Annex 3

Water flow trajectories on bare peat stabilisation sites

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Report to the Moors for the Future Partnership

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Analysis of six years of stormflow data at restored peatland sites in the southern Pennines suggests that lag times increase, peak discharge decreases, and storm hydrographs become less flashy following restoration. The effects are best characterised as a step change occurring in the year immediately following restoration. There are no consistent trends in hydrograph behaviour over the four years post-restoration. The findings support the hypothesis that changes in storm behaviour are driven by reduced overland flow velocities resulting from increased surface roughness. Future monitoring of the sites is recommended following additional changes to hillslope surface roughness (i.e. the establishment of sphagnum cover in site N). A minimum period of three years of monitoring is recommended to assess such changes to account for inter annual variability, but this does not need to be continuous with the existing data.

1.0 Introduction

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

Previous work in the area has used four key metrics to understand the effects of restoration on stormflow:

(i) **Lag time** – This is the time interval between maximum rainfall intensity and peak storm discharge. It 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.

(ii) **Peak storm discharge** – This is the maximum discharge measured during the storm event.

(iii) **Hydrograph shape index (HSI)** – This index provides a simple measure of overall hydrograph shape. High ratios represent more 'flashy' hydrographs which are quick to respond to rainfall and runoff generation, while low ratios indicate more attenuated hydrographs with lower peak flows relative to the size of the storm event.

(iv) **Percentage runoff** – This is the proportion of storm rainfall that reaches the stream channel to become discharge during a storm. Low values indicate substantial storage of water in the catchment, whereas high values indicate that most of the rainfall generates storm-flow.

Allott et al (2015) showed that lag time, peak storm discharge, and HSI are altered following restoration, indicating that the rate at which precipitation runs off the landscape and enters the gully channels has been slowed. However, previous work has only considered the differences between before and after restoration, and has not been able to ascertain the long term effect of peatland restoration on storm flow.

The aims of this report are threefold:

- Provide a baseline dataset for hydrograph behaviour at an intact peatland site.
- Investigate the impact of land management works (re-vegetation and gully blocking) on hydrograph behaviour.
- Create temporal trajectories for the impact of land management works on hydrograph behaviour to predict potential impact of future works of a similar nature.

2.0 Data sources

This report is based on hydrograph metrics extracted from water flow datasets collected and supplied by the MFFP on peatland restoration sites across the south Pennines between 2010 and 2015. Similar to our previous work on water table recovery trajectories (Evans and Shuttleworth, 2016), datasets were selected from the full range provided according to the following requirements:

1) There should be available data from a bare peat control site comparable to the restoration site.

2) Sufficient data are available pre- and post-restoration.

4) Suitable calibration data and notes are available to fully assess the viability of data sets.

4) Data quality and collation are sufficient so that the analyses could be completed in the time committed for this project.

Table 1: Data made availible and their suitibility to this study

Project name	Selection criteria			
	(1)	**(2)**	**(3)**	**(4)**
Making Space for Water	✓	✓	✓	✓
Kinder Catchment	✓	x	✓	x
Woodhead Gully Blocking	✓	x	✓	x

Table 1 summarises the data sources and whether they meet the above criteria. Data from the Kinder Catchment Project and Woodhead Gully Blocking Monitoring Programme do not meet all of the conditions required; there was only a short period of pre-restoration data collection (3 to 5 months) and limited processing of post-restoration data in both datasets (criteria 2), and it would not be possible to expand and potentially improve the suitability of the datasets within the time constraints of the project (criteria 4).

Therefore, this report focusses on data from the Making Space for Water (MS4W) project. To date, the MS4W dataset spans six years (2010-2015) and includes a full year of pre-restoration data (June 2010-June 2011). Data collected between 2010 and 2014 were originally processed for use in a Before-After-Control-Impact (BACI) analysis in Allott et al. (2015), so was readily available. We use these existing data combined with newly processed raw data collected in 2015 to construct trajectories of hydrological change through time following restoration at the two MS4W treatment catchments (N and O). Restoration commenced in July 2011 with the application of lime, seed and fertiliser. Additional gully blocking at site N was carried out in November 2011 and April 2012. The MS4W monitoring programme also includes two control sites: an intact catchment (P), and a bare peat control catchment (F) which have not been subject to any restoration treatments.

3.0 Data treatment

The experimental set up and data acquisition methods for MS4W are detailed in full in Allott et al. (2015). The 2015 data were treated in the same manner to the previously reported data. 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.

The parameters used to derive the four key hydrograph metrics (lag time, peak storm discharge, HSI, and percentage runoff) are shown in Figure 1. Lag time is derived from the time interval (in minutes) between maximum rainfall intensity and peak storm discharge (Figure 1a). Peak storm discharge (Peak Qs; L sec^{-1} ha^{-1}) is the difference between the maximum recorded discharge, and the coincident baseflow component (Figure 1b). 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 1b and c). Percentage runoff is the proportion of storm rainfall (Figure 1d) that reaches the stream channel to become discharge within the storm event (Figure 1c).

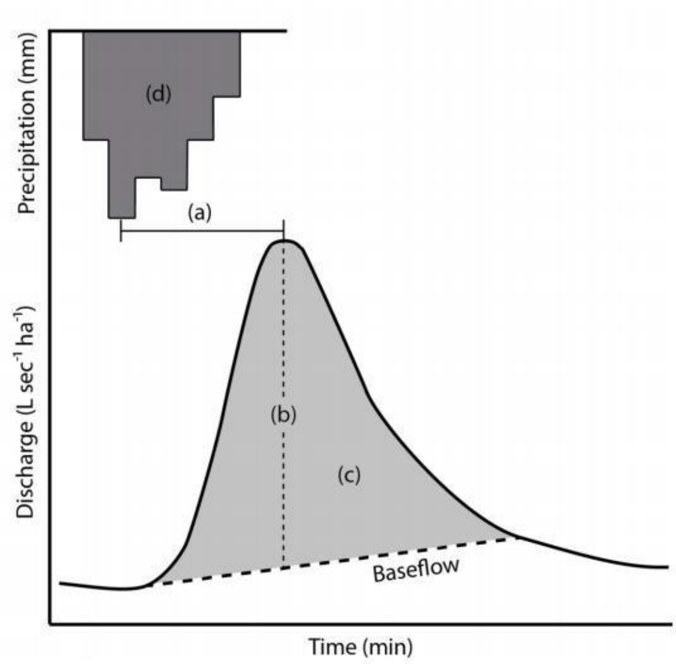

Figure 1: A typical storm hydrograph (from Allott et al., 2015). (a) indicates the time interval between maximum rainfall intensity and peak storm discharge used to determine lag-time; (b) indicates the magnitude of peak storm discharge, when the baseflow component has been deducted.; (c) the pale grey shaded area represents total storm discharge; (d) the dark grey shaded area represents total precipitation.

Storm-flow characteristics are influenced by antecedent conditions and the nature (intensity, duration, volume) of rainfall events. If we were to compare metrics derived from the entire data set, we could not be sure if observed differences in runoff behaviour were a consequence of the restoration treatments, or the nature of rainfall events. To eliminate this bias, we look at the relative difference between the treatment sites (N and O) and the bare control catchment (F).

Data for a total of 202 hydrographs were extracted from the 2015 raw datasets for F, N and O. There were 30 storm events where hydrographs could be extracted for all three catchments. These 90 hydrograph extractions (3 sites x 30 storm events) were added to the 2010-2014 data compiled by Allott et al. (2015) to produce the final dataset used in this report which spans the full 6 years of monitoring.

Hydrographs were also extracted from the raw data sets for catchment P to provide baseline stormflow characteristics for an intact area of peat. A total of 223 storms were extracted from the 2012-15 raw data. There were added to the existing hydrograph extractions from 2010-2011 to produce the final data set.

4.0 Stormflow characteristics through time

4.1. Stormflow characteristics in an intact peat catchment

Table 2 summarises the four key hydrograph metrics at the intact site (P) over the entire monitoring period to date (2010-2015). The median lag time is 75 min, median peak storm discharge is 1.38 L sec^{-1} ha^{-1}, median HSI is 0.05 and median runoff is 34.2%. These results are comparable to those presented in Allott et al (2015) for the same site for the 2010-11 period. To put this into the wider restoration perspective, Figure 2 shows the yearly median values for each metric at the intact and bare (F) sites. In order to account for inter annual hydroclimatic variability, only storms where data were available for both sites were used to construct the figure (*n* = 103).

Lag times at the intact site are consistently longer than at the bare site, with an average difference over the 5.5 years of 45 min. Peak storm discharge and HSI are consistently lower at the intact site, with average differences of 1.32 L sec^{-1} ha^{-1} and 0.09 respectively. The difference in percentage runoff is less clear; overall, the intact site was more productive of runoff by 8.3%, but both sites produced similar values in two of the monitoring years. The intact site releases proportionally more rainwater than the bare peat site which is consistent with higher water tables observed at this site (Allott et al. 2015). Despite this, the longer lag times, smaller peak discharges and smaller HSI all suggest that storm flow is relatively attenuated compared to the bare site. This is consistent with the hypothesis put forward by Allott et al (2015) – that the roughness provided by vegetation (and gully blocking) slows the flow of water through catchments, producing less 'flashy' hydrograph behaviour.

Table 2: Hydrograph metrics at the intact site (P) over the entire monitoring period to data (2010-2015).

Hydrograph metric	Median	95% confidence	
		Upper	Lower
Lag time (min)	75	65	85
Peak storm discharge (L sec^{-1} ha^{-1})	1.38	1.25	1.56
HIS	0.05	0.05	0.06
Runoff (%)	34.2	31.3	38.3

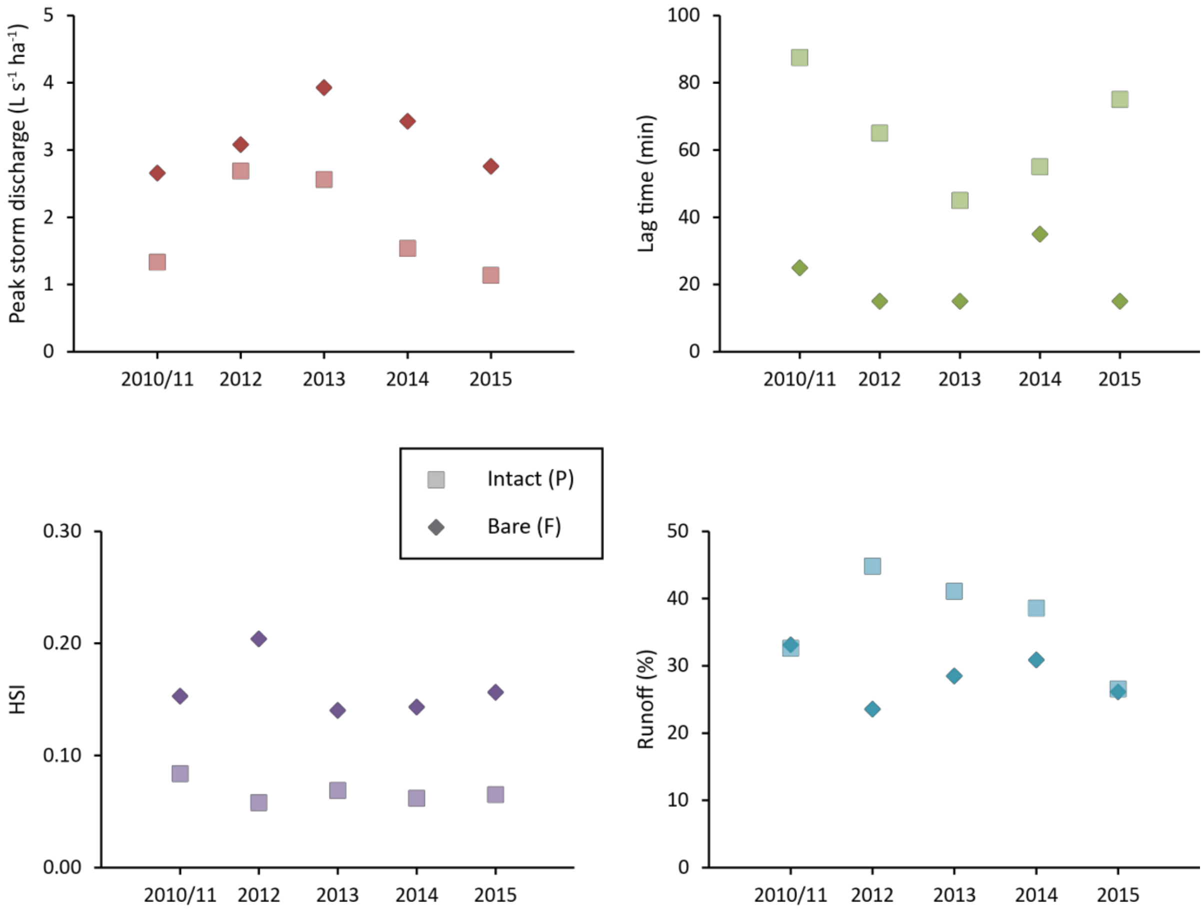

Figure 2: Hydrograph metrics at intact (Site P, squares) and bare peat (Site F, diamonds) sites demonstrating the typical scale of the difference between bare and intact sites.

4.2. Stormflow characteristics following peat restoration

Figure 3 shows the relative changes in the four key hydrograph metrics following restoration. Year 0 represents the 12 month sampling period prior to restoration. The y axes represent $(\text{metric})_{\text{treatment}}$ - $(\text{metric})_{\text{control}}$. Positive values on the y axis therefore indicate that the metric of interest is greater at the treatment site than at the bare control, while negative values indicate the opposite.

It is clear from visual inspection of the data that restoration has had an immediate effect on 3 out of the four metrics at the two MS4W treatment sites as previously shown by Allott et al (2015). Lag times became longer relative to the bare control, while both peak discharge and HSI were reduced in the immediately following restoration. There has been no consistent change in % runoff.

There are no subsequent directional trends in in the behaviour of any of the metrics following the pronounced step change in year 1. To demonstrate this, Kruskal-Wallace 1-way ANOVA were employed for each metric at each site to look for similarities/differences between each year. Groupings of statistically similar years are represented by lower case letters in Figures 3 a-h.

Lag time shows the clearest evidence of a consistent step change in behaviour following restoration. The K-W ANOVA splits the data into two groups. Lag times in Year 0 (i.e. before restoration) fall into Group a, while all subsequent years fall into Group b (Figure 3 a and b), demonstrating that lag times pre-restoration were significantly different to those post-restoration, and that lag times were statistically similar in the four years following restoration. This pattern is evident at both of the treatment sites. Comparable groupings can be seen for hydrograph shape (Figure 3 e and f), although in the second year post-restoration at site N, HSI fell into both group a and b, demonstrating similarities with both groups.

The step change is less clear for peak discharge, with the two treatment sites producing different K-W ANOVA groupings. At site O, the years were split into two groups (Figure 3d). Three out of the four years post-restoration fall into Group a, while one of the post-restoration years produced similar peak Q to the pre-restoration period (Group b). At site N, the years were split into three groups, with much cross over between the groups (Figure 3 c). However, although some of the post-restoration years were similar to the pre-restoration period (Group c), all post-restoration data fell into either Group a or Group b, while the pre-restoration data did not, showing that there has been a shift in peak Q following restoration.

The data in Figure 3 appear to indicate a step change in hydrograph form and timing in the year after restoration treatment. There is substantial variation in post restoration behaviour for some parameters indicative of variable catchment responses to inter-year variation in the number of storms and their behaviour. There are some indications that elements of this noise are non-random. Outliers in peak storm discharge (3c and d) appear to coincide with changes in percentage runoff (3g and h), and may indicate that dominant runoff pathways are altered with changes in rainfall intensity. Similarly the apparent increase in peak discharge over years 2-4 at site N might be linked to reduced impact of gully blocking as sediment fills behind blocks become stabilised. However, given the limited data available these interpretations are speculative. The simplest explanation of the observed data is a step change in lag times, HSI and peak discharge in response to restoration with subsequent variability interpreted as inter annual noise resulting from variation in the number and style of storms available for analysis. This is the approach taken in subsequent analysis.

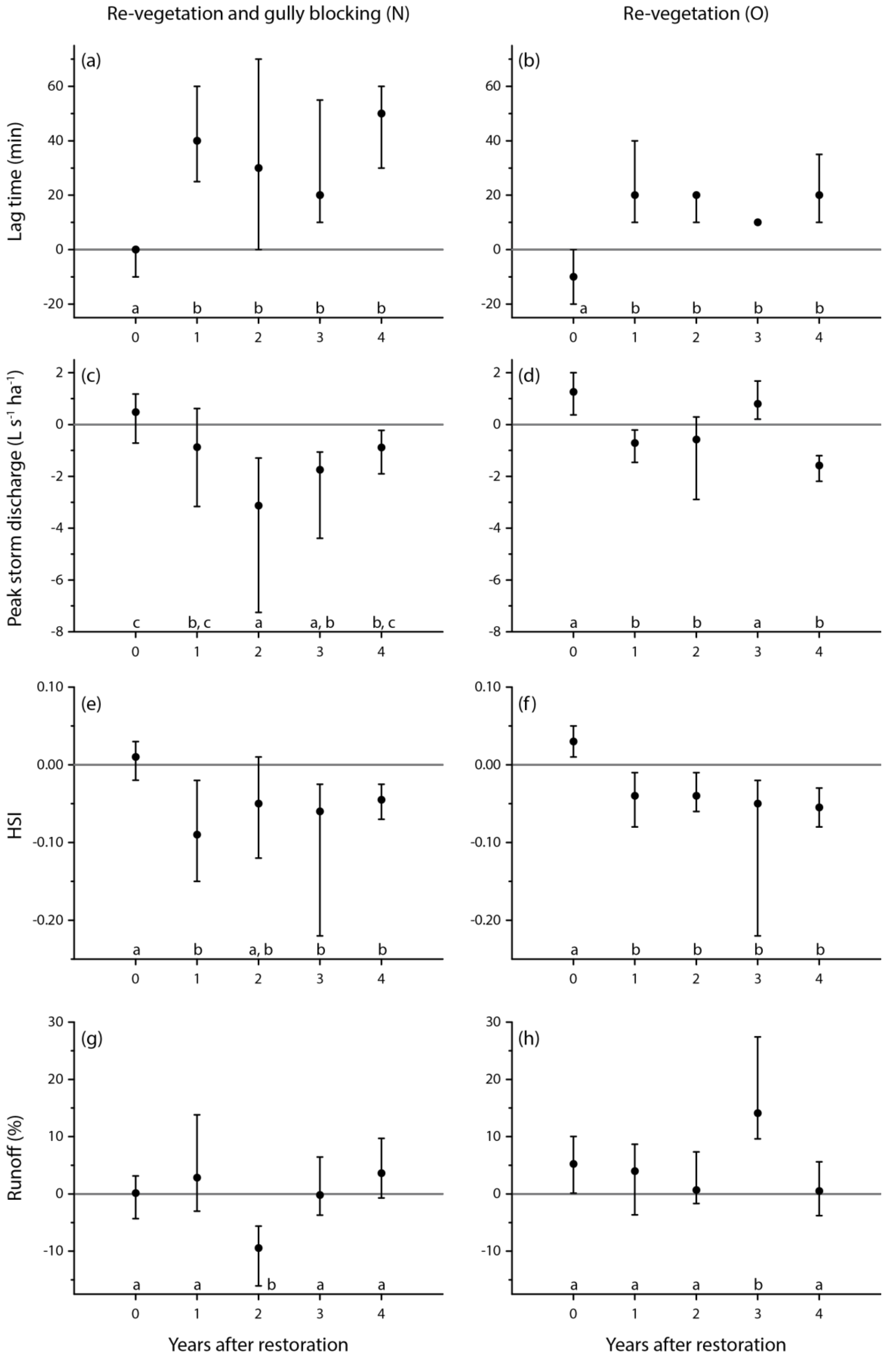

Figure 3: Points represent the median annual *relative* difference between the treatment sites (N and O) and the bare control site (F) for each metric. Error bars are the 95% confidence interval about the median. Lowercase letters denote years that are statistically similar years based on Kruskal-Wallace 1-way ANOVA.

5.0 Stormflow trajectories

As there are no directional trends in the data we can't produce trajectories as such, but by combining the extra year of data from 2015 to the data presented in Allott et al (2015) we can be more confident in determining the magnitude of the step change. The entire four year post-restoration data set can be used to determine the average (median) change over this period, with well constrained confidence intervals. The results from sites O and N cannot be combined as they represent two different restoration treatments, so we have calculated the magnitude of change following re- vegetation alone (site O), and following re-vegetation and gully blocking combined (site N) (Table 3). The step changes for lag time, peak discharge and HSI are represented graphically in Figure 4 (a to f). The y axis of these plots has been normalised so that pre-restoration (Year 0) the relative deviation is zero, so that the absolute magnitude of the step change can be seen. The median values and confidence intervals are overlaid with the annual data.

Table 3: Magnitude of the step change in stormflow behaviour at treatment sites N and O relative to control site F.

Hydrograph metric	Site	Median change	95% confidence Upper	95% confidence Lower
Lag time	N	40	50	30
(min)	O	30	30	20
Peak storm discharge	N	-1.85	-1.42	-2.98
(L sec^{-1} ha^{-1})	O	-2.18	-1.73	-2.64
HSI	N	-0.06	-0.05	-0.08
	O	-0.08	-0.06	-0.10

Following restoration:

- lag times increased by 30 minutes at the re-vegetated site (O) and 40 minutes at the re-vegetated and blocked site (N)
- peak storm discharge was reduced by 2.18 L sec^{-1} ha^{-1} at the re-vegetated site, and 1.85 L sec^{-1} ha^{-1} at the re-vegetated and blocked site
- HSI was reduced by 0.08 at the re-vegetated site, and 0.06 at the re-vegetated and blocked site.

The 95% confidence intervals for peak discharge and HSI at the two treatment sites overlap, indicating that there is no discernible difference between the effects of the two different treatments for these metrics (as found by Allott et al., 2015). However, the data suggest that additional gully blocking may increase lag times more than revegetation alone.

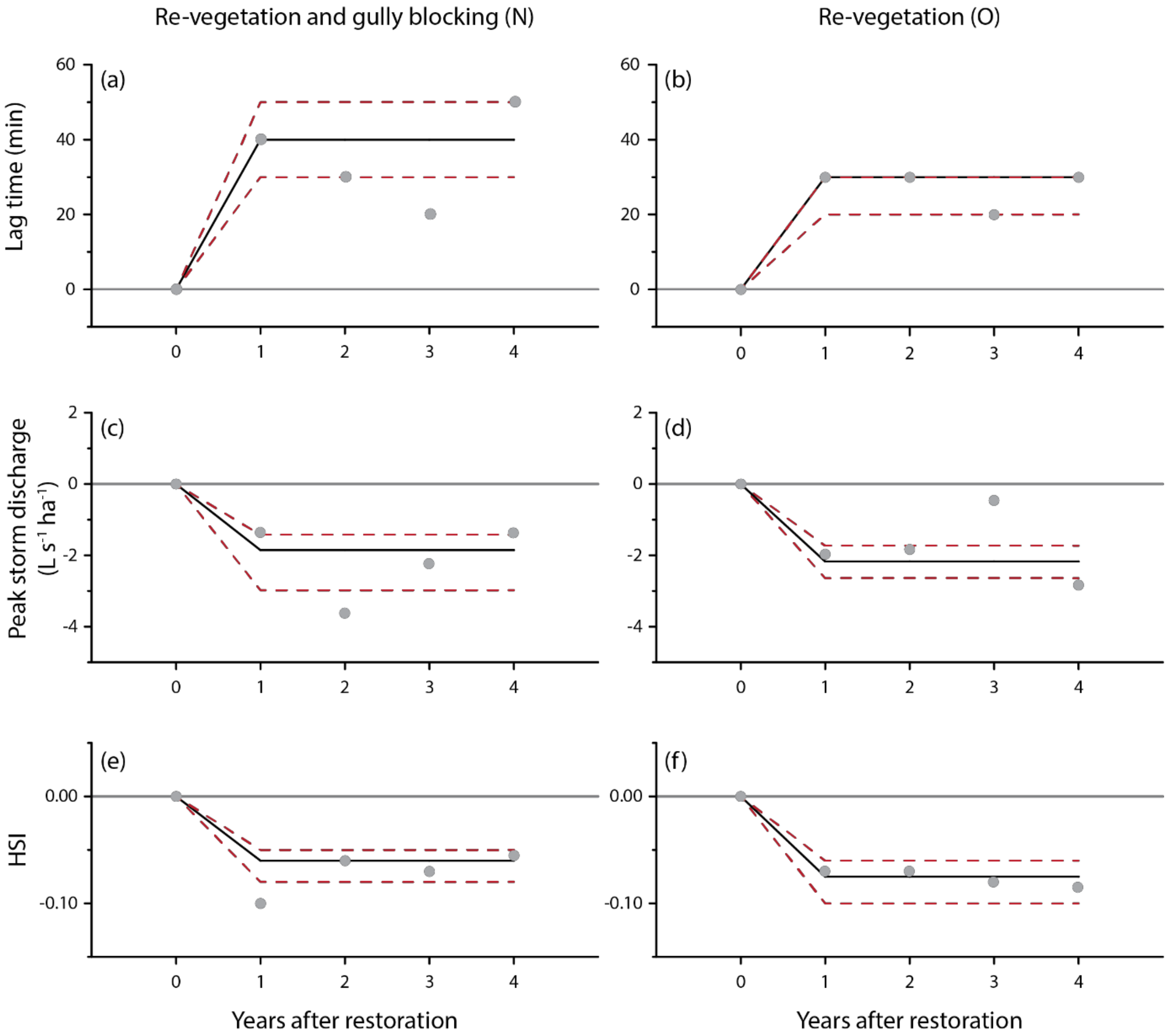

Figure 4: Step changes stormflow behaviour at treatment sites N and O relative to control site F. Solid black line represents the overall median for all post-restoration data. Red dotted lines represent the 95% confidence interval about the median. Grey points represent annual median values.

6.1 Implications for ongoing monitoring and future studies

- The observation of a rapid step change in these data further confirms the necessity of pre-restoration monitoring and a robust control to establish restoration effects in these systems. In these data there are no trends in post restoration behaviour so that the before-after comparison is paramount.
- As with all monitoring studies it is hard to rule out the potential of future change. However, the working assumption derived from Allott et al (2015) is that runoff changes at these sites are driven by changes in surface roughness. This is consistent with a step change in runoff behaviour linked to establishment of a vegetation cover over the first growing season post restoration. There is the potential for further change in roughness through successional changes in species mix and diversity of the vegetation cover but the lack of directional change in the first four years suggests this will not be a major effect. What may be significant is establishment of extensive sphagnum cover. Holden et al. (2008) demonstrated higher

surface roughness and lower overland flow velocities associated with sphagnum cover in peatlands.

- For these reasons, we recommend that future monitoring of runoff parameters at the site does not need to be continuous. Further monitoring at both sites once sphagnum cover has been established at site N (which has been plug planted with sphagnum) – a timescale of perhaps three years – would test both the effect of further sward diversification and sphagnum establishment. Ideally this phase of monitoring would extend to more than one year given the degree of inter- annual variability observed in years 1-4.
- We also emphasise the importance of collecting a robust pre-restoration baseline data set. Two of the three projects made available to this study did not have sufficient pre-restoration data, and both projects reports (Maskill et al., 2015a and 2015b) highlight that the limited pre-restoration time period was exceptionally wet, and therefore didn't provide an appropriate baseline.

7.1 0 Key findings and conclusions

1. Restoration of bare blanket peat using the 'Peak District Prescription' leads to increased storm lag times, decreased peak discharge, and smaller hydrograph shape index.
2. Runoff percentage is unaffected by restoration which implies that the effect is related to the timing of delivery of runoff to the channel system rather than to storage effects.
3. The further data analysis in this report supports the findings of Allott et al. 2015 that the most probable candidate mechanism is reduced overland flow velocities resulting from increased surface roughness.
4. Comparison of hydrograph parameters between intact and bare peat control sites over five years shows variation between the sites which is consistent with the changes observed on re-vegetation of the bare peat sites.
5. Analysis of the trajectory of hydrograph change over 5 years indicates that the effects are best characterised as a step change occurring in the year after restoration.
6. There is no consistent trend in the measured hydrograph parameters over the four years post restoration.
7. Further monitoring of the sites is recommended after the establishment of sphagnum cover in site N, which has the potential to significantly change hillslope surface roughness.
8. A minimum period of three years of monitoring is recommended to account for inter annual variability but this does not need to be continuous with the existing data. Targeted monitoring triggered by the establishment of significant sphagnum cover in the experimental site will maximise understanding and minimise cost.

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