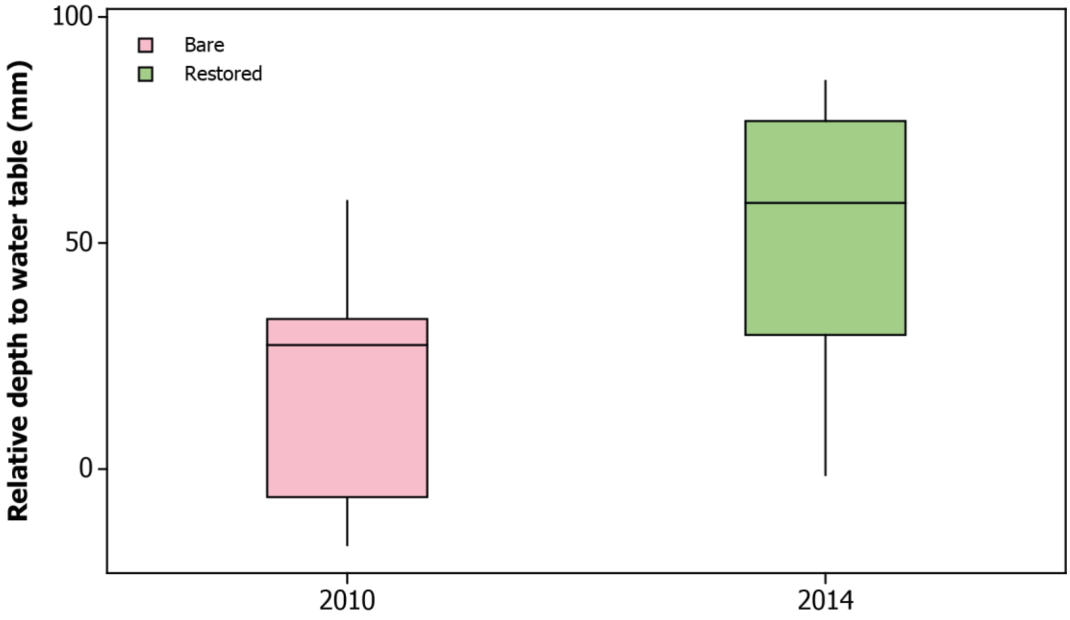


Figure 7: Distribution of the relative difference in water table depth between the control and treatment sites before (2010) and after (2014) treatment.

Tables

Field area	Type	Treatments	Number of dipwell clusters	Duration of campaign	Number of measurement days
Bleaklow	Space for time	bare / late stage re-veg	10 (5 at each type)	Oct – Nov 2009 / Sept – Dec 2011	2 /10
Bleaklow and Kinder	Space for time	intact / bare / late stage re-veg	12 (3 intact and re-veg, 6 bare)	Sep – Nov 2010	11
Kinder	BACI	bare / short term re-veg	6 (3 at each type)	Sep – Nov 2010 / Sep – Dec 2014	11 /12

Table 1: Details of the three water table field campaigns.

	Study 1		Study 2		
	Bare	Re-vegetated	Bare	Re-vegetated	Intact
Max	568	427	413	318	141
Q3	426	309	361	284	128
Median	374	284	345	243	77
Q1	323	259	252	223	63
Min	222	179	198	159	52

Table 2: Descriptive statistics for the two space-for-time water table studies.

	P - value	
Factor	Study 1	Study 2
Site	0.000	0.000
Date	0.000	0.000
Site * Date	0.000	0.012

Table 3: Results of the ANOVA employed to compare water table depths in the two space-for-time water table studies. Significant differences at $p < 0.05$ are highlighed in pink.

		Bare	Re-vegetated	Difference
Before	Max	422	439	60
	Q3	364	323	33
	Median	345	307	27
	Q1	255	257	-3
	Min	198	204	-17
After	Max	484	428	86
	Q3	391	325	74
	Median	342	293	59
	Q1	307	256	33
	Min	286	242	-1

Table 4: Descriptive statistics for water table depths before (2010) and after (2014) re-vegetation.

Factor	P - value
Site	0.000
Year	0.469
Site * Year	0.006

Table 5: Results of the ANOVA employed to compare water table depths before and after re-vegetation. Significant differences at $p < 0.05$ are highlighed in pink.

3 OVERLAND FLOW PRODUCTION

3.1 Introduction

Overland flow is a key runoff pathway in blanket peat systems. In intact blanket peatlands, the majority of storm-flow is produced as saturation excess overland flow, particularly on more gentle slopes and on footslopes where overland flow occurs most frequently (Holden & Burt, 2003). Evans et al. (1999) show that the generation of near-surface and overland flow is influenced by the maintenance of high water tables close to the peat surface. In contrast, degraded peats with depressed water tables are likely to produce more bypassing rapid subsurface storm-flow through macropore and soil pipe networks, and therefore generate less overland flow (Holden & Burt 2003). Furthermore, Allott et al. (2009) highlight the important influence of topography on water table in erosion impacted peatlands, thus variable hillslope morphology is also an important control on runoff production in these systems. Potential changes in overland flow generation associated with peatland restoration have been outlined in Section 1, and overland flow data are required to test the working hypotheses for hydrological change following restoration.

This section presents spatial and temporal overland flow data from the study sites in order to:

(i) assess overland flow in relation to topography (specifically interfluve surface vs footslope locations in eroded and restored peatlands);

(ii) evaluate the impact of re-vegetation on overland flow generation.

3.2 Methodology

3.2.1 Experimental Set-up and Data Collection

Sampling focused on the three main study catchments on Kinder Scout (F, N, and O), with additional data derived from the intact control (P) and late stage re-vegetated catchment (J) in order to place the results in the wider context of the peatland restoration continuum. Runoff generation was investigated in two stages. An initial sampling campaign collected data prior to restoration of sites N and O in 2010, and a second sampling campaign took place in 2014, three years after intervention. Sampling took place at weekly intervals between September and November 2010 (n = 11) and September and December 2014 (n = 12).

The occurrence of overland flow was detected using crest-stage runoff traps. These traps comprised a short tube, sealed at each end, but with holes drilled into the side to allow water to enter. Clusters of nine tubes were sunk into the peat surface at each site with their entry holes flush with the peat surface. Entry holes were aligned with the local slope so that any overland flow or surface ponding around the tube would result in the tube filling with water. The clusters were checked for the presence of water at weekly intervals throughout each sampling campaign. The number of tubes containing water was recorded, before ‘wet’ tubes were emptied to reset the cluster for the subsequent week of sampling. Tubes were emptied with a large syringe keeping disturbance to a minimum. The proportion of tubes containing water was used to calculate a runoff quotient (RQ) to allow runoff behaviour at each site to be compared. RQs can range between 0 and 1; a RQ of 1 would indicate that evidence of surface runoff was captured in all crest-stage traps in a cluster, while a RQ of 0 would mean no surface runoff was detected.

Three clusters of crest-stage traps were installed on interfluve surfaces at each site, apart from N and O where two and one cluster were installed respectively. Sites N and O were both re-vegetated in July 2011, and gully blocks were additionally installed at site N in November 2011 and April 2012. Gully edge water table drawdown, and hence an effect that gully blocking has on water table, is localised to within 2 m of gully edges (Allott et al., 2009); the crest-stage clusters were therefore positioned in interfluve surfaces in such a way that they would not be affected by the presence of the gully blocks. Consequently, runoff behaviour following restoration at sites N and O can be considered analogous, allowing data from the two sites to be combined. Sites N and O will henceforward be referred to as the *re-vegetated* treatment site, and F the *bare control*.

A secondary field study into the effect of topography on runoff generation was implemented during the 2014 sampling campaign. Three additional clusters of crest-stage traps were installed at both the treatment and bare control sites. These new clusters were situated at lower elevations than the original set up to confirm the hypothesis that overland flow occurs more frequently on footslopes than on interfluve surfaces in degraded systems, which would be consistent with the model of saturation excess overland flow dominated runoff.

The crest-stage clusters installed at site J were intended to serve as a late-stage re-vegetation comparison to the more recent re-vegetation on Kinder. However, there were significant differences in the relationship between site J and the intact control (P) between the two sampling campaigns, indicating that surface runoff at site J was not behaving in a consistent manner across the two sampling campaigns. Therefore, site J cannot be used as a control, and the results are not reported here. However, some additional overland flow data are available from 1 x 1 m runoff plots in operation during the 2010 sampling campaign. Two manual plots were installed each at sites J and P, and two further plots were installed at the then-bare peat Kinder catchments, with surface runoff and rainfall measured on a weekly basis. Because of operational difficulties, these runoff plots were not used in the 2014 sampling campaign, but the 2010 data provide insight into the relative differences in runoff production at bare, late-stage re-vegetated, and intact sites.

3.2.2 Data analysis

Three different statistical analyses were employed to examine the data. A mixed design ANOVA was used to analyse changes in overland flow before and after restoration at the bare and re-vegetated Kinder sites. A t-test was additionally employed to evaluate the relative difference between the two sites. Differences in overland flow generation on interfluve surfaces and footslopes were investigated using a repeat measures design ANOVA. The factors used in each statistical test are summarised in Table 6. Mauchly's test was used to test for sphericity. In cases where the assumption of sphericity was violated, the Greenhouse–Geisser correction was used to adjust the degrees of freedom.

3.3 Changes in overland flow generation following re-vegetation

This section discusses the relative changes in overland flow generation at the treatment (N and O), and bare control (F) sites on Kinder Scout following restoration by re-vegetation. The variation in the data is presented in Figure 8, the corresponding summary statistics are presented in Table 7, and the results of the mixed design ANOVA are presented in Table 8.

In 2010, before restoration, overland flow at both sites was highly variable but median RQ values were similar – 0.22 at the control and 0.19 at the treatment site (Table 7). In 2014, there was less surface runoff production at both sites. The greatest reduction was at the control site (median RQ = 0.04) where the occurrence of surface flow was also considerably less variable than in 2010 (Figure 8a). ANOVA indicates no significant difference in overland flow production between the two sites (Table 8). However, the intersection of the interaction lines in Figure 8b indicates that restoration has had some effect on the generation of surface runoff, relative to the control.

Overland flow production is linked to water table behaviour, so runoff generation is influenced by the same antecedent conditions (e.g. precipitation and temperature) that control water table depth. Consequently, as outlined in Section 2, the relative differences between the catchments must be considered (Figure 8c). In 2010 the median relative difference in RQ at the two sites was negative (-0.07; Table 7), indicating that prior to restoration, the treatment site was slightly less productive of overland flow than the control. In 2014 the relationship is reversed – the median relative difference in RQ was positive (0.11) – demonstrating that after restoration, the treatment site had become more productive of runoff than the control. Indeed, before restoration, the distribution of relative RQ was relatively evenly spread around zero (Figure 8c) meaning there was no consistent difference in surface runoff production at the two sites, but after restoration relative RQ on all bar one measurement day was positive, indicating that the re-vegetated site was consistently more productive of overland flow. This equates to an 18% increase in relative overland flow production, and is statistically significant ($P = 0.041$; Table 8).

3.4 Influence of topography on overland flow generation

Figure 9 shows the differences in overland flow generation on interfluves and footslopes at bare and recently re-vegetated sites. The corresponding summary statistics are presented in Table 9, and the results of the repeat measures ANOVA are presented in Table 10. Significantly more runoff was detected at footslope plots regardless of vegetation cover ($P = 0.000$). This is consistent with a saturation excess overland flow dominated hydrology (Holden & Burt, 2003). The disparity between the high and low lying plots is more pronounced at the bare site where median RQ differs by 0.29 (versus 0.15 at the re-vegetated site). This difference is exemplified by the converging gradients of the interaction lines in Figure 9b, but is not statistically significant ($P = 0.135$; Table 10), indicating that re-vegetation does not substantially change the dominant overland flow mechanism in erosion impacted peatlands.

3.5 Kinder in the wider peatland restoration context

Figure 10 compares the pre-restoration runoff data generated from the runoff plots installed at the then-bare Kinder sites, with runoff plot data from the intact (P) and late stage re-vegetation (J) reference sites. Figure 11 compares the pre- and post-restoration runoff data described in Section 3.3 with concurrent data collected from the crest-stage clusters at the intact control site (P). The corresponding summary statistics are presented in Table 11 and Table 12.

Figure 10 and Figure 11 both show that the intact site was highly productive of surface runoff, and that the high level of production was consistent between the two sampling campaigns. In 2010, the late stage re-vegetated site was slightly more productive of surface runoff than the bare site, but both experienced substantially less surface water generation compared to the intact site. Typically only 2 – 7 % and 4 – 12 % of weekly rainfall became overland flow at the bare and late-stage restored sites respectively (based on Q1 and Q3; Table 11), compared with 36 – 74 % at the intact site. The Kinder sites produced significantly lower RQ values than the intact site in both 2010 and 2014 (Figure 11a). In 2014, surface runoff production had increased at the Kinder treatment site relative to the bare control, but as discussed in Section 3.3, this change was subtle, and was not comparable to the level of overland flow generated at the intact control.

3.6 Key results: overland flow production

1. Surface runoff production is highly variable in restored and unrestored blanket peatlands in both space and time.
2. Overland flow is more regularly generated at intact sites.
3. In areas impacted by erosion (both bare and re-vegetated), lower lying areas (footslopes) are more productive of surface runoff than interfluve surfaces.
4. Overland flow production increases by 18% on interfluve surfaces following re-vegetation.
5. However, surface runoff remains less prevalent at re-vegetated sites than in intact areas.

3.7 Figures and Tables

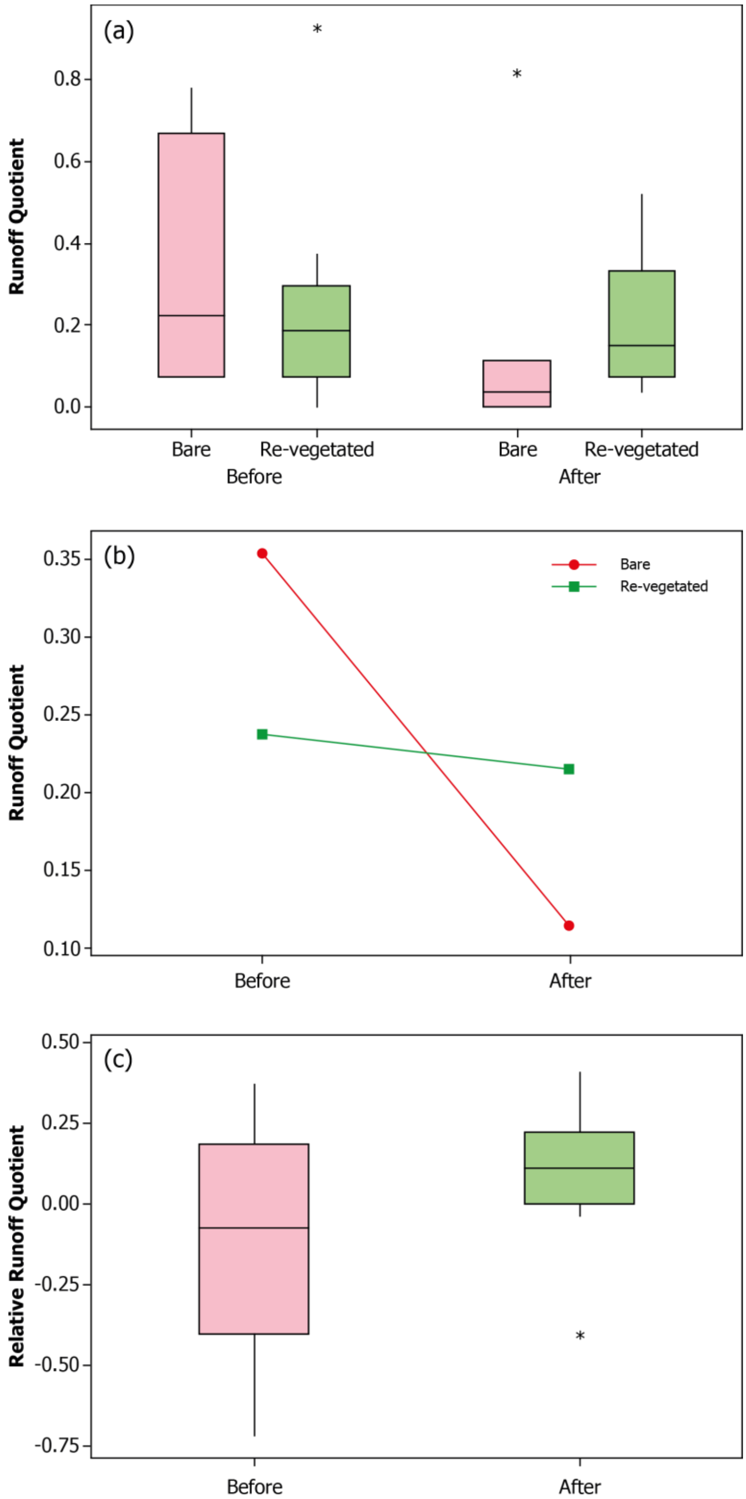


Figure 8: Runoff quotient (RQ) values at bare control and re-vegetated sites before and after treatment.
(a) Distribution of RQ values at bare control and re-vegetated sites before and after treatment; (b) Interaction plot of RQ values at bare control and re-vegetated sites before and after treatment; (c) Distribution of the relative difference in RQ values between bare control and re-vegetated sites, before and after treatment

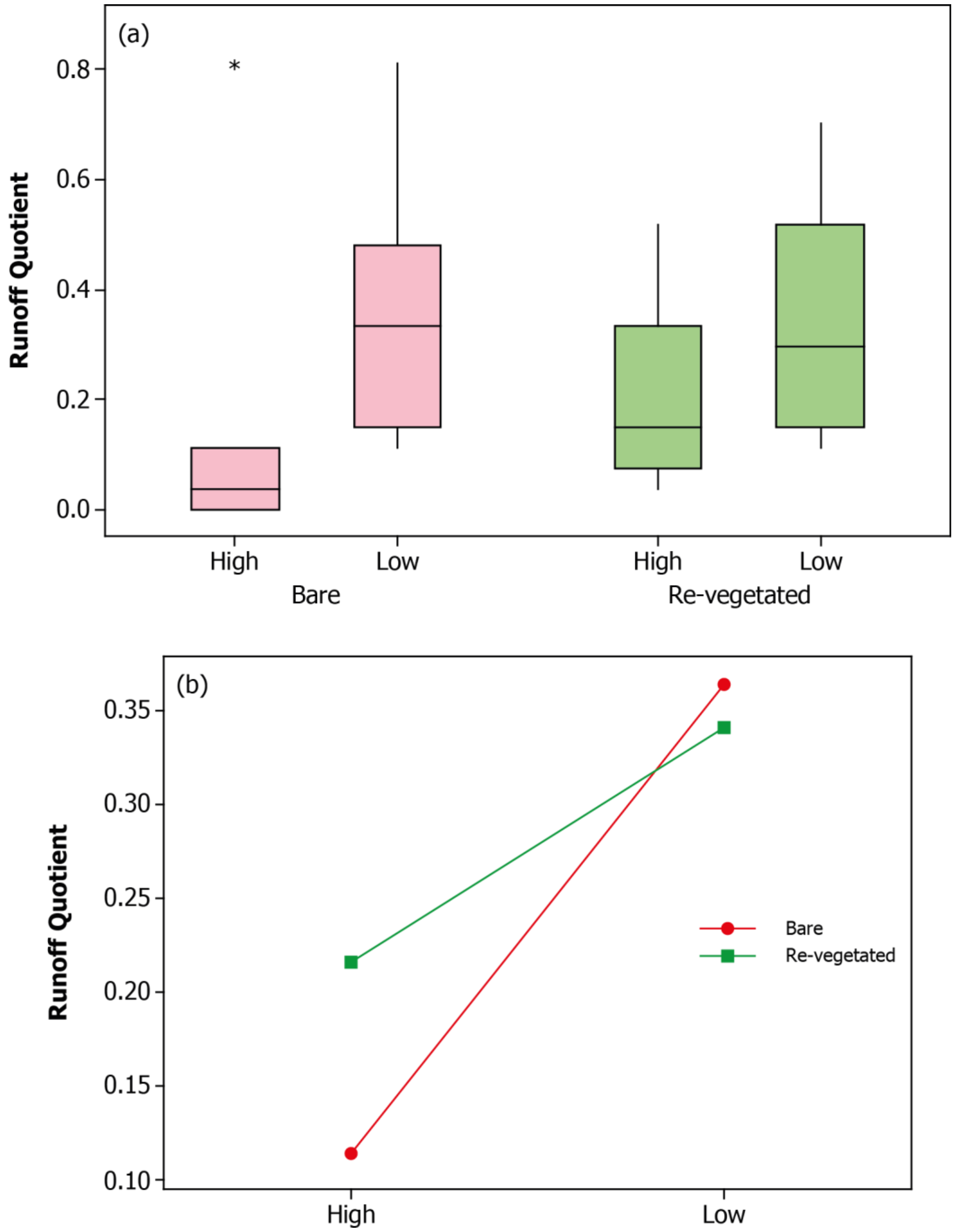


Figure 9: Runoff quotient (RQ) values on interfluve surfaces and footslopes at bare control and re-vegetated sites.
(a) Distribution of runoff quotient (RQ) values and (b) Interaction plot showing the differences in RQ values on interfluve surfaces and footslopes at bare control and re-vegetated sites.

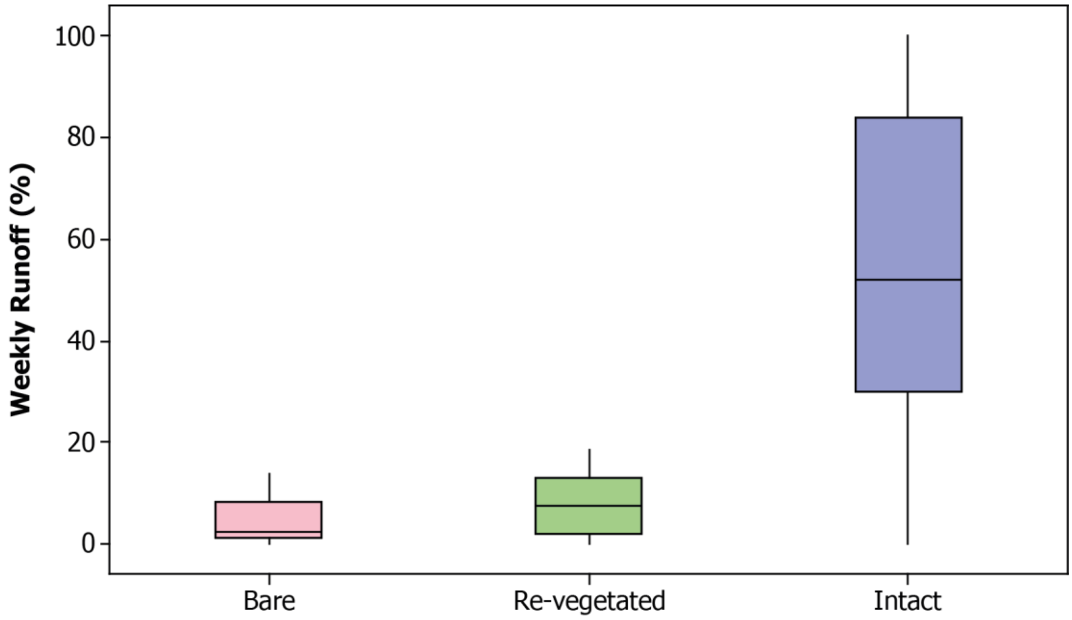


Figure 10: Distribution of % weekly runoff values at bare, re-vegetated and intact sites in 2010.

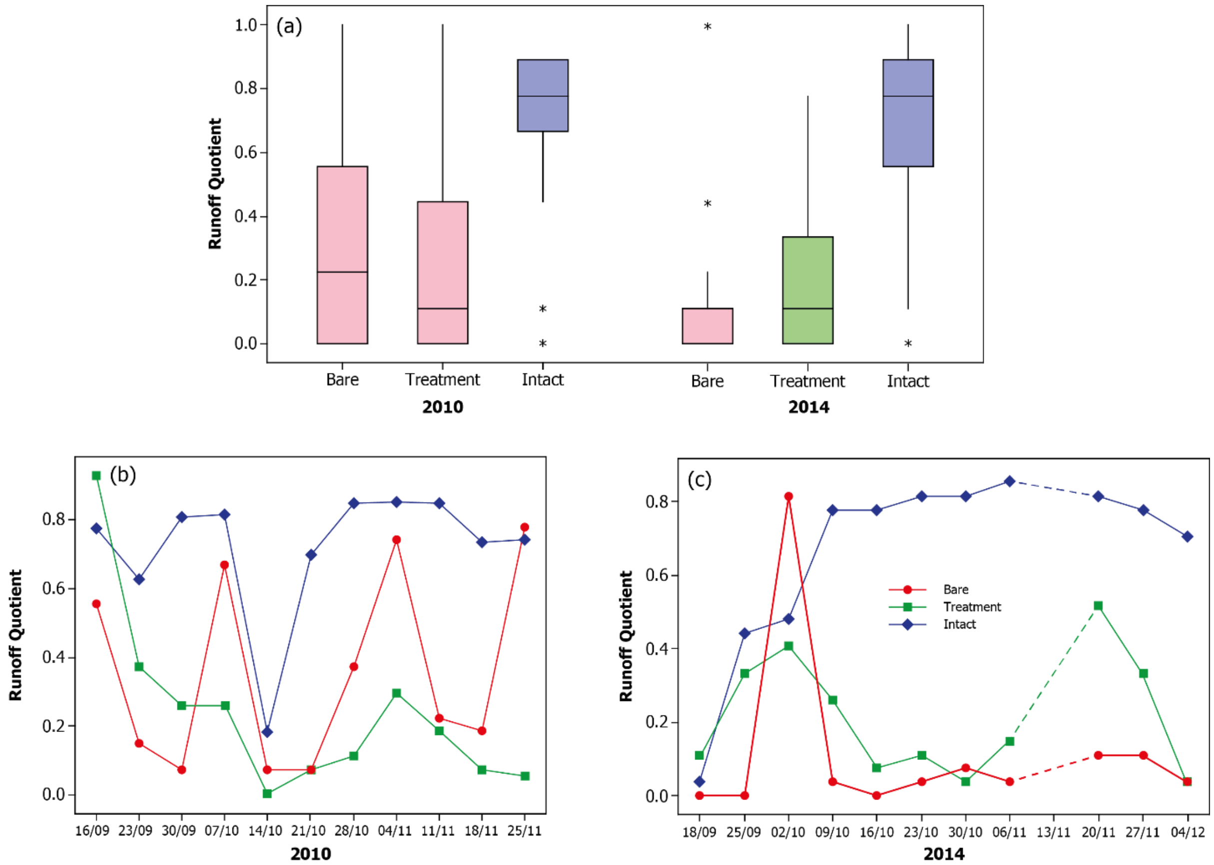


Figure 11: Runoff quotient values and surface runoff production
(a) Distribution of runoff quotient (RQ) values at bare and intact control sites, and re-vegetated treatment sites, before (2010) and after (2014) restoration; (b) Variation in surface runoff production through time at the control and treatment sites before restoration; (c) Variation in surface runoff production through time at the control and treatment sites after restoration.

Study	Years	Sites	Test	Dependent variable	Fixed factors	Within-subject factor
Before and after restoration	2010 and 2014	F, N, O	Mixed design ANOVA	RQ	Site, Year	Measurement date
			t-test	Relative RQ	Year	-
Interfluves vs. footslopes	2014	F, N, O	Repeat measures ANOVA	RQ	Site, Position	Measurement date

Table 6: Details of the overland flow field campaigns.

		Control	Treatment	Difference
2010	Max	0.78	0.93	0.37
	Q3	0.61	0.28	0.09
	Median	0.22	0.19	-0.07
	Q1	0.11	0.07	-0.33
	Min	0.07	0.00	-0.72
2014	Max	0.81	0.52	0.41
	Q3	0.09	0.33	0.22
	Median	0.04	0.15	0.11
	Q1	0.02	0.09	0.04
	Min	0.00	0.04	-0.41

Table 7: Descriptive statistics for runoff quotient (RQ) values before (2010) and after (2014) re-vegetation.

Test	Factor	P - value
ANOVA	Site	0.915
	Year	0.077
	Site * Year	0.199
t-test	Relative difference	0.041

Table 8: Results of the ANOVA and t-test employed to compare overland flow production before and after re-vegetation. Significant differences at $p < 0.05$ are highlighed in pink.

		Bare	Re-vegetated
Interfluves	Max	0.81	0.52
	Q3	0.09	0.33
	Median	0.04	0.15
	Q1	0.02	0.09
	Min	0.00	0.04
Footslopes	Max	0.81	0.70
	Q3	0.43	0.52
	Median	0.33	0.30
	Q1	0.22	0.17
	Min	0.11	0.11

Table 9: Descriptive statistics for runoff quotient (RQ) values on interfluve surfaces and footslopes.

Factor	P - value
Site	0.345
Position	0.000
Site * Position	0.135

Table 10: Results of the ANOVA employed to compare overland flow production on interfluve surfaces and footslopes. Significant differences at p < 0.05 are highlighed in pink.

	Bare	Late stage re-vegetated	Intact
Max	13.65	18.50	100.00
Q3	7.30	12.28	74.34
Median	2.22	7.45	52.01
Q1	1.63	3.77	36.44
Min	0.00	0.00	0.00

Table 11: Descriptive statistics for % weekly runoff values at bare, re-vegetated and intact sites in 2010.

		Bare	Recently re-vegetated	Intact
2010	Max	0.78	0.93	0.85
	Q3	0.61	0.28	0.83
	Median	0.22	0.19	0.78
	Q1	0.11	0.07	0.72
	Min	0.07	0.00	0.19
2014	Max	0.81	0.52	0.85
	Q3	0.09	0.33	0.81
	Median	0.04	0.15	0.78
	Q1	0.02	0.09	0.59
	Min	0.00	0.04	0.04

Table 12: Descriptive statistics for runoff quotient (RQ) values at bare, re-vegetated and intact sites, before (2010) and after (2014) restoration.

4 STORM-FLOW CHARACTERISTICS

4.1 Introduction

Much work on blanket peat restoration has focussed on mined and drained peatlands (e.g. Charman, 2002; Holden et al., 2004), where efforts focus on increasing biodiversity and restoring peatlands to an actively accumulating state. Less attention has been paid to eroded peatlands, and little is known about the effects of restoration on hydrological behaviour in erosion impacted systems. However, as discussed in Section 1, there is theoretical and some empirical evidence to suggest that re-vegetation of bare peat and blocking of erosion gullies will alter storm-flow runoff pathways and change storm hydrograph responses.

In order to assess the effects of re-vegetation and gully blocking on storm-flow behaviour, four key hydrograph metrics are investigated: (i) lag-time, (ii) peak storm discharge, (iii) Hydrograph Shape Index (HSI), and (iv) percentage runoff (see Section 4.2.2.1 for more detail). By considering post-restoration changes in these metrics, the following questions can be addressed:

1. Does storm-flow behaviour change after restoration?
2. What is the magnitude of any observed changes?
3. Is any effect of treatment immediate (i.e. discernible within one year of intervention), and is there further progressive change with time after restoration?
4. Do re-vegetation and gully blocking both impact storm-flow behaviour?

The ultimate aim of the MS4W programme is to test the hypothesis that peatland restoration reduces downstream flood risk. Downstream flooding results from high magnitude events, so in addition to analysis of the full storm-flow dataset, we consider hydrographs derived from the highest recorded total rainfall values to evaluate whether observed patterns in storm-flow behaviour are also evident during large events.

4.2 Methodology

4.2.1 Experimental Set-up and Data Collection

Monitoring focused on the three main study catchments on Kinder Scout (F, N, and O), with additional data derived from the intact control (P) and late stage re-vegetated (J) catchments (Table 13). Intensive monitoring started at the five catchments in June 2010. V-notch weirs and pressure transducers were installed at the catchment outlets. Pressure transducers recorded the depth 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 continuously monitor flow depth at 10 minute intervals. Rain gauges were also installed, and set to continuously monitor rainfall at 10 minute intervals.

Rainfall and discharge data are available for each catchment from June 2010 to September 2011, and April 2012 to December 2014. 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. Restoration commenced at sites N and O in July 2011 with applications of lime, seed and fertilizer, and gully blocking at site N was carried out in November 2011 and April 2012. Data from 2010 and 2011 (prior to July 2011) therefore represent pre-restoration conditions, and data from April 2012 onwards represent post-restoration conditions.

4.2.2 Numerical Data Acquisition

For each catchment the available rainfall and runoff data between June 2010 and December 2014 were collated. Hydrographs were extracted for all rain 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.

4.2.2.1 Hydrograph metrics

Lag-time

Lag time was derived from the time interval (in minutes) between maximum rainfall intensity and peak storm discharge (Figure 12a). Lag time gives an indication of the rate at which precipitation runs off the landscape and enters the channel, with longer lag times indicating that water is being released more slowly.

Peak storm discharge

Peak storm discharge (Peak Q_s; L sec^{-1} ha^{-1}) is the difference between the maximum recorded discharge, and the coincident baseflow component (Figure 12b). During and immediately following storm events baseflow becomes elevated. Due to the ephemeral and 'flashy' nature of flow in peatland catchments this is limited, but baseflow does become slightly elevated following storm events, even in the micro-catchments used in this study. To account for this, the 'constant slope' method (McCuen 1998) was used to separate the storm-flow component of the hydrograph from the baseflow component. This method assumes that baseflow increases linearly throughout the storm event (Figure 12).

Hydrograph Shape Index (HSI)

The HSI is defined as the ratio of peak storm discharge (L sec^{-1} ha^{-1}) to total storm discharge (m^3 ha^{-1}) (Figure 12b and c). This index provides a simple measure of overall hydrograph shape; relatively high ratios represent more 'flashy' hydrographs which are highly reactive to rainfall and runoff generation, while relatively low ratios indicate more attenuated hydrographs with lower peak flows relative to the size of the discharge event.

Percentage runoff

Percentage runoff is the proportion of storm rainfall that reaches the stream channel to become discharge within the storm event. Low percentage runoff values indicate substantial within-storm storage of water in the catchment, whereas high percentage runoff values indicate that most of the rainfall generates storm-flow. The parameter is derived from total storm rainfall and total storm discharge (Figure 12 c and d).

4.2.2.2 Rainfall metrics

Two rainfall characteristics were also derived to compliment the hydrograph metrics: total rainfall (mm), and maximum rainfall intensity (mm $10min^{-1}$). Storm-flow characteristics are strongly influenced by the antecedent conditions leading up storm events, and the intensity and duration of rainfall.

Table 14 shows that there are strong correlations between precipitation variables and hydrograph characteristics, so variation in rainfall characteristics between sites could influence runoff generation and thus obscure or bias any differences in storm-flow behaviour between catchments. Particularly notable relationships include the significant effects of maximum rainfall intensity on both lag time and the HSI.

4.2.3 Analysis

A general linear model (GLM) approach based on an analysis of variance (ANOVA) was employed to determine the statistical significance of the influence of restoration on the four key runoff metrics. For the space-for-time studies where differences in sites were considered without a time factor, *Site* was the only factor used. For the before-after-control-impact studies, *Year* or *Before/After* were introduced as within-subject factors. Tukey's pairwise comparison was applied post-hoc, in order to assess where any significant differences lie. All relationships were tested at the 95 % level ($P \leq 0.05$).

4.3 Before restoration

Kinder site comparison

It is important to determine whether runoff in the three Kinder catchments (F, N and O) was responding to rainfall events in a similar way prior to restoration, to set a baseline for the post-restoration comparisons. Rates of data capture were high throughout the pre-restoration monitoring programme, as the relatively wet late-summer/autumn conditions in 2010 resulted in over 45 identifiable storm events of varying magnitude, providing a substantial data set with which to evaluate pre-restoration runoff characteristics. The four key hydrograph metrics and three rainfall behaviour metrics were analysed using a one-way between groups ANOVA. Figure 13 shows the relative spread of data for the four hydrograph metrics at the three sites, and the results of the various hydrograph and rainfall ANOVAs are presented in Table 15. Summary statistics for this period are presented in Table 18.

The 2010/11 dataset captured a range of rainfall totals and intensities, with the largest rainfall event totalling nearly 36 mm, and peak storm discharges ranging from 0.3 L sec^{-1} ha^{-1} to nearly 50 L sec^{-1} ha^{-1} (Table 18). There were no significant differences in any of the rainfall metrics, so we can assume that any variation in hydrograph metrics were a result of catchment characteristics rathe r than variations in rainfall. Catchment O appears to have a flashier response than the other two catchments, with higher peak flows and higher HSI values (Figure 13, Table 18), consistent with the smaller area and consequently shorter routing lengths of this catchment. However, these differences are not statistically significant, so we can assume that any change in runoff behaviour after restoration is due to intervention. Figure 14 exemplifies the similarities in hydrograph behaviour at the three sites.

This pre-restoration dataset provides an excellent foundation for evaluating the subsequent impacts of peat restoration on catchment hydrology and storm-flows.

Kinder in the wider context of peat restoration in the area

To supplement the main study, the pre-restoration hydrograph data detailed above can also be compared to concurrent data from the intact reference site (P) and 'late stage' restored reference site (J). We have already established that the three Kinder catchments were behaving in a hydrologically similar manor prior to restoration (Section 0), so in order to make a broader spatial comparison of the hydrological behaviour and characteristics of catchments with different degradation and restoration conditions, data from the three then-bare Kinder catchments have been combined. This allows the establishment of a further baseline for comparison with the post-restoration data. For the rest of this section, the Kinder sites will be referred to as *bare*, the 'late stage' restored site as *re-vegetated*, and the intact reference site as *intact*.

Figure 15 shows the relative spread of data for the four hydrograph metrics at the three sites, and ANOVA (one-way between groups) results are presented in Table 16. Summary statistics are presented in Table 17. There are clear differences in storm-flow behaviour dependent on restoration status. Lag times differed significantly at all three sites. Median lag times at the bare site were extremely short (20 min) - half that of the re-vegetated site and less than a third that of the intact site (70 min). Both the bare and re-vegetated catchments produced higher peak storm discharges than the intact catchment, but while the bare site produced high HSI values, indicating a 'flashy' system, the re-vegetated catchment produced HSI values similar to the intact site, indicating that the presence of vegetation may attenuate flow. All sites produced variable amounts of runoff. This was found to be similar at the bare and intact sites, but while covering a similar range, values were statistically significantly higher at the re-vegetated site. This indicates that catchment factors other than vegetation may influence the amount of runoff produced.

4.3.1 Effect of restoration on storm-flow

4.3.1.1 Data quality control

Data for a total of 547 hydrographs were extracted from the Kinder micro-catchments: 161 storms for catchment F, 188 for catchment N, and 198 for catchment O. The extracted metrics for these storms are summarised in Table 18. The full dataset covers a total of 329 storm events. However, this includes 223 storms where hydrographs fitting the strict selection criteria could only be extracted for a single site. There were 68 storm events where hydrographs could be extracted for all three catchments.

As storm-flow characteristics are influenced by antecedent conditions and the nature of rainfall events, the mismatch in storm events in the complete data set could lead to substantial bias when comparing metrics between catchments. For example, in 2014, only 19% of storms extracted for catchment F had total rainfalls in excess of 10 mm, while 49% of storms extracted for catchment O exceeded 10 mm total rainfall (Table 19a), and in 2012, less than 14% of storms had a maximum rainfall intensity greater than 2 mm $10min^{-1}$ at catchment O, but 39% of storms extracted for catchment F exceeded this (Table 19b). Overall, the distribution of maximum rainfall intensity was significantly different at the three catchments ($P = 0.049$). A further parameter – the precipitation shape index– which is the ratio of maximum rainfall intensity to total rainfall and gives an indication of the relative overall intensity of the storm event was also significantly different (P = 0.018). Consequently, if we were to compare metrics derived from the entire data set, we could not be sure if observed differences in runoff behaviour are a consequence of the restoration treatments, or the nature of rainfall events. We can eliminate this bias by disregarding storms that could not be characterised for all three catchments.

By analysing only the 219 hydrographs derived from the 68 storms events for which metrics could be extracted for all three catchments, runoff behaviour resulting from similar rainfall and antecedent conditions can be directly compared. This 'paired' dataset allows for a strict and robust comparison of the data, and is the primary dataset used for all subsequent statistical analysis of hydrograph metrics. There is still a considerable amount of 'noise' in the reduced dataset, due to the variety of rainfall behaviours and antecedent conditions encompassed; total rainfall ranges from 4 to 56 mm, and maximum rainfall intensity ranges from 0.3 to 9 mm, leading to a wide range of runoff responses in the extracted storm-flow metrics. This 'noise' masks changes in streamflow behaviour which may result from restoration. 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 is done by deriving the *relative difference* between the metrics produced by control and treatment sites.

4.3.1.2 Lag

The yearly descriptive statistics for lag-time are presented in Table 20, the distributions of lag-times by year and are presented in Figure 16. As established Section 0, lag-times were similar at three catchments prior to treatment; median lag-times ranged between 15 and 30 min, and the catchments experienced a similar range of lag-times (Table 20, Figure 16a). There was a well-defined step change in lag behaviour at the two treatment catchments from 2012 onwards, indicating that the effect of restoration was immediate. This is clearly reflected in the relative data (Figure 16b), which shows that in the years following restoration, the vast majority lag-times at two treatment catchment were longer than at the bare control.

The relative increase in lag-time following restoration, regardless of treatment type, is statistically significant (P = 0. 000; Table 21). Median lag-time relative to control increased by 35 min at catchment N, and 20 min at catchment O (Figure 17a). If we assume that without intervention, catchments N and O would have continued to behave in a similar way as catchment F, restoration has increased lag-times by 267% and 67% in catchments N and O respectively (Table 22). Catchment N produces a steeper interaction line than catchment O in the interaction plot in Figure 17b. This indicates that the increase in relative lag-time was more pronounced at catchment N following restoration, suggesting that the presence of gully blocks may have increased lag-times further than re-vegetation alone. However, despite catchment N exhibiting a substantially greater increase in lag time than those catchment O, there is no statistically significant difference between the effect of restoration at the two sites (P = 0.061; Table 21).

4.3.1.3 Peak Qs

The relationship between Peak Q_s and restoration is less clear than that for lag-time. Before treatment, a similar range of Peak Q_s was produced at all three catchments (Figure 18a), with the two treatment catchments producing slightly higher median Peak Q_s than control catchment F. In

2012, the year immediately following restoration, treatment catchment O exhibited the lowest median Peak Q_s while treatment catchment N exhibited the highest; but the subsequent two years of monitoring (2013 and 2014) produce the opposite relationship with the lowest median Peak Q_s at N, and the highest at O (Table 20 and Figure 18a). This indicates that restoration has changed the relationship between Peak Q_s produced at the control and treatment sites, but we must look at the relative difference between the treatment catchments and the control to fully understand the nature of the change. Figure 18b shows that in the years following restoration, the majority of Peak Q_s produced at each of the treatment catchments were lower than at the bare control.

When considering the difference in relative Peak Q_s before and after treatment (Figure 19), there is a statistically significant reduction in Peak Q_s at the two treatment sites following restoration, regardless of treatment type ($P = 0.010$; Table 21). Median relative Peak Q_s was reduced by 37% at catchment N, and 8 % at catchment O (Table 22). Again, despite restoration seemingly having a greater impact at catchment N, there is no statistically significant difference in the effect of the two treatments ($P = 0.528$), indicating that the gully blocks in N have had no additional effect on Peak Q_s.

4.3.1.4 HSI

Before treatment, all three catchments produced very similar HSI values (Figure 20); median HSI at all sites was either 0.17 or 0.18 (Table 20). In the three years following restoration, both of the treatment catchments (N and O) consistently produced substantially lower median HSI values than the control catchment (F), indicating that intervention had an immediate effect on this, and therefore on hydrograph shape. When considering the difference in relative HSI before and after treatment, there is a statistically significant reduction at the two treatment sites following restoration, regardless of treatment type ($P = 0.000$) (Figure 21).

Median relative HSI was reduced by 0.08 at catchment N, and 0.04 at catchment O (Table 22). If we assume that without intervention, catchments N and O would have continued to behave in a similar way as control catchment F, this represents reductions in HSI of 38% and 19% respectively. The interaction plot in Figure 21b shows that the reduction in HSI at the two treatment sites behaved in a very similar way, and there is no statistically significant difference in the effect of the two treatments ($P = 0.843$), indicating that the gully blocks in catchment N have had no additional effect on the reduction of HSI.

4.3.1.5 Runoff

Before treatment, the proportion of rainfall entering the channel varied greatly between storms at all three catchments (Figure 22); the inter-quartile range in % runoff was 43.5 at control catchment F, and 35.6 at the two treatment catchments. In the three years following restoration, there is no consistent pattern in relative runoff behaviour in the three catchments. The interaction plot in Figure 23b shows that there is a slight reduction in runoff following restoration; however, it is clear from the box plots in Figure 23a that this is minimal, and there is no statistically significant difference in % runoff after restoration, regardless of treatment ($P = 0.461$). The parallel lines in the interaction plot in Figure 23b indicate that while catchment O is significantly more productive of runoff ($P = 0.001$), the relationship between the two treatment sites is not altered by differing interventions ($P=0.905$). This difference in runoff production in the two treatment catchments is consistent with the smaller area and shorter routing lengths of catchment O, noted in Section 0.

4.3.2 High magnitude events

In order to assess the effect of restoration on storm-flow characteristics produced by large magnitude storms, data from the ten biggest pre- and post- restoration storms were compared. In 2013 there was a relatively high magnitude event (c. 50 mm total rainfall) which has no comparable event in the before dataset (largest storm c. 32 mm total rainfall). This large event significantly skews the distribution of rainfall metrics, so that the before and after data are not comparable (total precipitation, $P = 0.031$; max precipitation, $P = 0.006$). Removing this anomalously large storm (and replacing it with the 11th biggest storm) produces a comparable set (total precipitation $P = 0.865$; max precipitation $P = 0.065$). As with the analysis of the main data set, the analysis of the large storms was based on standardised metrics from the two treatment sites relative to the control. The variation in the data is presented in Figure 24, the summary statistics are presented in Table 23, and the results of the one-way between groups ANOVAs are presented in Table 24.

The changes in hydrograph behaviour, discussed in Section 4.3.1, are still apparent when only considering the largest storms in the dataset. There are still no significant differences between the two treatment sites, or the interaction terms, (Table 24), indicating that storm-flow behaves in the same way regardless of treatment type during large events. As with the full data set, % runoff does not change, indicating that restoration has no effect on the amount of runoff produced, regardless of storm magnitude.

Relative lag times increased significantly at both of the treatment sites (Figure 24; Table 24), but the magnitude of the change at site N was less than that found in the whole dataset. After restoration, median lag time at the bare control (F) and re-vegetated only (O) sites were the same for high magnitude storms as for all storms (15 and 25 min respectively), but median lag time at N was 35 min – 20 min less than when all storms are considered. Nevertheless, the relative difference in lag at site N was double that of site O, and represents a 133% increase in lag for high magnitude storms after restoration (Table 25). Figure 24b shows that post-restoration, Peak Qs produced by large storms were considerably lower at the two treatment sites relative to the bare control (54% at N, 12 % at O; Table 25). This reduction is greater than when considering the whole dataset (Table 22), but (unlike the whole dataset) does not yield a statistically significant difference ($P = 0.140$; Table 24). This is likely due to two substantial outliers in the 'before' data; in small datasets such as this, the mean is easily skewed by such values which can affect the power of statistical tests. It is clear from the boxplot in Figure 24 that in general, Peak Q_s was markedly reduced. HSI was also substantially reduced during large storms at the two treatment sites following restoration (Figure 24c). The magnitude of this change was less than for the whole dataset at both sites (Table 22 and Table 25), but the reduction was still statistically significant ($P = 0.0018$; Table 24) indicating that hydrographs produced by large storms became less 'flashy' after restoration.

4.4 Key results – Storm-flow

1. Storm hydrographs and their associated metrics are highly variable in blanket peat systems and are strongly controlled by nature of rainfall events and antecedent conditions.
2. Despite this variability, clear and significant differences in storm-flow behaviour can be detected at sites with different restoration status (Figure 25).

3. Bare sites behave differently to intact sites, producing flashier hydrographs with shorter lag times, and higher peak discharges.
4. Following restoration:
    - lag times increase by up to 267%
    - peak storm discharge decreases by up to 37%
    - hydrograph shape index reduces by up to 38%
    - there is no consistent change in percentage runoff
5. This indicates that restoration attenuates flow in headwater peatland catchments, with stormwater released at a slower rate than in unrestored systems, but that there are no detectable changes in within-storm catchment storage after restoration.
6. Although there are some apparent additional benefits of gully blocking, there is no statistically significant difference in hydrograph changes between the re-vegetated catchment and the catchment which was re-vegetated and gully blocked.
7. The observed changes in hydrological response are statistically significant for high magnitude events, so persist in large storms.

4.5 Figures and tables

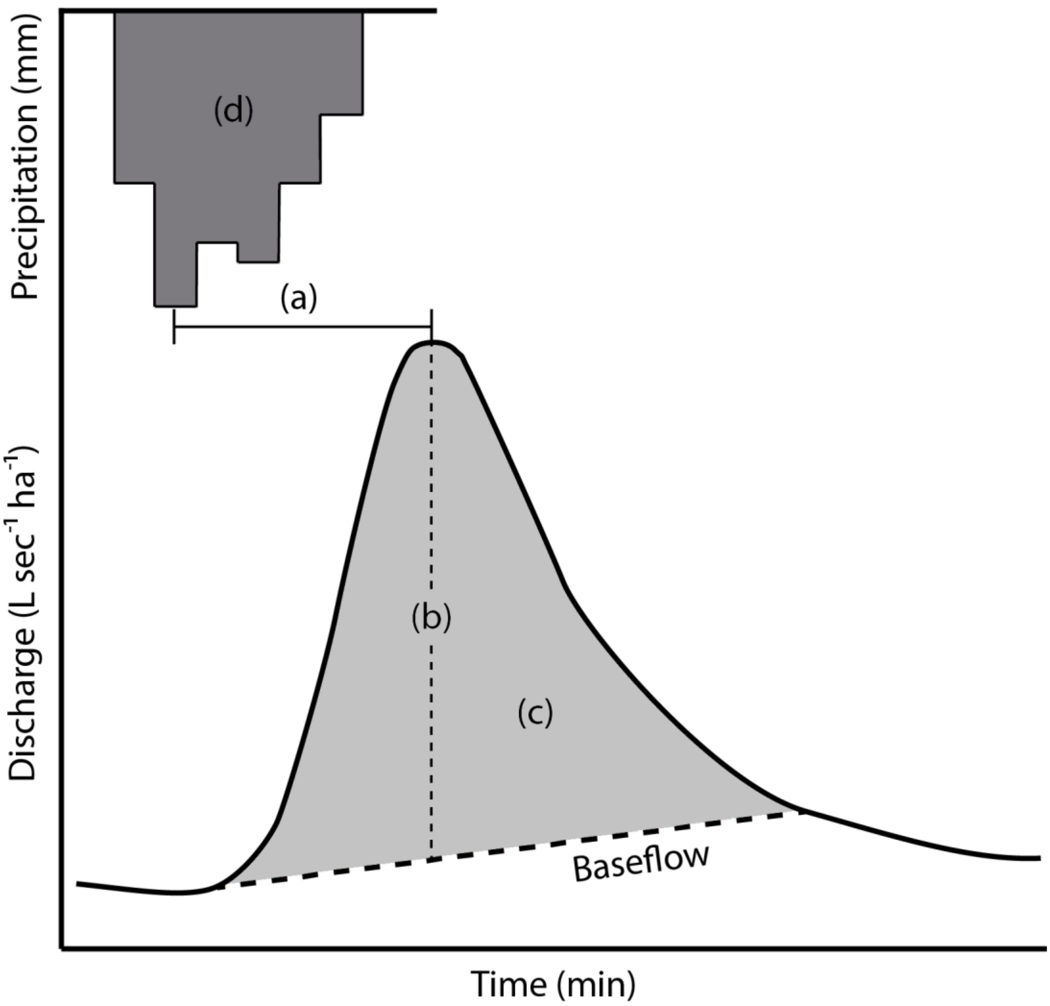


Figure 12: A typical storm hydrograph.
(a) indicates the time interval between maximum rainfall intensity and peak storm discharge used to determine lag-time; (b) indicates the magnitude of peak storm discharge, when the baseflow component has been deducted.; (c) the pale grey shaded area represents total storm discharge; (d) the dark grey shaded area represents total rainfall/precipitation.

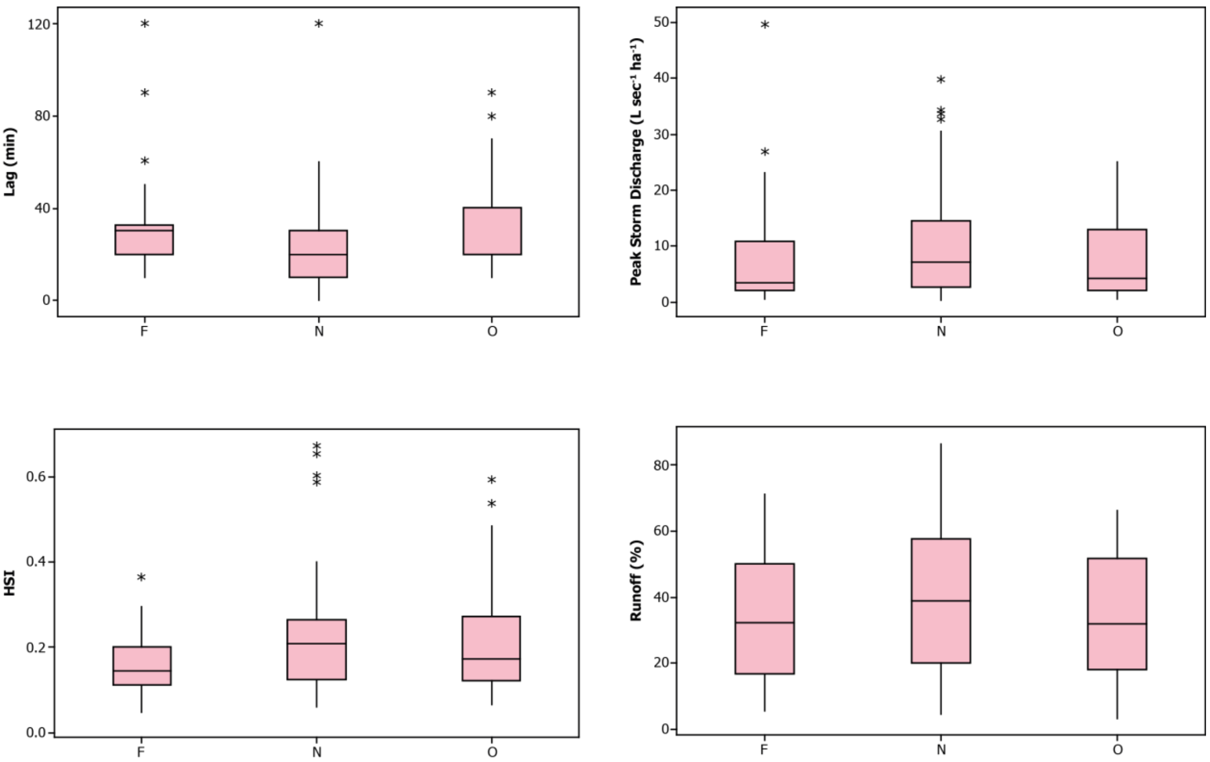


Figure 13: Distribution of the four key hydrograph metrics at sites F, N and O before restoration.

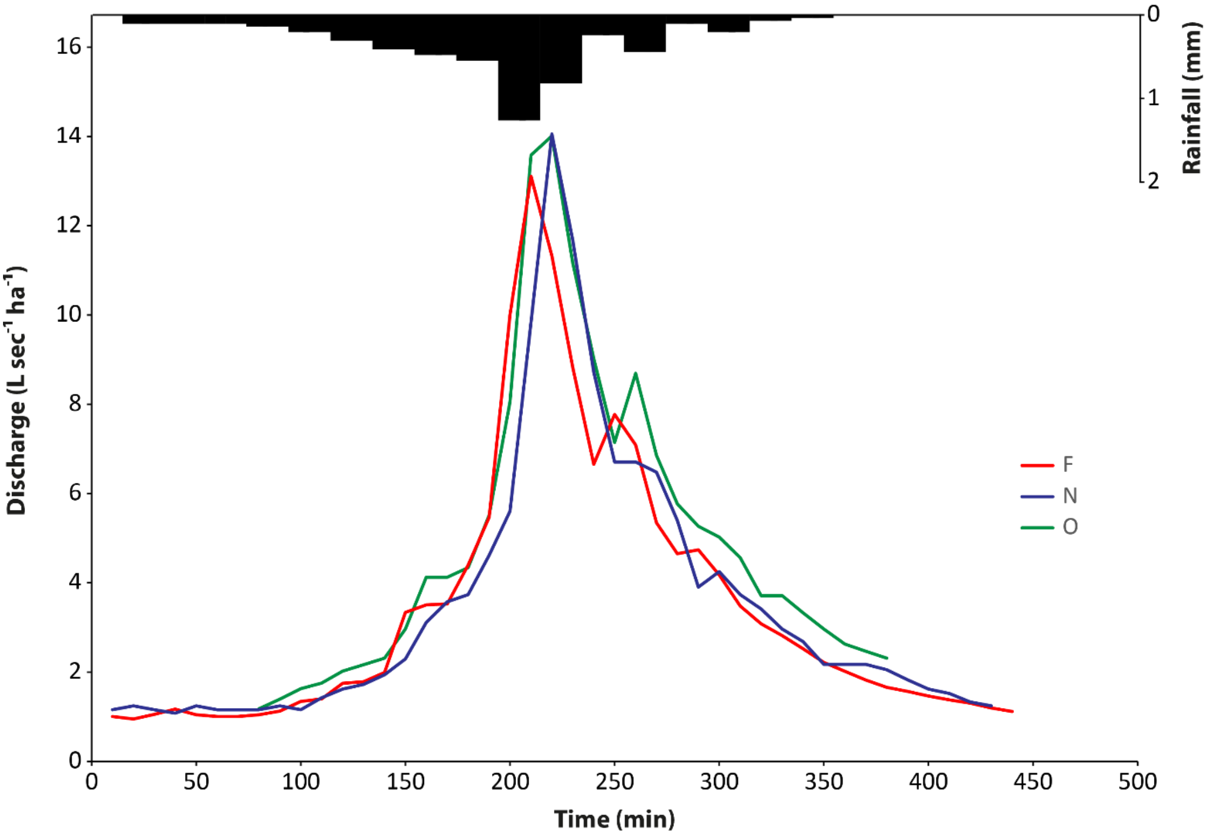


Figure 14: Example of storm hydrograph responses at sites F, N and O before restoration (4/11/2010).

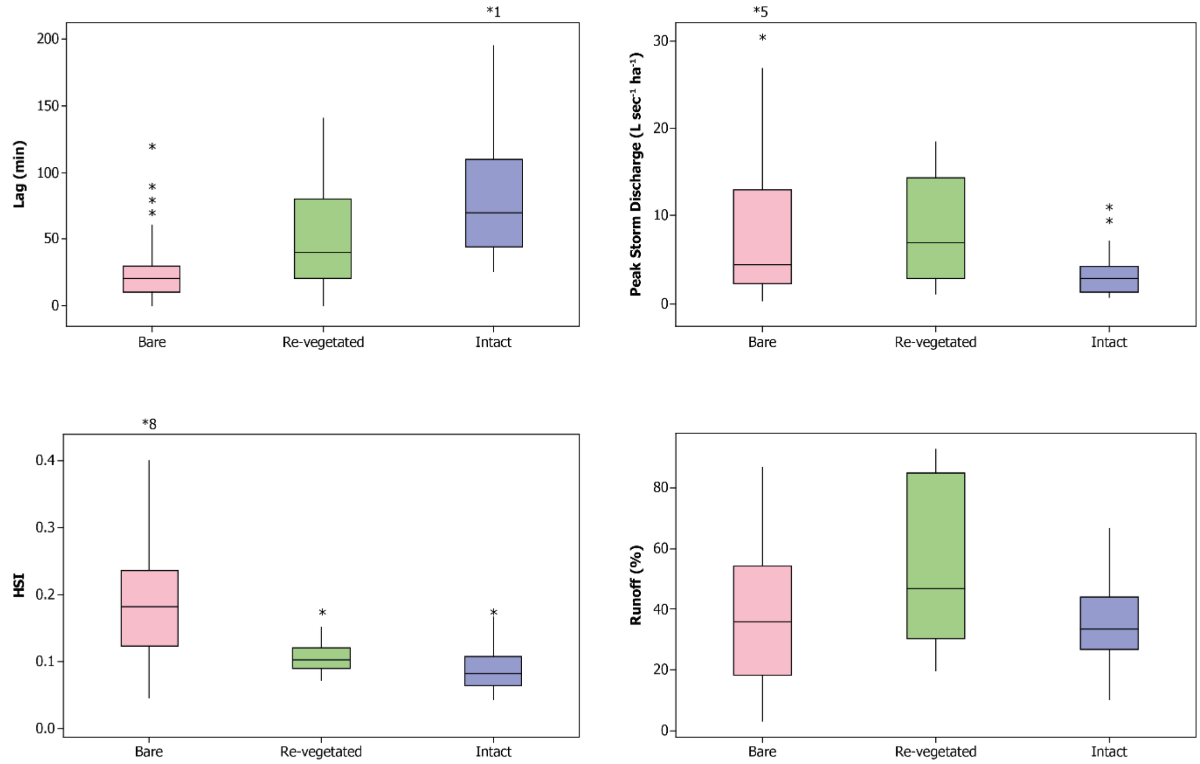
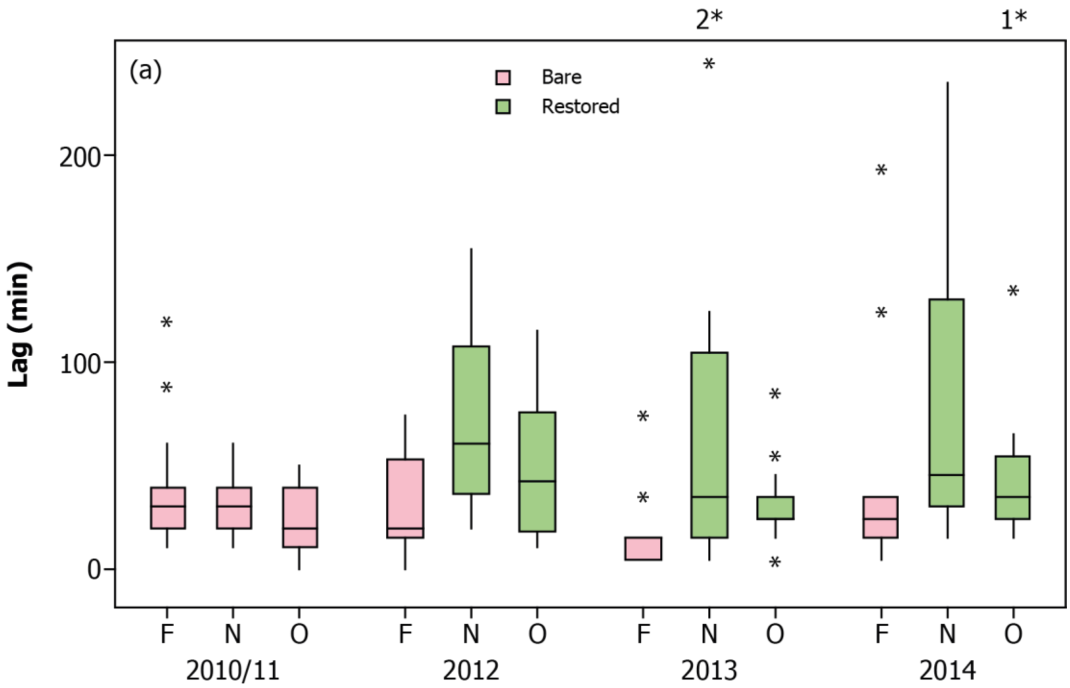


Figure 15: Distribution of the four key hydrograph metrics at bare Kinder sites, and late-stage re-vegetated and intact Bleaklow sites.



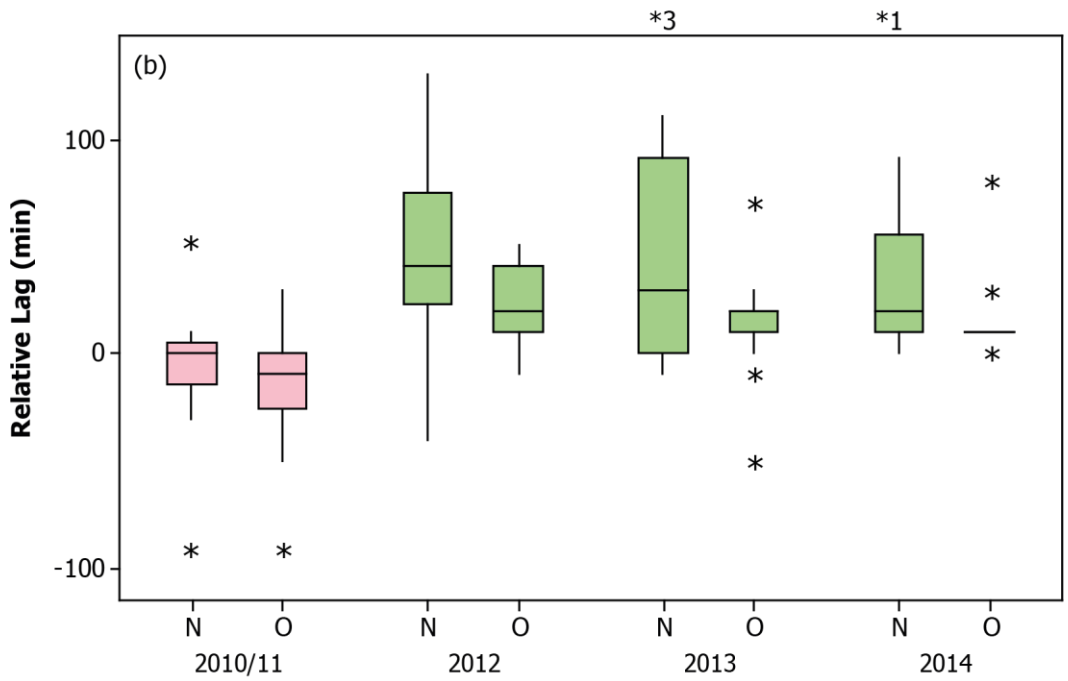


Figure 16: Distribution of lag-times by year.
(a) all three Kinder catchments; (b) the two treatment catchments relative to the control catchment. Starred numbers outside of bounding box represent the number of outliers exceeding the range of the y axis. Data derived from the paired-storm dataset.

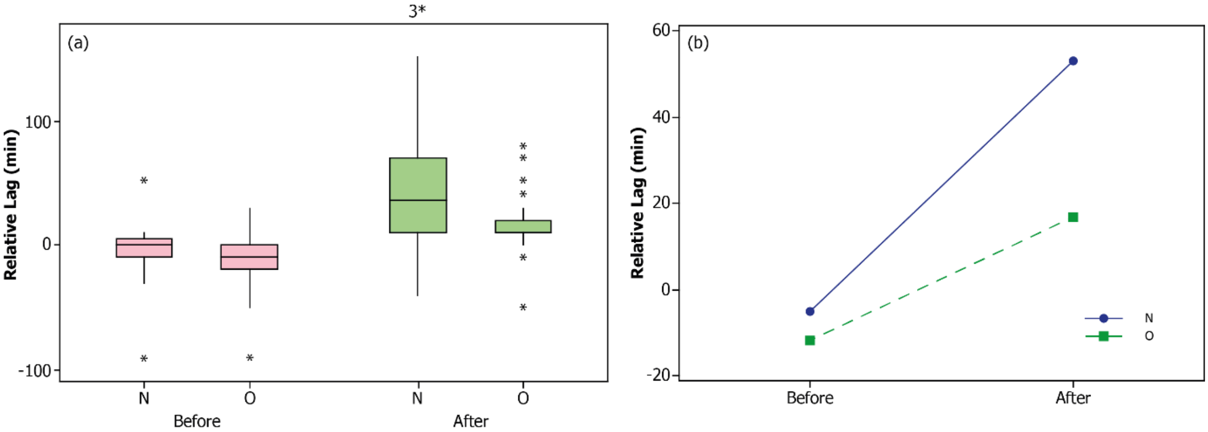


Figure 17: Lag-time differences before and after treatment.
(a) Distribution of lag-times at the two treatment catchments relative to the control catchment, before and after treatment. Starred numbers outside of the bounding box represent the number of additional outliers which exceed the range of the y axis; (b) Interaction plot showing the differences in lag-time in the treatment catchments before and after restoration. Data derived from the paired-storm dataset.

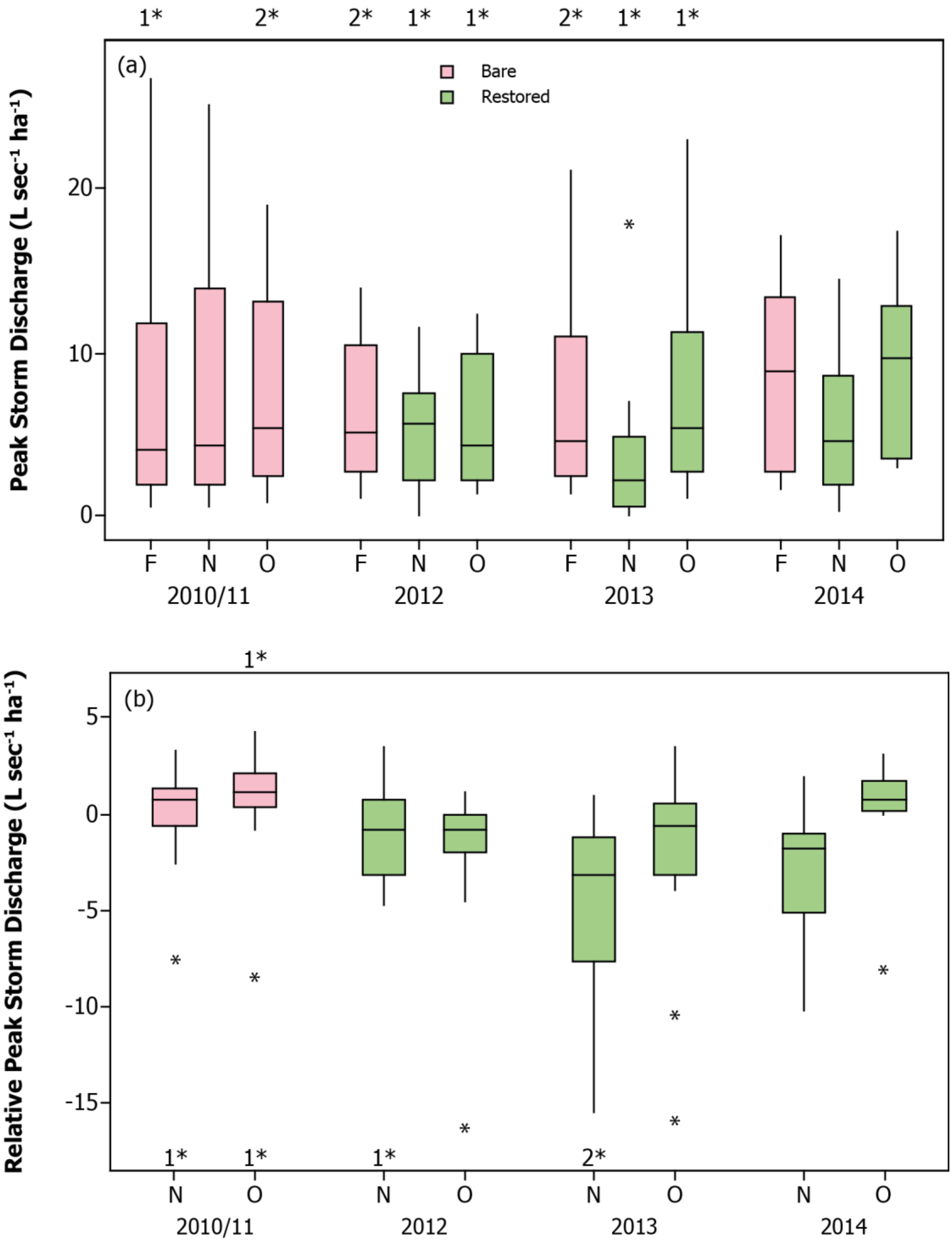


Figure 18: Distribution of peak storm discharge by year.
(a) At all three Kinder catchments; (b) At the two treatment catchments relative to the control catchment. Starred numbers outside of bounding box represent the number of outliers exceeding the range of the y axis. Data derived from the paired-storm dataset.

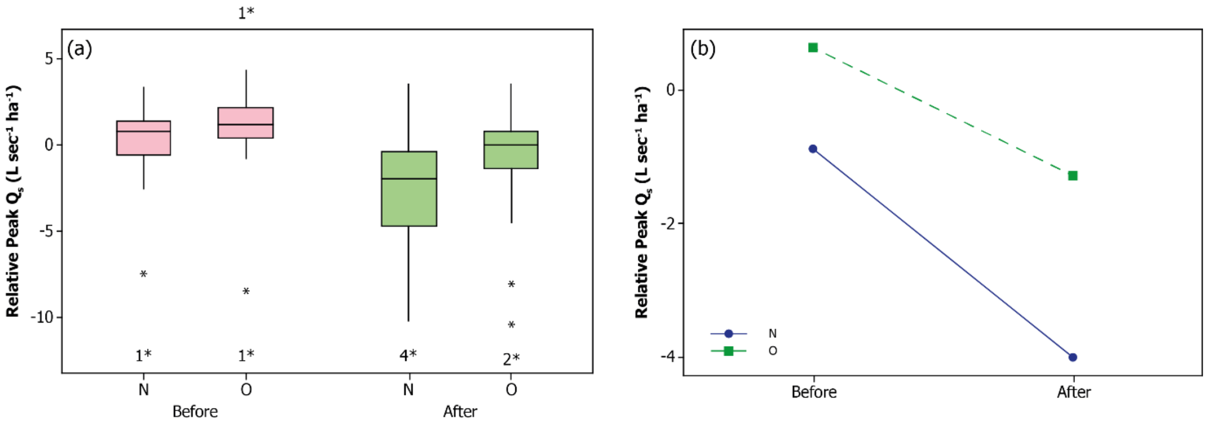


Figure 19: Peak storm discharge (Peak Q_S) differences before and after treatment.

(a) Distribution of peak storm discharge (Peak Q_s) at the two treatment catchments relative to the control catchment, before and after treatment. Starred numbers outside of the bounding box represent the number of additional outliers which exceed the range of the y axis; (b) Interaction plot showing the differences in Peak Q_s in the treatment catchments before and after restoration. Data derived from the paired-storm dataset.

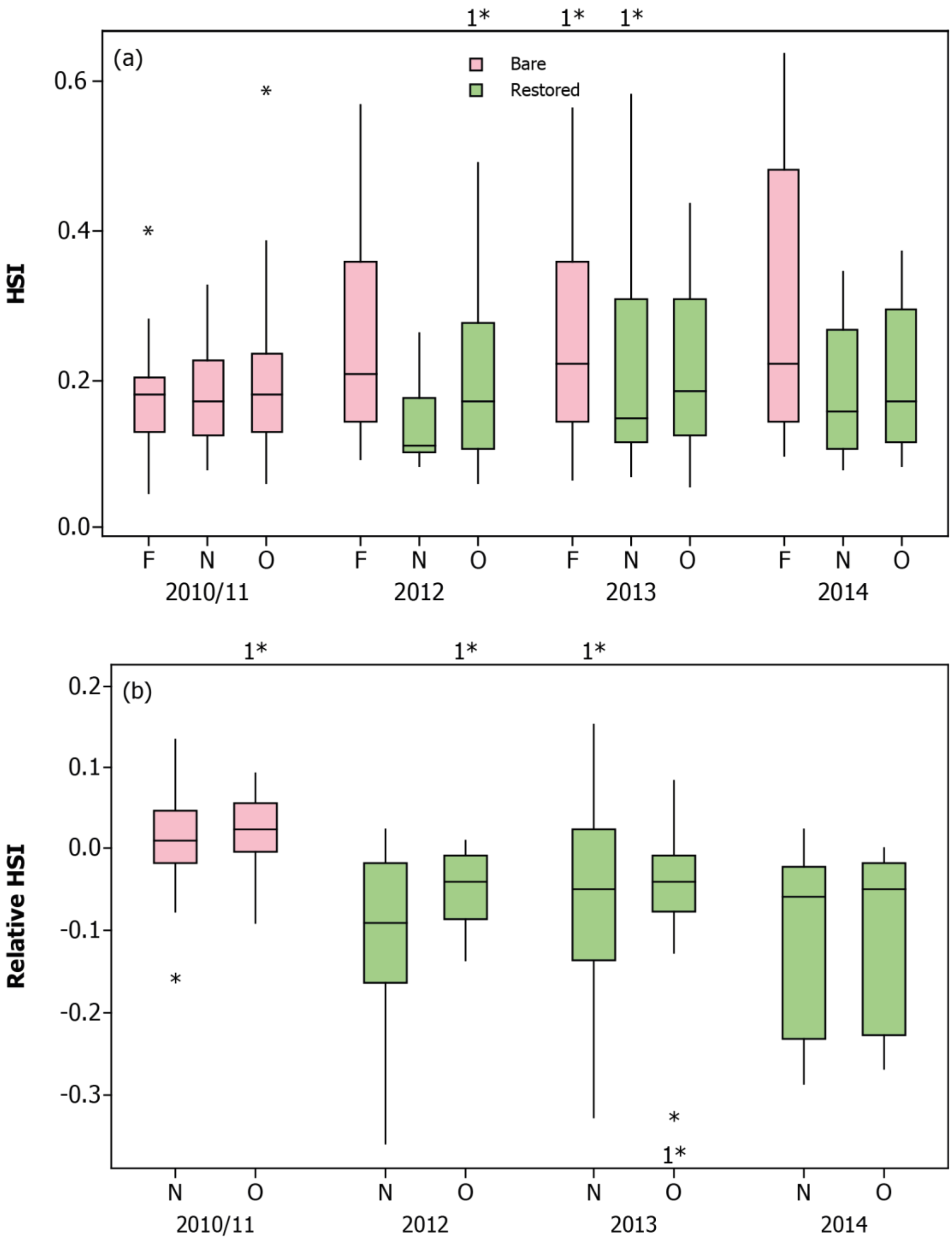
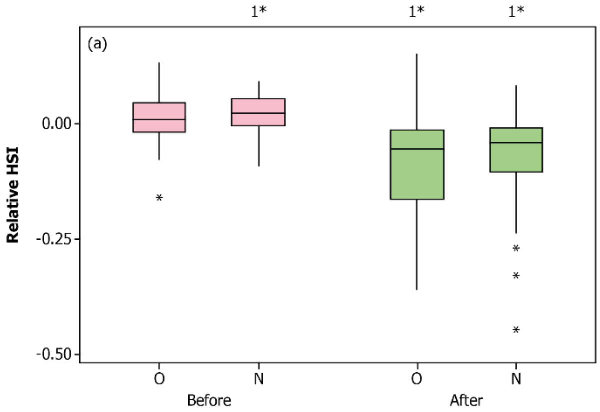


Figure 20: Distribution of Hydrograph Shape Index (HIS) by year.

(a) At all three Kinder catchments; (b) At the two treatment catchments relative to the control catchment. Starred numbers outside of bounding box represent the number of outliers exceeding the range of the y axis. Data derived from the paired-storm dataset.



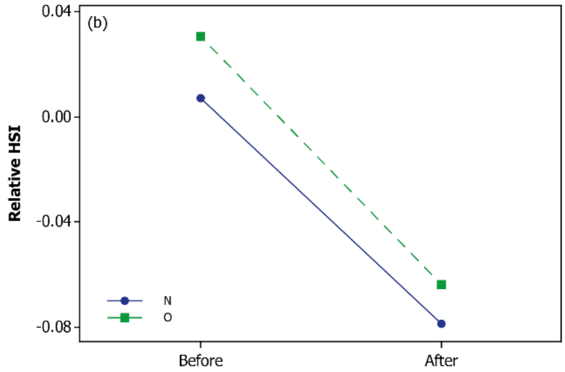


Figure 21: Peak storm HSI differences before and after treatment.

(a) Distribution of peak storm HSI at the two treatment catchments relative to the control catchment, before and after treatment. Starred numbers outside of the bounding box represent the number of additional outliers which exceed the range of the y axis; (b) Interaction plot showing the differences in HSI at the treatment catchments before and after restoration. Data derived from the paired-storm dataset.

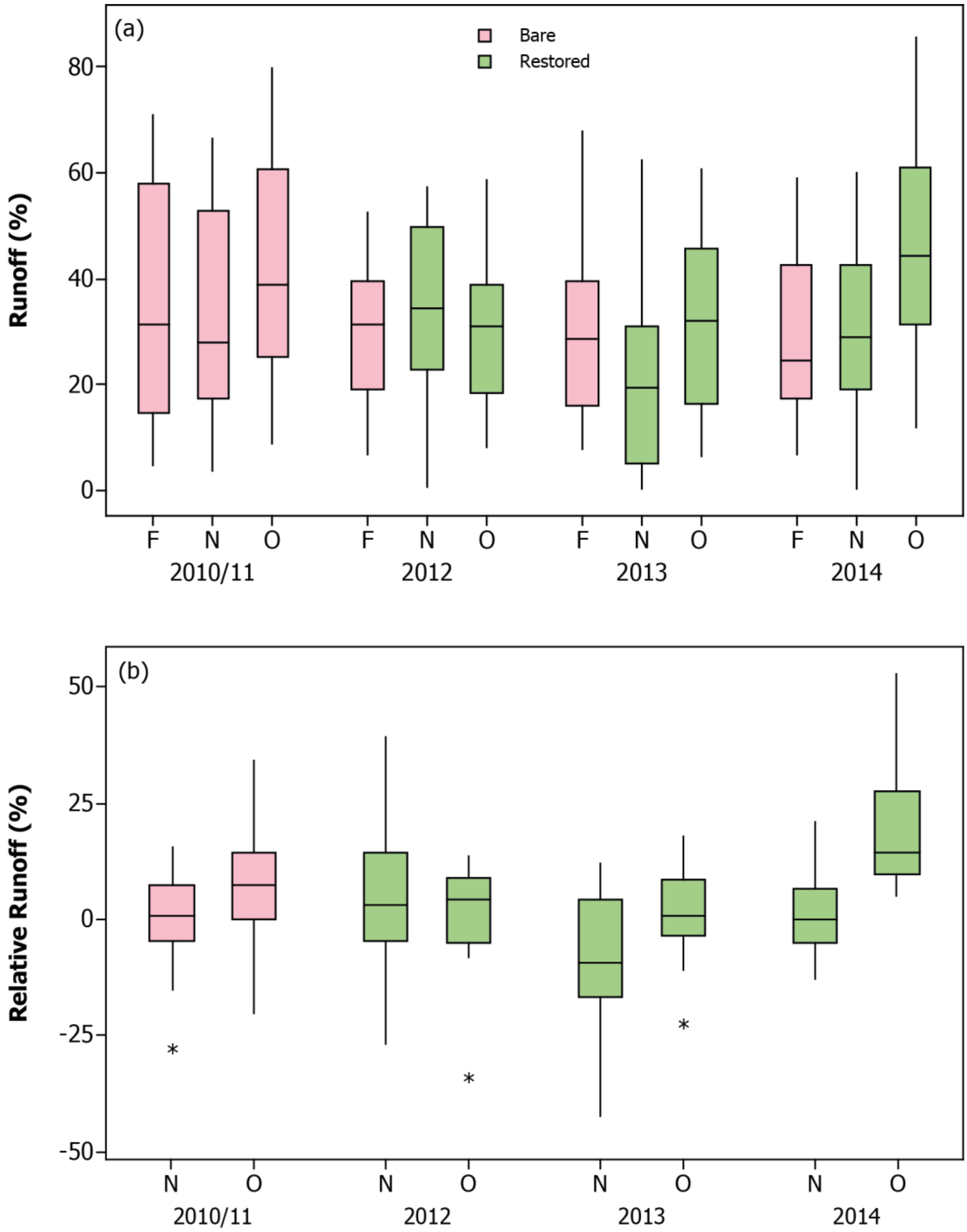


Figure 22: Distribution of pecentage runoff by year.

(a) At all three Kinder catchments; (b) At the two treatment catchments relative to the control catchment. Starred numbers outside of bounding box represent the number of outliers exceeding the range of the y axis. Data derived from the paired-storm dataset.

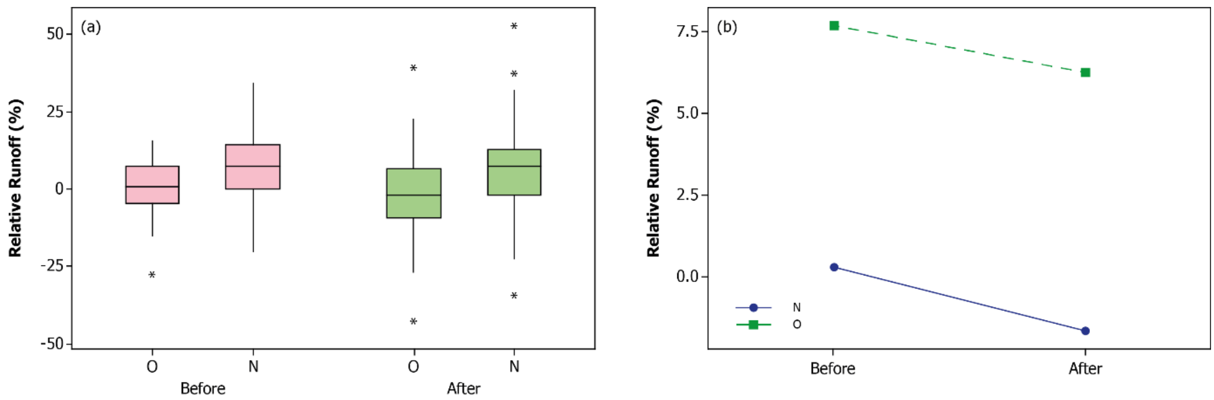


Figure 23: Distribution of and differences in percentage runoff before and after treatment.

(a) Distribution of percentage runoff at the two treatment catchments relative to the control catchment, before and after treatment. Starred numbers outside of the bounding box represent the number of additional outliers which exceed the range of the y axis; (b) Interaction plot showing the differences in percentage runoff in the treatment catchments before and after restoration. Data derived from the paired-storm dataset.

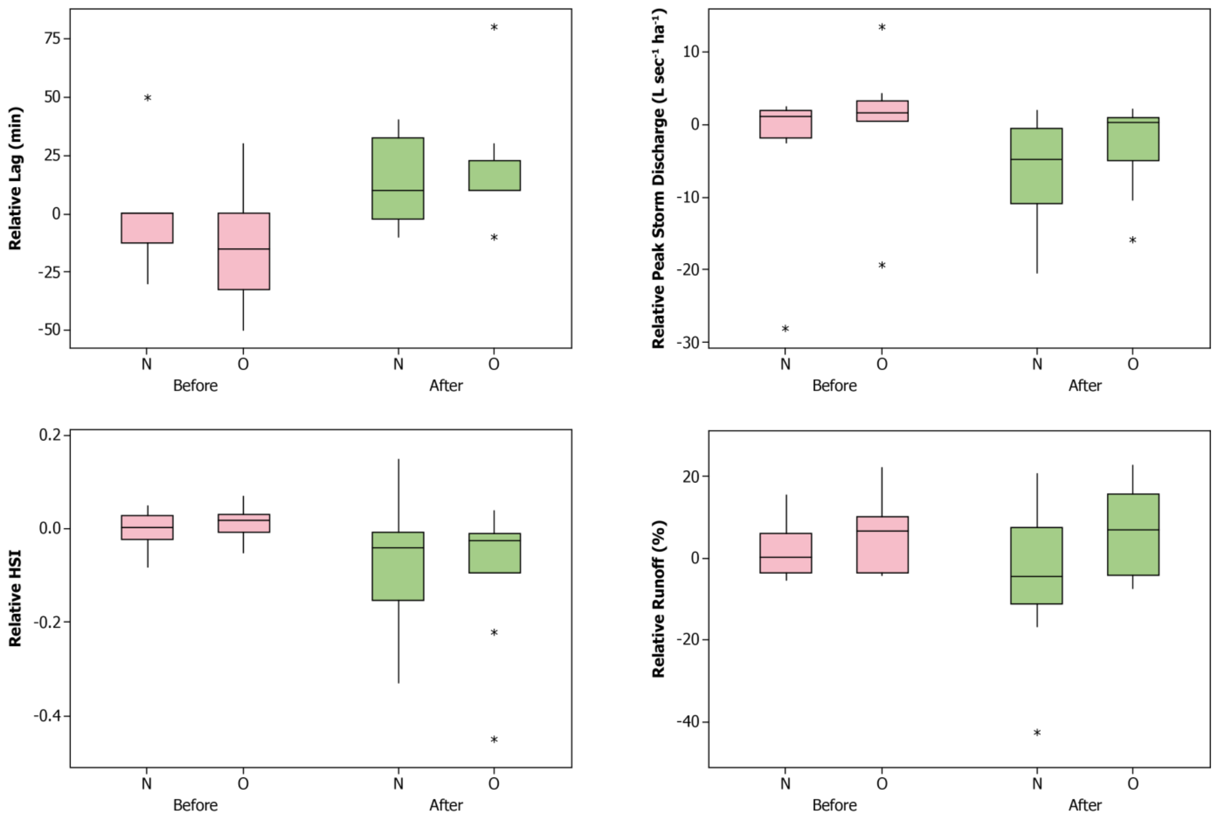


Figure 24: Distribution of the four key hydrograph metrics for high magnitude events at the two treatment catchments relative to the control catchment, before and after treatment.

Data derived from the paired-storm dataset.

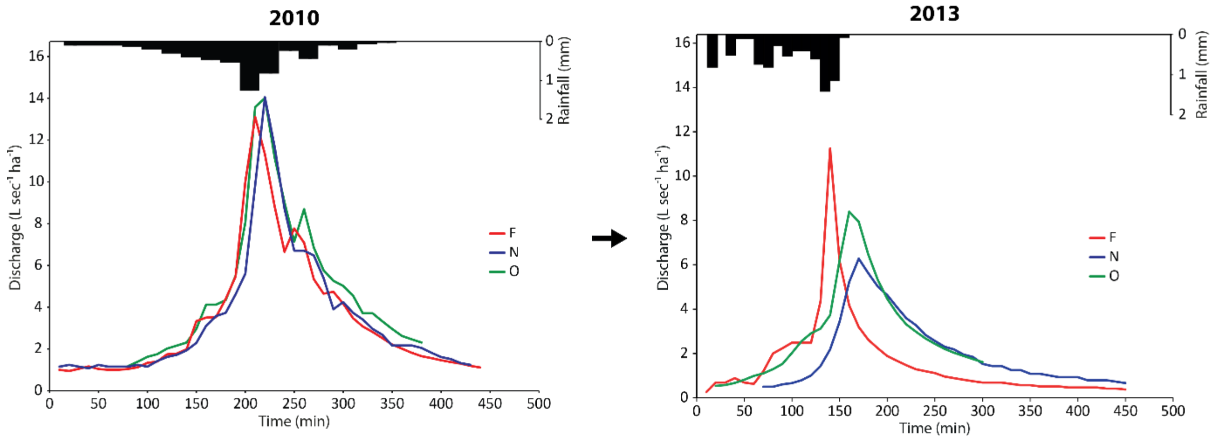


Figure 25: Example of storm hydrograph responses to typical autumn storm events at sites F, N and O in 2010 before restoration (4/11/2010) and in 2013 after restoration (16/10/2013).
Note the shifts in lag times and peak discharges at the restored sites (N, O) relative to the control site (F).

	F	N	O	P	J
Catchment type	Eroded (Control)	Eroded (Experimental)	Eroded (Experimental)	Intact (Reference)	Late-stage restoration (Reference)
Treatment/s	None	Re-vegetation (seeded 2011) Gully blocked (2011/12)	Re-vegetated (seeded 2011)	None	Re-vegetated (seeded 2003)
Catchment area (m^2)	7008	7096	4468	5120	2952
Altitude of catchment outlet (m)	612	611	611	504	584
Catchment relief (m)	6	8	6	11	13
Proportion of catchment gullied (%)	32.9	28.5	22.9	8.4	28.5

Table 13: Kinder micro-catchment characteristics.

Total rainfall	Max rainfall intensity	Lag	PeakQ	HSI	Runoff	
	0.457	-0.2	0.717	-0.206	0.588	**Total rainfall**
		-0.471	0.695	0.403	0.479	**Max rainfall intensity**
			-0.583	-0.632	-0.337	**Lag**
				0.338	0.828	**PeakQ**
					-0.028	**HSI**
						Runoff

Table 14: Spearman rank correlation matrix based on rainfall and hydrograph metrics for the pre-restoration storm dataset at sites F, N, O, and P.
Correlations significant at <0.001 are shaded red, and correlations significant at <0.01 are shaded green.

Metric	P- value
Lag	0.194
Peak Qs	0.284
HSI	0.052
Runoff	0.326
Total rain	0.870
Max rain	0.579
PSI	0.448

Table 15: Results of the ANOVA employed to compare hydrograph metrics and rainfall characteristics in the Kinder micro-catchments before restoration.
Significant differences at $p < 0.05$ are highlighed in pink.

Metric	ANOVA	Post-hoc testing of difference		
		Bare / Intact	Bare / Re-vegetated	Re-vegetated / Intact
Lag	0.000	0.000	0.038	0.008
Peak Qs	0.012	0.010	0.987	0.155
HSI	0.000	0.000	0.017	0.890
Runoff	0.010	0.952	0.009	0.014

Table 16: Results of the ANOVA employed to compare the four key hydrograph metrics at bare Kinder sites, and late-stage re-vegetated and intact Bleaklow sites.
Significant differences at $p < 0.05$ are highlighed in pink.

		Bare	Re-vegetated	Intact
Lag (min)	Max	120	140	260
	Q3	30	75	104
	Median	20	40	70
	Q1	10	20	48
	Min	0	0	25
Peak Storm Discharge (L sec^{-1} ha^{-1})	Max	49.7	18.4	10.9
	Q3	12.7	14.3	4.1
	Median	4.4	6.9	2.9
	Q1	2.2	3.4	1.3
	Min	0.3	0.9	0.6
HSI	Max	0.68	0.17	0.18
	Q3	0.24	0.12	0.10
	Median	0.18	0.10	0.08
	Q1	0.12	0.09	0.07
	Min	0.05	0.07	0.04
Runoff (%)	Max	86.5	92.4	66.6
	Q3	53.6	80.1	42.6
	Median	35.7	46.7	33.2
	Q1	18.2	33.9	27.8
	Min	3.2	19.8	10.2

Table 17: Descriptive statistics for the four key hydrograph metrics at bare Kinder sites, and late-stage re-vegetated and intact Bleaklow sites.

		2010-11			2012			2013			2014		
		F	N	O	F	N	O	F	N	O	F	N	O
	N	34	44	45	36	46	42	45	42	53	37	35	47
Lag (min)	Max	120	90	120	75	330	205	215	355	315	195	235	275
	Q3	32.5	40	30	25	133.8	76.25	30	157.5	75	45	125	75
	Median	30	20	20	15	75	45	15	80	35	25	75	45
	Q1	20	20	10	15	38.8	25	5	15	25	15	35	25
	Min	10	10	0	0	5	10	5	-5	5	5	15	5
Peak Storm Discharge (L sec^{-1} ha^{-1})	Max	49.7	25.1	40.1	31.7	29.3	30.8	63.4	31.8	62.3	31.6	14.4	17.2
	Q3	11.9	12.9	14.4	10.0	5.7	5.0	8.1	3.7	5.3	9.1	5.4	7.1
	Median	4.0	4.2	7.1	4.3	3.0	3.1	4.1	2.1	2.8	4.1	3.5	3.6
	Q1	2.0	2.2	2.6	2.2	1.8	1.9	2.0	0.2	1.2	2.2	1.2	2.4
	Min	0.5	0.5	0.3	0.5	0.1	0.7	0.6	0.0	0.4	0.6	0.1	0.1
HSI	Max	0.36	0.59	0.68	0.98	0.36	0.77	0.89	1.71	0.49	0.83	0.71	0.55
	Q3	0.20	0.27	0.26	0.46	0.14	0.21	0.32	0.32	0.24	0.41	0.17	0.23
	Median	0.14	0.17	0.59	0.27	0.11	0.14	0.20	0.13	0.16	0.23	0.12	0.15
	Q1	0.11	0.12	0.21	0.18	0.09	0.10	0.13	0.10	0.10	0.17	0.08	0.09
	Min	0.05	0.07	0.12	0.09	0.04	0.06	0.06	0.06	0.05	0.10	0.05	0.04
Runoff (%)	Max	71.0	66.3	86.5	52.3	72.2	58.8	67.9	124.3	63.3	59.1	61.9	106.9
	Q3	50.1	51.9	57.5	31.6	45.7	39.2	40.6	33.6	41.4	33.6	46.4	48.0
	Median	32.1	32.0	38.9	22.5	31.6	29.0	26.8	20.2	28.8	22.9	29.8	35.5
	Q1	16.6	18.2	20.1	13.4	22.6	19.2	13.3	0.6	16.8	14.9	15.8	22.7
	Min	5.5	3.2	4.5	4.2	0.4	8.2	3.3	0.0	2.8	3.4	0.1	0.5

Table 18: Descriptive statistics for the four key hydrograph metrics by year, based on the full dataset.

(a)

	Proportion of storms with < 10 mm total rainfall (%)			Proportion of storms with > 10 mm total rainfall (%)		
	F	**O**	**N**	**F**	**O**	**N**
2010 / 11	65	75	66	35	25	34
2012	69	61	74	31	39	26
2013	69	64	74	31	36	26
2014*	81	51	70	19	49	30

(b)

	Proportion of storms with maximum rainfall intensity < 2 mm (%)			Proportion of storms with maximum rainfall intensity > 2 mm (%)		
	F	O	N	F	O	N
2010 / 11	88	94	82	12	6	18
2012*	61	86	69	39	14	31
2013	69	76	83	31	24	17
2014	70	71	72	30	29	28

Table 19: Distribution of storm events with differing rainfall characteristics at the three Kinder micro-catchments over the four years of sampling, based on the full dataset.

		2010-11			2012			2013			2014		
		F	N	O	F	N	O	F	N	O	F	N	O
	N	20	20	20	16	16	16	19	19	19	13	13	13
Lag (min)	Maximum	90	60	50	75	155	115	75	355	85	195	235	275
	Q3	30	37.5	37.5	52.5	107.5	76.25	15	105	35	35	130	55
	Median	30	20	15	20	60	42.5	15	35	25	25	45	35
	Q1	20	20	10	15	36.3	17.5	5	15	25	15	30	25
	Minimum	10	10	0	0	20	10	5	5	5	5	15	15
Peak Storm Discharge ($L\ sec^{-1}\ ha^{-1}$)	Maximum	49.7	25.1	40.1	31.7	29.3	30.8	63.4	31.8	62.3	16.9	14.4	17.2
	Q3	13.0	14.7	14.3	10.4	7.3	9.7	11.0	4.7	11.1	13.3	8.5	12.7
	Median	4.9	6.1	7.5	5.1	5.6	4.2	4.5	2.2	5.2	8.8	4.5	9.4
	Q1	2.4	2.9	3.2	2.6	2.1	2.1	2.5	0.6	2.7	2.6	1.7	3.5
	Minimum	0.5	0.5	0.8	1.1	0.1	1.2	1.2	0.0	1.0	1.6	0.2	2.9
HSI	Maximum	0.28	0.33	0.59	0.57	0.26	0.77	0.89	1.21	0.44	0.64	0.34	0.37
	Q3	0.20	0.20	0.24	0.36	0.18	0.28	0.36	0.31	0.31	0.48	0.27	0.29
	Median	0.16	0.16	0.20	0.21	0.11	0.17	0.22	0.14	0.18	0.22	0.16	0.17
	Q1	0.12	0.12	0.11	0.14	0.10	0.10	0.14	0.11	0.12	0.14	0.11	0.12
	Minimum	0.05	0.08	0.06	0.09	0.08	0.06	0.06	0.07	0.05	0.10	0.08	0.08
Runoff (%)	Maximum	71.0	66.3	79.6	52.3	57.1	58.5	67.9	62.2	60.5	59.1	60.0	85.4
	Q3	61.1	56.4	63.7	39.4	49.8	39.0	39.6	30.9	45.6	42.5	42.6	61.0
	Median	40.3	40.9	48.5	31.4	34.2	31.1	28.7	19.4	32.0	24.4	28.8	44.1
	Q1	19.1	19.7	28.3	19.1	22.7	18.4	15.8	5.1	16.4	17.3	19.2	31.2
	Minimum	5.8	3.7	8.7	6.6	0.4	8.2	7.7	0.2	6.5	6.8	0.3	11.7

Table 20: Descriptive statistics for the four key hydrograph metrics by year, based on the paired dataset.

Factor	Lag	Peak Q	HSI	Runoff
Site	0.010	0.028	0.362	0.001
Before/After	0.000	0.010	0.000	0.461
Interaction	0.061	0.528	0.843	0.905

Table 21: Results of the ANOVA employed to compare the four key hydrograph metrics in the two treatment catchments relative to the control catchment before and after restoration. Significant differences at $p < 0.05$ are highlighed in pink.

	Site	Expected*	Recorded	Difference	% Change
Lag (min)	N	15	55	40	267
	O	15	25	10	67
Peak Q (L sec^{-1} ha^{-1})	N	5.9	3.7	-2.2	-37
	O	5.9	5.4	-0.5	-8
HSI	N	0.22	0.14	-0.08	-38
	O	0.22	0.18	-0.04	-19
Runoff (%)	N	29.5	25.6	-3.9	-13
	O	29.5	34.3	4.8	16

Table 22: Changes in the four key hydrograph metrics at the two treatment sites following restoration.

*Significant differences at $p < 0.05$ are highlighed in pink. *Expected values taken from the bare control, based on the assumption that the treatment sites would have behaved this way without intervention.*

		Before			After		
		F	N	O	F	N	O
Lag (min)	Max	90	60	50	195	235	275
	Q3	30	45	20	30	42.5	42.5
	Median	25	20	10	15	35	25
	Q1	20	20	10	15	17.5	25
	Min	10	10	0	5	5	5
Peak Q (L sec^{-1} ha^{-1})	Max	49.7	25.1	40.1	33.4	17.9	22.9
	Q3	16.5	14.9	18.6	16.3	9.8	12.6
	Median	11.3	12.6	12.4	11.8	5.4	10.4
	Q1	5.3	7.6	7.4	7.9	3.5	6.0
	Min	2.2	4.1	4.9	1.5	0.2	3.6
HSI	Max	0.28	0.33	0.31	0.89	0.56	0.44
	Q3	0.19	0.17	0.19	0.28	0.26	0.23
	Median	0.14	0.12	0.16	0.18	0.15	0.16
	Q1	0.11	0.11	0.11	0.12	0.10	0.11
	Min	0.07	0.08	0.09	0.06	0.07	0.05
Runoff (%)	Max	71.0	66.3	69.7	67.9	62.2	81.8
	Q3	61.1	63.4	63.7	52.1	50.4	56.8
	Median	52.2	50.6	57.5	39.3	32.1	44.3
	Q1	39.1	45.5	41.2	14.3	14.7	28.7
	Min	12.6	27.0	34.8	6.8	0.3	6.5

Table 23: Descriptive statistics for the four key hydrograph metrics derived from the ten highest magnitude storms before and after restoration, based on the paired dataset.

Factor	Lag	Peak Q	HSI	Runoff
Site	0.566	0.158	0.951	0.065
Before/After	0.001	0.140	0.018	0.448
Interaction	0.200	0.882	0.692	0.319

Table 24: Results of the ANOVA employed to compare the four key hydrograph metrics derived from the ten highest magnitude storms before and after restoration. Significant differences at p < 0.05 are highlighed in pink.

		Expected*	Recorded	Difference	% Change
Lag	N	15	35	20	133
	O	15	25	10	66
Peak Q	N	11.8	5.4	-6.4	-54
	O	11.8	10.4	-1.4	-11
HSI	N	0.18	0.15	-0.03	-15
	O	0.18	0.16	-0.02	-8
Runoff	N	39.3	32.1	-7.2	-18
	O	39.3	44.3	5.0	12

Table 25: Changes in the four key hydrograph metrics at the two treatment sites following restoration derived from the ten highest magnitude storms before and after restoration.

*Significant differences at p < 0.05 are highlighed in pink. *Expected values taken from the bare control, based on the assumption that the treatment sites would have behaved this way without intervention.*

5 DISCUSSION

5.1 Evidence of impact

Restoration has had a pronounced effect on the hydrology of the peatland headwater catchments in this study, producing statistically significant changes in water table depth, runoff production, and storm-flow behaviour. Re-vegetation has raised water tables by 35mm after three years, and up to 102 mm after 8 years, 're-wetting' the treated catchments, which in turn has increased the incidence of overland flow. Restoration has also had a substantial impact on storm hydrograph characteristics – increasing average lag times by up to 35 min (267%), decreasing average Peak Q_s by up to 37%, and HSI by up to 38%. However, there has been no change in the proportion of storm event rainfall that becomes storm discharge. Gully blocking does seem to enhance the benefits of re-vegetation in 'slowing the flow' through restored systems (lag-times in particular appear to be substantially increased by the presence of blocks), but this additional effect is not statistically significant within the variability of the data. The observed changes to hydrograph behaviour are also evident in high magnitude events, indicating that the hydrological impacts of restoration in peatland headwaters have significant implications for downstream storm-flow behaviour and flood risk.

5.2 Process controls - What might be causing these effects?

5.2.1 Water table

The comparison of water tables before and after restoration presented in Section 2.4 suggests that re-vegetation has a rapid (c. 3 years) impact on water table depth. Possible reasons for this include: (i) increased infiltration due to root penetration; (ii) reduced evapotranspiration due to the insulating properties of vegetation cover and increased surface albedo associated with the change from dark bare peat to vegetated surfaces. The data outlined in Section 3.4 indicate that the bare peat catchments experience saturation excess overland flow, so infiltration does not appear to be a limiting factor on water table depth in erosion impacted systems. Further analyses of net radiation and evapotranspiration data are needed to confirm the latter hypothesis.

The spatial studies detailed in Section 2.3 showed that at late stage (c. 7-8 years) re-vegetated sites, the relative difference in water table between bare and restored sites was greater than after three years (90 – 102 mm versus 35 mm), suggesting that there may be a longer term recovery of water table conditions. Re-vegetation may encourage structural changes in the peat matrix over time, reducing hydrophobicity and increasing the peat's ability to retain water. However, it must be noted that these observations span peatlands with differing topographic and slope settings, so the observed spatial patterns may be due to variable topography, rather than maturity of restoration. Further monitoring of the Kinder micro-catchments is needed to examine these effects.

5.2.2 Surface runoff

Section 3 shows that the erosion impacted catchments (both bare and re-vegetated) are productive of saturation excess overland flow. This is contrary to the hypothesis that infiltration excess overland flow would dominate at bare sites. Incidence of overland flow increases following re-vegetation, consistent with the raised water tables discussed in Section 2. However, re-vegetation does not restore runoff conditions to those of an intact site, suggesting water table recover may be limited by the topographic effects of gullying as outlined above (Section 5.2.1).

Despite the observed increase in overland flow, percentage runoff values do not change following restoration (Section 4.3.1.5) indicating that there is no change in catchment storage during storm events. This suggests that other runoff processes, such as subsurface storm-flow (c.f. Holden and Burt, 2003; Daniels et al., 2008), must be prevalent in erosion impacted systems.

5.2.3 Hydrograph response

When considering the changes to storm-flow runoff and associated hydrograph response the four working hypotheses in Section 1, Hypothesis 4: "*Re-vegetation and gully blocking will increase surface roughness effects, with peat surface re-vegetation reducing overland flow and gully blocks and associated gully and re-vegetation reducing channel velocities*" is explain all of the observed changes, and is the only hypothesis where the predicted process responses are met (

Table 26). The roughness effect from the newly re-instated vegetation is key in slowing the flow of storm water through the catchment, with some additional in-channel roughness potentially provided by gully blocks. There is no change in catchment storage during storm events, but increased lag times and decreased Peak Q_s and HSI indicate that the rate at which storm rainfall enters and travels through the channel has been attenuated.

5.3 Implications for downstream flood risk and flood risk assessment

The significant post-restoration changes in hydrology observed in this study will reduce flood risk at the headwater scale. These headwater effects will propagate downstream, with the potential to substantially reduce flood risk at the wider catchment scale. However, the extent of any reduction in downstream flood risk will depend on two important scale factors:

1. The scale of restoration relative to the size of the catchment (i.e. the proportion of the catchment area that is treated).

2. Catchment and sub-catchment geography and associated hydrograph synchronisation effects (i.e. the extent to which delivery of water from restored sub-catchments becomes 'decoupled' from the wider catchment hydrograph, and therefore reduces downstream peak flow). This is an important consideration, although it should be noted that restored blanket peats are typically located at the extreme upper end of drainage and catchment networks, so that any increase in storm-flow travel times from these systems would be expected to reduce downstream peak flows.

The use of monitoring approaches to evaluate these scale effects, and to quantify the benefits of restoration on downstream flood risk reduction, is problematic. This is due to multiple influences on flow regimes in wider catchments and confounding factors, making it difficult to isolate the effects of restoration within empirical storm-flow datasets. It is also extremely difficult to identify suitable control systems at the large catchment scale (i.e. where all catchment attributes are identical except for restoration effects). However, the benefits of restoration effects on flood risk reduction at larger catchment scales can be quantified using hydrological models (e.g. Lane & Milledge, 2012). Importantly, the results of the current study provide the basis for realistic and robust hydrological modelling of downstream flood risk change. It has quantified changes in lag times and peak flows from headwaters associated with restoration, and has clearly demonstrated the hydrological process that underlie these effects. These two factors permit appropriate model formulation and calibration (See Annex 6).

5.4 Key findings

1. Restoration by re-vegetation and gully blocking has had statistically significant effects on peatland hydrology and storm-flow behaviour, specifically:

    - Reducing depth to water tables (up to 38%);
    - Increasing overland flow production (up to 18%);
    - Increasing storm-flow lag times (up to 267 %);
    - Reducing peak storm discharge (up to 37 %);
    - Attenuating storm hydrograph shape (up to 38 % reduction in HSI).

    However, there has been no change in percentage runoff within storm events (i.e. the proportion of storm rainfall producing discharge).

2. These results indicate that:

    - Catchments become wetter following re-vegetation (exemplified by decreased depth to water table and increased incidence of overland flow);
    - There is no change in catchment storage during storm events (exemplified by no change in percentage runoff);
    - Storm-flow is slowed/attenuated (exemplified by increased lag times, decreased peak storm discharge, and reduced HSI).

3. Gully blocking has apparent additional benefits for attenuating flow, but these are not statistically significant.

4. The observed changes are consistent with the hypothesis that re-vegetation and gully blocking has an increased surface roughness effect. Surface re-vegetation reduces overland flow velocities, and gully blocks and associated gully floor re-vegetation may also reduce in-channel velocities.

5. Peat restoration by re-vegetation and gully blocking has benefits for downstream flood risk reduction by ‘slowing the flow’ in peatland headwater catchments, but modelling is required to evaluate the benefits at larger catchment scale. This study provides robust empirical data and process analysis to calibrate such models.

5.5 Recommendations

1. Re-vegetation of eroded peatlands leads to a partial but significant restoration of runoff hydrology, delaying the release of storm-flow from headwaters with potential positive impacts for downstream flood risk reduction. **These positive impacts need to be incorporated into ecosystem service assessments of the restoration of upland peatlands.**

2. The presence of vegetation cover provided by nurse crop grasses has been shown to be key in attenuating the flow of storm water through the catchments. However, Holden et al (2008) demonstrated that *Sphagnum* spp. had a significantly greater slowing effect on overland flow than peatland cotton grass cover, so **Sphagnum re-introduction should be prioritised as an additional restoration measure in these blanket peat systems.**

3. **Longer term monitoring is essential to fully understand the continuing and potentially time-dependent impacts of peatland restoration**. Further monitoring of water tables at the main Kinder micro-catchments will provide further evidence for the trajectory of water table recovery through time, and help us understand the possible changes to peat structure which may drive this. Continued monitoring in these catchments would also confirm the long term effects of gully blocking, and any progressive changes in storm-flow behaviour as the vegetation cover matures from nurse grasses to sedge dominated heath, and (potentially) *Sphagnum* spp. recovery or introduction.

4. The finding of this study would not have been possible without the use of a bare peat control micro-catchment due to the inherent variability in storm-flow response associated with synoptic conditions, and additional year-to-year hydrological and climate noise. Therefore, **it is essential to maintain the bare control micro-catchment and site**, in order to effectively monitor the effects of any future restoration trajectories or the addition impacts of further treatments, such as the large-scale reintroduction of *Sphagnum* spp.

4. **Modelling is required to evaluate the flood reduction benefits of headwater restoration at a larger catchment scale**. The data produced in this report provides a detailed empirical and process grounding on which to base such models.

Hypothesis		Predicted changes		Changes Observed in Data?
1	Re-vegetation will increase evapotranspiration rates, lowering water tables and increasing soil water storage	(i)	Increased depth to water table	NO
		(ii)	Reduced overland flow generation	NO
		(iii)	Increased lag times	YES
		(iv)	Lower runoff ratios	NO
2	Re-vegetation will increase infiltration rates through the reduction of surface peat hydrophobicity and root penetration, increasing water tables and reducing soil water storage	(i)	Decreased depth to water table	YES
		(ii)	Increased overland flow generation	YES
		(iii)	Decreased lag times	NO
		(iv)	Higher runoff ratios	NO
3	Re-vegetation and gully blocking will increase within-storm catchment storage due to surface ponding of water within vegetation and in pools behind blocks respectively.	(i)	Lower runoff ratios	NO
		(ii)	Increased lag times	YES
4	Re-vegetation and gully blocking will increase surface roughness effects, with peat surface re-vegetation reducing overland flow velocities and gully blocks and associated gully re-vegetation reducing channel velocities	(i)	No change in runoff ratios	YES
		(ii)	Increased lag times	YES

Table 26: Summary predictions from the four working hypotheses of hydrological process change following restoration proposed in Section 1, and whether these predictions are met in the data.

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