Assessing the effects of ditch blocking on Dissolved Organic Carbon and rainfall-runoff regimes: results from a climatically marginal shallow peatland

Emilie Grand-Clement[1], David J. Luscombe[1], Pia Benaud[1], Josie Ashe[1], Naomi Gatis[1], Morag Angus[2], David Smith[2], Richard E. Brazier[1]

[1] Centre for Resilience, the Environment, Water and Waste, University of Exeter, UK
[2] South West Water Limited, Exeter, UK

SUMMARY

This study addresses an evidence gap on the restoration potential of climatically marginal shallow peatlands by investigating short-term (five years post-rewetting) effects of ditch blocking on runoff and water quality. Results from two sites in south-west England (UK) showed reductions in peak flows ranging from 29 % to 32 % after rewetting, indicating modifications of rainfall-runoff regime in these catchments as a consequence of rewetting. In addition, a statistically significant reduction in total rainfall-runoff event discharge was observed at one of the study sites. The findings suggest an increase in the temporary storage of flow during rainfall-runoff events and an overall attenuation of storm hydrographs. Water quality responses to rewetting did not show any significant change in either DOC or colour concentrations during rainfall-runoff events. It is likely that such behaviour is due to the spatially limited success of rewetting interventions in significantly raising water tables in these shallow peatlands, and thus to a limited reduction in decomposition of vegetation and peat. No significant changes in DOC loads (normalised by rainfall) leaving the catchments were observed either. It is possible that a longer post-rewetting period will be needed to see any change in water quality, as vegetation responds in the longer (> 5 years) term.

KEY WORDS: DOC, ecohydrology, Exmoor National Park, peatland, rewetting

INTRODUCTION

Damage to peatlands is known to have negative effects on a number of ecosystem services (Bonn *et al.* 2010) including the supply of clean water from peaty catchments (Ritson *et al.* 2016). Land management practices such as burning and drainage are linked with increased dissolved organic carbon (DOC) export (e.g. Strack *et al.* 2008, Yallop & Clutterbuck 2009, Clutterbuck & Yallop 2010), thereby causing a loss of carbon from a long-term store (Billett *et al.* 2010, Bain *et al.* 2011). High DOC concentrations in water also affect the health of riverine ecosystems (Urban *et al.* 1989) giving water a low aesthetic value that requires a further complex and expensive treatment process for drinking water production (Ritson *et al.* 2016). Additionally, incomplete removal of DOC combined with addition of chlorine during the treatment process leads to the formation of carcinogenic compounds (Richardson *et al.* 2007).

Recognition of the value of peatlands, especially in the contexts of drinking water provision (Xu *et al.* 2018) and reduction of greenhouse gas (GHG) emissions (Mander *et al.* 2024), has prompted substantial investment in physical interventions aimed at mitigating effects of anthropogenic damage. Techniques such as revegetation (e.g. Caporn *et al.* 2018) and blocking of drainage ditches are now employed in both northern and tropical peatlands (Quinty & Rochefort 2003, Schumann & Joosten 2008, Ritzema *et al.* 2014, Grand-Clement *et al.* 2015, Hugron *et al.* 2020) in an attempt to rewet peatlands, further reinstate their hydrological functioning, and promote changes in vegetation cover. In many cases, the long-term goal of physical interventions for restoration is the return of a functioning peatland.

Overall, improvements seem to be site specific and occur at different timescales (Joosten *et al.* 2012, Alderson *et al.* 2019). Restoration, especially when successfully leading to vegetation change, can also increase a peatland's resilience to fire in comparison with degraded sites (Blier-Langdeau *et al.* 2022). However, evidence confirming near-natural conditions after restoration is sparse, even after ten years (Artz *et al.* 2018). Whilst a return to carbon accumulation may be possible at decadal scales (Schwieger *et al.* 2021), the full restoration of different peatland functions such as biodiversity, peat structure or hydrological regime is not guaranteed, thereby weakening resilience to future disturbance

(Loisel & Gallego-Sala 2022). The limitation in our understanding of long-term change following rewetting particularly concerns shallow, climatically marginal peatlands, that have been less studied than their deeper, northern counterparts (Grand-Clement *et al.* 2013). The need for rapid restoration to increase the chances of success and improve resilience to climate change (Glenk *et al.* 2021), as well as the need for sound and targeted monitoring (Loisel & Gallego-Sala 2022), are also highlighted.

Rainfall-runoff regimes in damaged peatlands have been shown to be flashy and sensitive to the spatial heterogeneity of peatland structure (e.g. slope gradient, hydraulic conductivity, connectivity) and function (including water table depth) (Holden & Burt 2003, Luscombe *et al.* 2016). Previous studies have found that peatland restoration can modify both the rainfall-runoff regime and water table behaviour (Shantz & Price 2006, Holden *et al.* 2011, Shuttleworth *et al.* 2019). In particular, restoration can attenuate event discharge (Gatis *et al.* 2023) and peak runoff (Shantz & Price 2006, Wilson *et al.* 2011b) despite the theoretical reduction in short-term water storage capacity of the peat body (i.e. raised water table). However, such change is not always observed, and the spatial complexities of water table depth and runoff connectivity often make the effect of restoration difficult to predict. This heterogeneity and the variability between sites (including variability in peat depth) and geographical characteristics also make the comparison between studies and the extrapolation of findings more widely across different peatlands quite difficult.

Understanding the complexity of storm derived runoff following rewetting provides insights into how DOC export can be altered by such activities. Theoretically, it is anticipated that rewetting will lead to the development of anaerobic conditions closer to the peatland surface due to raised water tables, thereby reducing decomposition (Worrall *et al.* 2007, Haapalehto *et al.* 2010, 2014) and increasing carbon storage (e.g. Wilson *et al.* 2013). As a result, it is generally thought that rewetting reduces DOC fluxes (Evans *et al.* 2016), although conclusions seem to differ. A number of studies have reported a short-term (i.e. up to 4 years) increase in DOC concentrations following rewetting (Worrall *et al.* 2007, Waddington *et al.* 2008, Wilson *et al.* 2011a, Gatis *et al.* 2023). However, in the longer term (i.e. over 5 years), DOC concentrations post-restoration tend to decrease compared to pre-restoration values in temperate upland bogs (e.g. Wallage *et al.* 2006, Armstrong *et al.* 2010), cutaway boreal bogs (Haapalehto *et al.* 2014, Strack *et al.* 2015) and fens (Höll *et al.* 2009). Other studies have found no improvement in either DOC or particulate organic carbon (POC) following the blocking of drainage ditches (Menberu *et al.* 2017, Evans *et al.* 2018). The range of change observed also varies, from clear to limited. When positive change does occur, post-restoration measurements are usually intermediary between damaged and pristine (Strack *et al.* 2015), highly variable between sites, and have only reached levels similar to those of pristine peatlands in a few studies (e.g. Frank *et al.* 2014). Local improvements in DOC are also likely to be affected by overlapping, large-scale (e.g. regional or continental) processes improving or hindering change. For instance, a general and large-scale increase in DOC concentrations has been observed by the UK Upland Waters Monitoring Network (UWMN) since the late 1980s (Williamson *et al*. 2022), and in northern ecosystems more generally (de Wit *et al*. 2021). This is likely to be largely due to atmospheric chemistry and the recovery from acidification (e.g. Skjelkvåle *et al.* 2001, Evans *et al.* 2005), although climatic drivers are becoming increasingly important in influencing DOC exports (de Wit *et al*. 2021). These points underline the need for caution in the expectations and objectives for peatland restoration projects (Evans *et al.* 2018).

The quotient of colour and carbon concentration (Colour/Carbon) and the Specific UV Absorbance at 254 nm (SUVA) have both been used as an indicator of the characteristics of carbon and, to some extent, of its origin within the peat profile. Drained peatlands have a higher aromatic content (Blodau & Siems 2012) compared to near-natural and restored sites, with DOC originating primarily from degraded and humified aerobic peat layers (Höll *et al.* 2009, Frank *et al.* 2014). Additionally, there is some evidence that successful rewetting might lead to a decrease in aromaticity (Höll *et al.* 2009) associated with a shift towards carbon originating from fresher plant material, increased vascular plant coverage and photosynthesis (Strack *et al.* 2015).

Carbon storage and DOC losses depend on the interaction between DOC production and transport through runoff. Most of the DOC losses from peatlands tend to occur during stormflow events (Hinton *et al.* 1997, Schiff *et al.* 1997, Clark *et al.* 2007), when DOC is exported by near-surface flowpaths following rapid and short-lived water table rises (Schiff *et al.* 1997). Examining DOC export at catchment scales can therefore afford an overall perspective on processes driving the system. Indeed, if the aim of restoration is to limit DOC export from a long-term carbon store, then it is essential to consider the transport process (measured by loads or yields of DOC exported) concomitantly with DOC production (measured by DOC concentrations). Transport by varying flow regimes can mitigate potential increases in DOC concentration (Roulet & Moore 2006), thereby reducing overall DOC exports as less water tends to leave restored peatlands during storms (O'Brien *et al.* 2008, Gibson *et al.* 2009, Turner *et al.* 2013), although results can also show large variations between sites and studies, making it difficult to draw clear-cut conclusions (Pickard *et al.* 2022).

Studies examining the effects of restoration on water quality and quantity have been biased toward deep peat systems (over 1.5 m depth), due to their extensive coverage and large carbon stores (e.g. Wallage *et al.* 2006, Armstrong *et al.* 2010), with comparatively little information on the behaviour of shallow peatlands. To fill this gap in knowledge, we focus on understanding the behaviour of shallow, spatially extensive peatlands in the south-west of Britain that are located at the southernmost geographical extent of peatlands in the UK, to understand their potential for restoration as analogues of shallow peatlands affected by future changes in climate elsewhere in Europe. Previous studies have shown that antecedent soil moisture conditions exert a particularly strong control on DOC loss from these shallow drained peatlands, with increases in DOC losses following dry periods (Grand-Clement *et al.* 2014). However, whether the rewetting of such environments can successfully alter runoff and limit DOC exports is currently unknown.

Research on shallow, climatically marginal peatlands is particularly important as modelling has predicted that the effects of climate change may compromise active peat accumulation in the south-west of the UK by as early as 2080 (Gallego-Sala *et al.* 2010), putting these marginal peatlands at risk of further degradation and creating landscapes that may irreversibly lose their carbon stocks. As more recent modelling is even more pessimistic (Ritson *et al.* 2025), the need to understand the effects of peatland rewetting and restoration has become increasingly urgent. Against this background, the study reported here evaluates the effectiveness of rewetting through the process of ditch blocking within shallow peatlands by testing the following hypotheses:

H1: Ditch blocking will reduce storm runoff through a modification of the hydrological structure and function.

H2: Ditch blocking will lead to a significant decrease in DOC and colour concentrations in storm-derived runoff.

H3: Ditch blocking will reduce the export of DOC at the headwater catchment scale during high flow events.

METHODS

Study sites

Exmoor National Park is located in the south-west of the UK, lying across the border between the English counties of Devon and Somerset (51° 9' N, 3° 34' W; Figure 1). Its climate is subject to a strong maritime influence (Phillips & McGregor 2001), with 30-year (1991–2020) average monthly temperature ranging from 6 °C to 12 °C and average annual precipitation 1441 mm year^{-1} (MetOffice 2025). When compared with more northerly peatland areas, the peatlands of Exmoor are shallow (Grand-Clement *et al.* 2013) with an average peat depth of 33 cm (Bowes 2006). Human activities including burning, drainage and peat cutting are likely to have reduced the peat depth substantially. Domestic peat cutting has occurred since medieval times (Riley 2014) whilst drainage for grazing and agricultural reclamation since 1850 has caused additional extensive damage. The resulting dense network (approximately every 20 m) of small drainage ditches (~ 0.5 m wide by ~ 0.5 m deep) has modified the hydrological structure and

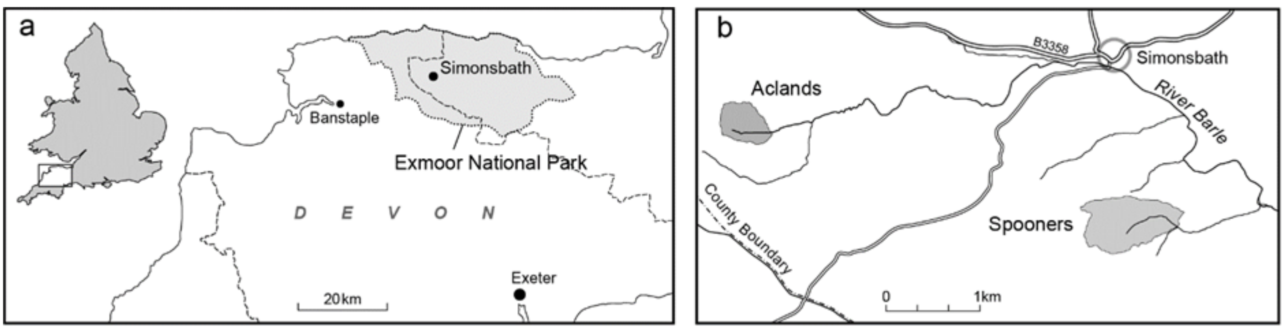

Figure 1. Location map of Exmoor National Park (a) and the two study headwater catchments (b), after Grand-Clement *et al*. (2014).

functioning of the peat (Luscombe 2014, Luscombe *et al.* 2016). The vegetation is largely dominated by *Molinia caerulea* (L.) Moench (purple moor grass; Chambers *et al.* 1999) which is typical of degraded blanket mire and wet heath communities (M25 and H15 in the British National Vegetation Classification (NVC); Rodwell 1991), although other mire and heath species such as *Sphagnum* spp. and *Eriophorum* spp. are present (Drewitt & Manley 1997).

The present study was conducted within two headwater sub-catchments with shallow peat soils (Natural England 2025) known as 'Aclands' (51° 07′ 53.55″ N, 3° 48′ 39.58″ W, 17.9 ha) and 'Spooners' (51° 07′ 26.77″ N, 3° 44′ 55.96″ W, 46.5 ha) (Figure 1), and are considered to be representative of the environmental conditions and damage across the whole of Exmoor (Luscombe 2014). An intensive monitoring programme was set up in 2011 to study effects of peatland rewetting (Grand-Clement *et al.* 2014, Luscombe 2014, Gatis *et al.* 2015, Luscombe *et al.* 2016, Gatis *et al.* 2019, Gatis *et al.* 2020). Average measured peat depth in the Aclands catchment was 0.37 m (min = 0.3 m, max = 0.4 m, n = 4) and 0.46 m in the Spooners catchment (min = 0.29 m, max = 0.71 m, n = 4) (Table 1; Gatis *et al.* 2020). The peat in both catchments was found to be rain-fed, although thermal imagery revealed the presence of a spring in the Spooners catchment (Luscombe *et al*. 2015). The two catchments also present highly humified peat with a von Post index (von Post & Granlund 1926) of H7–H9 (Gatis *et al*. 2019) overlying thin silty clayey palaeosols (~ 15 cm) and the Morte Slates Formation (Carey *et al*. 2020). Although no soil carbon concentrations are available from the experimental catchments, measurements from a neighbouring site (Long Holcombe, 51° 06' 9.53″ N, 3° 45' 23.33″ W) show a mean carbon content (measured by Loss On Ignition) in the organic layer of 55 % (n = 21 up to 30 cm depth), dropping to 12 % in the mineral layer (42 cm depth) (N. Gatis, unpublished data).

The experimental design included pre- and post-rewetting periods, with all drainage ditches on each monitoring site being blocked in March 2013 or 2014 (Table 1) using a combination of peat and/or wood depending on individual ditch characteristics, at a minimum spacing of 7 m (Grand-Clement *et al.* 2015). The lack of a suitable undrained area prevented the establishment of a control catchment.

Data collection

Water quantity

The hydrological monitoring design and data acquisition methods are detailed by Luscombe (2014) and Luscombe *et al*. (2016). Briefly, flow at each of the catchment outlets was gauged using rated flume structures and stage/velocity monitoring equipment (ISCO 2150 area-velocity meter, Teledyne ISCO, USA) (Luscombe 2014). Data were logged every 15 minutes using a remote telemetry system (Adcon Telemetry GmbH, Germany). Data gaps (October 2011 and February 2012 for Aclands; January and February 2012 for Spooners) occurred due to sensor and telemetry malfunctions; these periods were excluded from analysis. Rainfall data were recorded at the same time intervals using a NOMAD Portable Weather station in each catchment (Casella, USA) and a 0.2 mm tipping-bucket raingauge.

Water quality

To capture water quality changes in storm conditions, water samples were collected at the outlet of each catchment on a flow-proportional basis, i.e., at regular intervals of flow increase and decrease during rainfall-runoff events. Automatic pump samplers (Teledyne ISCO, USA) taking up to 24 one-litre samples were linked to pressure transducers located in the channels (Impress Sensors and Systems Ltd., UK) and to a telemetry system (Adcon telemetry GmbH, Germany). Samples were collected as soon as practicable (typically within 48 hours), subsequently

Table 1. Site characteristics and restoration periods for the Aclands and Spooners catchments.

Site	Mean peat depth (m) (n=3)	Contributing area (ha)	Drainage density (m of drain ha^{-1})	Pre-restoration period studied	Post-restoration period studied
Aclands	0.37	17.9	418	Jan 2012 to Mar 2014 (2 years)	Apr 2014 to Dec 2018 (4.5 years)
Spooners	0.46	45.5	176	Mar 2012 to Mar 2013 (1 year)	Apr 2013 to Dec 2018 (5.5 years)

stored at < 4 °C in the dark, and analysed within one week. No events occurred during periods of drought and, therefore, no samples were collected in June–July 2013, July 2014 and September 2014 at Aclands or in July 2013 and July 2014 at Spooners. All samples were syringe filtered using Whatman WCN 0.45 µm filter papers (Wallage & Holden 2010) prior to analysis for pH, DOC and colour.

Laboratory analysis

DOC was measured by UV spectrometry using a TriOS ProPS analyser (TriOS GmbH, Germany). UV-vis absorbance measurements at 254 nm and colour measurements at 400 nm were performed by UV–Vis spectrometry (Unicam UV4-100 analyser, Thermo-Fisher Scientific, UK). The following metrics were calculated as proxies for DOC composition (e.g. aromaticity, molecular weight): the colour per carbon unit (Colour/Carbon) was estimated by dividing Abs_{400} by the DOC concentration (Wallage *et al.* 2006) and the Specific UV Absorbance (SUVA) is the quotient of Abs_{254} and DOC concentration (Edzwald & Tobiason 1999).

Quality control

The use of spectroscopy for DOC measurement allows fast and cheap analysis, which is particularly suitable for routine monitoring. However, results have been shown to be affected by land use, management and climate change, especially when based on a single wavelength (Wallage & Holden 2010), and therefore this technique is considered less accurate than chemical analyses. To account for this, results were validated using chemical analysis as follows. Until 2016, selected samples were regularly analysed at the South West Water (SWW) Limited analytical facility, where DOC was measured by thermal oxidation (Hach Lange TOC analyser, USA) and colour was determined by Segmented Flow analysis (Skalar, The Netherlands). After 2016, selected samples were analysed at the University of Exeter by thermal oxidation using a Total Carbon Analyser (Shimadzu TOC-L, Japan) measuring non-purgeable organic carbon (NPOC).

The regression between the two methods showed a significant linear relationship and, therefore, good agreement between all methods, with R^2 values of 0.85 between Spectroscopic and SWW data ($p < 0.05$) and 0.88 between Spectroscopic and NPOC ($p < 0.05$). However, the Lin's concordance coefficient indicated consistent over-estimation by spectroscopy compared to all chemical methods, with values of 0.33 (95 % confidence interval 0.26–0.4) for the comparison between Spectroscopic and SWW, and 0.07 for the comparison between Spectroscopic and the thermal oxidation method (95 % confidence interval 0.05–0.09). Therefore, linear regressions were applied to the data to correct and recalculate the DOC measurements used for data analysis thereafter. In addition, the relationship between colour (Abs_{400}) and DOC (measured by the spectroscopic method) was explored (see Appendix).

Data analysis

Event separation

Rainfall and flow features from sub-hourly time series were identified, paired and extracted (along with descriptive metrics) using a semi-automated rule-based approach. This technique (Ashe 2024) was based on methods initially developed by Deasy *et al*. (2009), Glendell *et al*. (2014) and Luscombe (2014), and implemented by Puttock *et al*. (2021), Graham *et al*. (2022) and Gatis *et al*. (2023).

To summarise, flow data were pre-processed as input for quality control (i.e., cleaned of noise, outliers and other periods of anomalous observations). Baseflow/quickflow was estimated by implementing flow separation on the padded time series (2880 reflected values) with seven passes of a single parameter recursive digital filter (alpha value of 0.98) after Ladson *et al*. (2013). Rainfall events for the period of interest were identified as periods of rainfall over the median categorised as either continuous (rainfall occurring on consecutive time steps) or isolated. The span for minimum permitted gaps between periods of continuous rainfall was set through visual inspection, and rainfall event periods separated by less than this span (90 minutes) were aggregated.

To adapt thresholds for interannual variation and seasonality of baseflow, flow events were delineated using the digitally filtered quickflow on thresholds values representing i) the local rate of change, ii) a global baseline threshold, and iii) a global event magnitude threshold. Where a response event was paired with the same initiating rainfall as the previous one, it was assumed that rainfall contributing to the new event occurred during the falling limb of the previous one, and the event window was bounded by the peak of the previous flow response. Event and antecedent rainfall metrics were calculated for each event window and erroneous events were identified and removed through visual inspection of the time series and distribution of metrics calculated. Overall, 197 pre-rewetting events at Aclands and 158 at Spooners were extracted (Table 2). The corresponding numbers of post-rewetting events were 318 for Aclands and 439 for Spooners.

Water quantity events
A parametric analysis of variance (one way ANOVA and "least significant difference" *post hoc* testing) was performed on the flow data (Q_t and Q_p) from each site. Appropriate transformation (log10) was performed to ensure normal distribution of the data. This testing examined the existence and significance of the relationship between any given pair of data (Q_t or Q_p distributions).

Water quality events
The delineated events described above were applied to the water quality dataset collected throughout the period of observations. This analysis focused on storm flow only. Therefore, samples falling outside of the delineated events were not considered. To ensure good representation of water quality during the events selected, the analysis was further restricted to events during which at least three samples were taken covering an accumulated discharge of at least 70 % of the total discharge. In total, 26 events at Aclands and 27 at Spooners were used (Table 2).

DOC was averaged on an event basis using Flow Weighted Mean Concentrations (*FWMC*) to account for variations in flow and number of samples between events (Dinsmore *et al.* 2013):

$$FWMC = \frac{\sum(C_i \times t_i \times Q_i)}{\sum(t_i \times Q_i)} \qquad [1]$$

where DOC (*FWMC*) is expressed in mg L^{-1}, C_i is the instantaneous concentration (mg L^{-1}), t_i is the time step between samples (s) and Q_i the instantaneous discharge (m^3). Other water quality metrics (i.e. Abs_{400}, Colour/Carbon, pH and SUVA) were averaged per event.

Each DOC concentration (C_i) was multiplied by its corresponding discharge value (Q_i), giving instantaneous load, and further averaged over the time period of the event. For each event, we calculated the total loads over the time sampled using the RiverLoad package in RStudio (Nava *et al.* 2019) using Method 5 (Walling & Webb 1985, Littlewood 1992):

$$F = K \times Q_r \times \left(\frac{\sum_{i=1}^{n} C_i \times Q_i}{\sum_{i=1}^{n} Q_i}\right) \qquad [2]$$

where *F* defines the total DOC load for the time period (g), *K* is the time between samples (s), Q_r the mean quickflow discharge from the continuous record throughout the event (m^3), Q_i the instantaneous discharge (m^3), C_i the instantaneous concentration (mg L^{-1}) and *n* the number of samples. Loads were further normalised by total event rainfall to allow inter-annual comparisons under varying climatic conditions.

Statistical analysis was undertaken in R version 4.0.5 with data formatting, summary statistics and plotting conducted using the Tidyverse package (Wickham *et al.* 2019). Where data were normally distributed or could be successfully (log10) transformed, statistical significance was assessed using a Student's t-Test. Alternatively, a Mann-Whitney test was performed on data that were not normally distributed. When boxplots are used to illustrate the results, the top of each box represents the third quartile and the bottom represents the first quartile; the box is separated by the median value; the whiskers extend to the lowest and highest values within the 1.5 interquartile ranges; points outside the whiskers are outliers; and the small 'x' indicates the mean value.

RESULTS

Hydrological and climatic conditions

The 2010–2018 record of annual rainfall totals for the Spooners catchment (Figure 2) shows important interannual differences. In particular, the pre-rewetting period includes an unusually wet year (2012) with 1901 mm of rainfall, the 30-year (1991–2020) average being 1441 mm (MetOffice 2025). In contrast, the post-rewetting period was consistently drier than the long-term average with 2017 and 2018 being particularly dry, each with 958 mm of rainfall.

Table 2. Number of events separated and used for hydrological analysis and water quality analysis at Aclands and Spooners pre- and post-restoration.

	Hydrological events		Water quality events	
Site	Pre-restoration	Post-restoration	Pre-restoration	Post-restoration
Aclands	197	318	8	18
Spooners	158	439	8	19

In the Spooners catchment, all rainfall-runoff events normalised by rainfall generated significantly less total discharge (Figure 2B) and lower peak discharge (Figure 3B) post-rewetting ($p < 0.001$). For smaller rainfall events (< 10 mm), rewetting reduced total discharge by 32 % ($p \leq 0.001$) and peak discharge by 29 % ($p \leq 0.001$). The reduction in peak and total event discharge was less significant for larger rainfall events (> 10 mm) than for the smaller ones, with $p = 0.002$ for total discharge and $p = 0.036$ for peak discharge.

In the smaller Aclands catchment the rewetting response for all rainfall/runoff events normalised by rainfall was neither significant nor negative. For larger rainfall events (> 10 mm), total event discharge (Figure 2A) and peak event discharge (Figure 3A) pre- and post-rewetting were not significantly different ($p > 0.05$). For smaller rainfall events (< 10 mm), total and peak discharge increased post-rewetting (Figure 4).

Water quality change

There was no significant change in mean DOC concentrations post-rewetting ($p > 0.05$ for both sites) (Figure 5A), with mean values of 7.3 mg L^{-1} and 7.1 mg L^{-1} at Aclands before and after ditch blocking, respectively, and a mean of 10.2 mg L^{-1} prior to ditch blocking and 8.2 mg L^{-1} after ditch blocking at Spooners (Table 3). Similarly, for colour, the change in mean Absorbance before and after rewetting (Figure 5) was not statistically significant ($p > 0.05$) for either site. To account for differences in number of events monitored and rainfall experienced between the pre- and post-rewetting periods, loads were normalised by rainfall. At Aclands, mean normalised loads per event (Table 3, Figure 5C) ranged from 0.6 kg mm^{-1} to 0.9 kg mm^{-1}, whilst the normalised loads at Spooners ranged from 4.6 to 2.6 kg mm^{-1}.

No statistically significant changes between pre- and post-rewetting data for Colour/Carbon (Table 3) and SUVA (Table 3, Figure 6) were found for either site. Mean SUVA values measured before and after ditch blocking changed from 4.6 to 4.8 at Aclands and from 4.6 to 4.7 at Spooners.

DISCUSSION

H1: Ditch blocking will reduce storm runoff through a modification of the hydrological structure and function

As for many other rewetting interventions, the aim was to return the hydrological functioning of the peatlands to something analogous to that of a pristine blanket bog complex (Lindsay 2010). Variations in annual weather patterns meant that the post-rewetting period was drier than the pre-rewetting period (Figure 2). This difference is manifest in the rainfall-runoff events studied, and illustrates a limitation of the “before-and-after” monitoring method.

Whilst the difference in hydrological inputs could obscure some results of the rewetting process, we limit this effect by analysing individual rainfall-runoff events pre- and post-rewetting and normalising the results by rainfall. No consideration is given to changes in baseflow and, therefore, to the catchment water balance. At the smaller Aclands catchment (with shallower mean peat depth), no

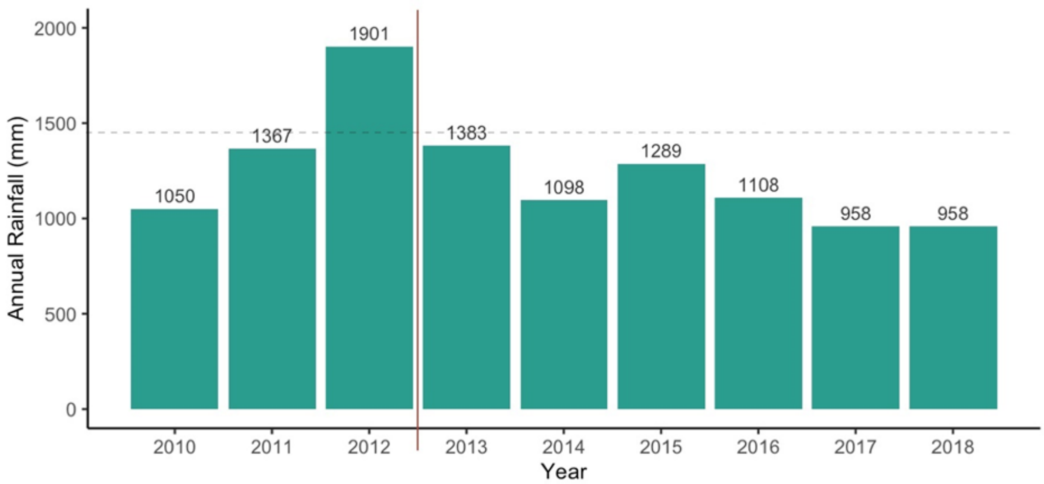

Figure 2. Annual rainfall totals for the Spooners catchment from 2010 to 2018. The horizontal dashed line indicates the 30-year average for 1991–2020 (MetOffice 2025), and the solid red vertical line highlights the restoration period.

significant change was observed in either total discharge (Figure 3A) or peak discharge (Figure 4A) (Luscombe 2014). However, significant changes in total rainfall, total runoff and peak runoff were observed at the larger Spooners catchment. Here, significant reductions in peak flow and baseflow were particularly evident for smaller rainfall events (Figure 4B), indicating that rewetting had driven an important change in the overall runoff behaviour of the catchment, perhaps owing to increased water storage in the restored peatland ponds.

As found in other studies (e.g., Allott *et al.* 2009), our data indicate a spatially complex response to rewetting. At Spooners, where the drainage system was more established and effective, drain-blocking has caused a more profound change in the hydrological connectivity of the shallow peat. In addition, increased pool storage behind drain blocks will lead to increased temporary storage in the landscape, even though the peat has not been uniformly rewetted (Goulsbra *et al.* 2014, Luscombe *et al.* 2016). This increased storage has been shown

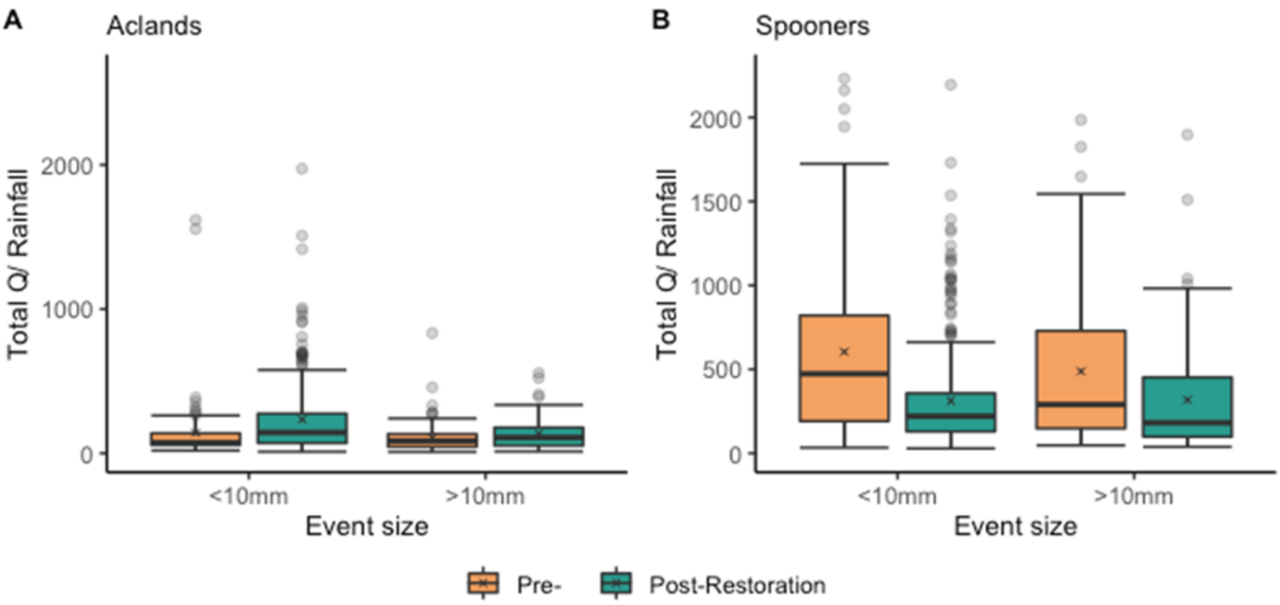

Figure 3. Total discharge (Total Q) normalised by total rainfall (m^3 mm^{-1}) for small events (total rainfall < 10 mm) and large events (total rainfall > 10 mm) pre- and post-restoration for Aclands (A) and Spooners (B).

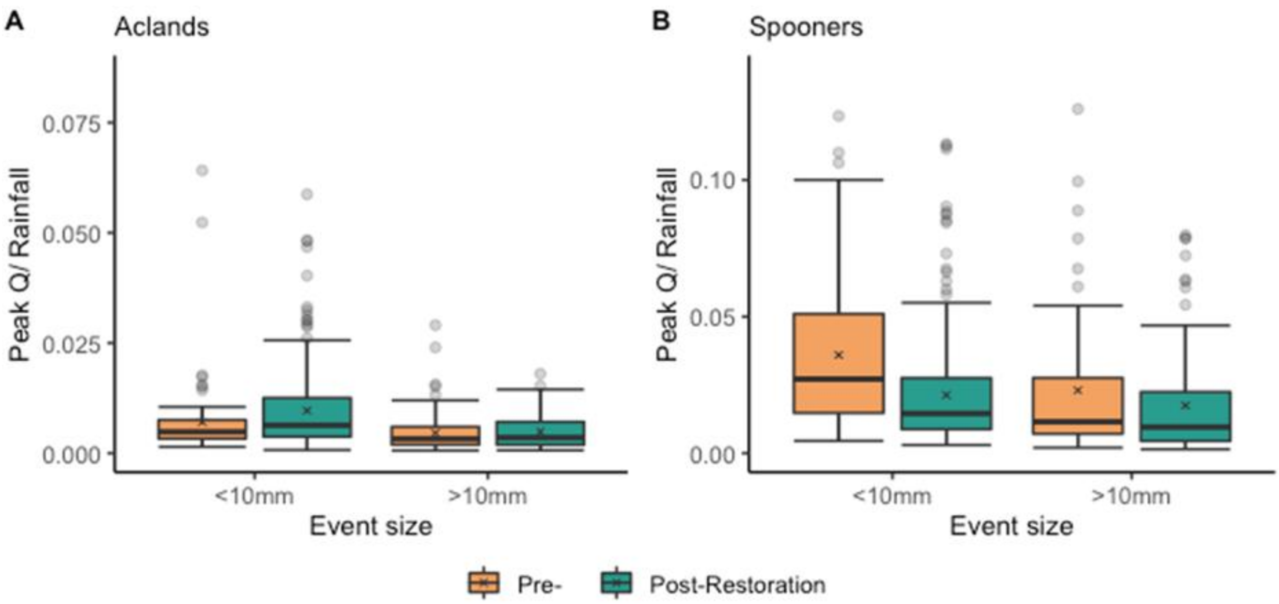

Figure 4. Peak discharge (Peak Q) normalised by total rainfall (m^3 s^{-1} mm^{-1}) for small events (total rainfall < 10 mm) and large events (total rainfall > 10 mm) pre- and post-restoration for Aclands (A) and Spooners (B).

to bring benefit in terms of natural flood management (NFM) by contributing to a reduction in flood risk at other locations downstream (e.g., Allott *et al.* 2019). However, similar interventions at the Aclands site failed to reproduce this effect. This may be due to the pre-rewetting drainage system being shallow and vegetated, with poor internal connectivity to the main channel (Luscombe *et al.* 2014), which could limit the potential additional effect of peat blocks in impeding the runoff of rainfall. In addition, the overall distribution of rainfall event magnitude was notably different, and the contributing area of the catchment was less than half that at Spooners.

H2: Ditch blocking will lead to a significant decrease in DOC and colour concentrations in storm derived runoff

Previously published evidence has pointed towards a short-term increase in DOC concentrations after peatland restoration (e.g., Wallage *et al.* 2006, Worrall *et al.* 2007, Gatis *et al.* 2023), followed by a longer-term decrease (Turner *et al.* 2013). The results presented here show that the rewetting on Exmoor has not led to a statistically significant change in DOC concentrations at either of the monitored sites, five years on. This observation concurs with other recent studies stressing a lack of consistent response and water quality improvement after interventions on peatlands (Evans *et al.* 2018, Williamson *et al.* 2020, Gatis *et al.* 2023). The range of mean event DOC concentration across our sites and study periods was 2–15 mg L^{-1} (Table 3), which is lower than concentrations reported for other sites in the UK. Where higher concentrations have been measured (Turner *et al.* 2013, Evans *et al.* 2018) the peats were deeper (e.g., > 1m deep) with different plant communities involving *Eriophorum* spp., *Calluna vulgaris* and *Sphagnum* spp. Additionally, these peats may have had a lower degree of humification, which has been shown to lead to higher DOC concentrations (Kalbitz & Geyer 2002). However, the data presented here were averaged per rainfall-runoff event and occasional DOC peaks were still recorded (e.g., the maximum value ever recorded at Spooners pre-rewetting was 42 mg L^{-1}). The DOC concentrations measured during rainfall-runoff events are also higher than concentrations measured on Spooners at monthly intervals during a low flow period in 2016–2017 by Ritson *et al.* (2019) (mean of 3.2 mg L^{-1}), which confirms increased release of DOC during rainfall events compared to low or baseflow conditions. As suggested by Gatis *et al.* (2023), the disparity in DOC concentrations between different geographical areas and peat depths highlights the need for caution when setting expectations on the potential short-term effect of rewetting on water quality.

It is likely that the lack of change in DOC concentrations observed on Exmoor is due to the limited effect of rewetting on the shallow peat and vegetation. Indeed, although ditch blocking has caused a decrease in depth to water table in the areas closer to the drainage features (Luscombe 2014, Luscombe *et al.* 2016), this effect has not been

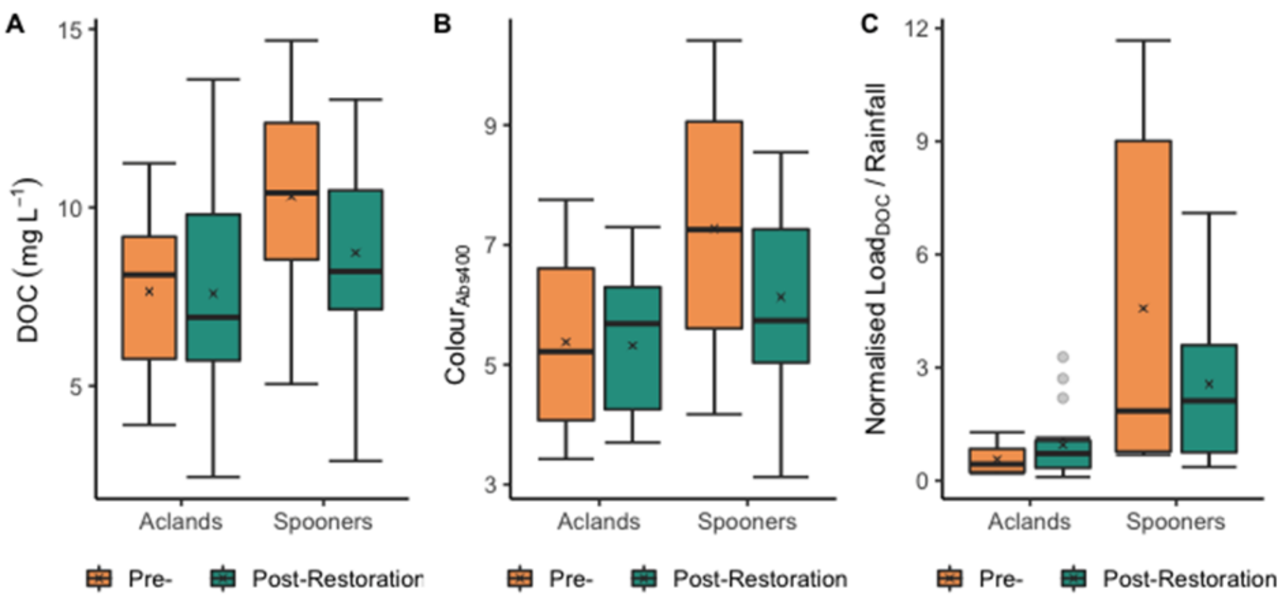

Figure 5. (A) Dissolved organic carbon (DOC) concentrations (mg L^{-1}); (B) Absorbance at 400 nm; and (C) rainfall normalised DOC loadings for Aclands and Spooners, pre- and post-restoration.

uniform for the catchment monitored (Gatis *et al.* 2015, Brazier *et al.* 2020) or brought the water tables up to the ground surface. In particular, previous studies on the same sites and over the same timescale have found that the small increase in water table had not been sufficient to significantly change vegetation species composition, and therefore substantially alter the C balance (Gatis *et al.* 2020). In turn, the spatially limited raising of the water table is unlikely to have reduced the depth of peat subject to aerobic conditions and has therefore not significantly affected decomposition (Gatis *et al.* 2020). This is confirmed by the lack of significant change in Colour/Carbon and the reduction in SUVA. All of this evidence suggests that rewetting has not profoundly altered the processes (or locations) producing DOC in Exmoor peat, and has not led to the production of more labile and fresh DOC, as has

Table 3. Pre- and post-restoration event summary statistics for dissolved organic carbon (DOC; mg L^{-1}), absorbance at 400 nm (Abs_{400}), DOC load normalised by rainfall (kg mm^{-1}) to account for differences between pre- and post-restoration rainfall, Colour (Abs_{400})/Carbon (DOC) and SUVA (Abs_{254}/DOC). No statistical differences were observed. #15 events for Abs_{400}.

	catchment	Aclands		Spooners	
Metric	pre- or post-restoration	pre-	post-	pre-	post-
	number of events	8	18#	8	19
DOC (mg L^{-1})	mean	7.3	7.1	10.2	8.2
	range	3.6–11	2.4–13.7	4.8–14.7	2.8–12
Abs_{400}	mean	5.4	5.3	7.3	6.1
	range	3.4–7.8	3.7–7.3	4.2–10.4	3.1–8.6
Normalised DOC load (kg mm^{-1})	mean	0.6	0.9	4.6	2.6
	range	0.2–1.3	0.1–3.3	0.7–11.7	0.4–7.1
Colour (Abs_{400})/Carbon (DOC)	mean	0.76	0.76	0.73	0.77
	range	0.69–0.96	0.71–0.89	0.68–0.86	0.67–1.1
SUVA (Abs_{254}/DOC)	mean	4.64	4.81	4.65	4.7
	range	4.22–5.39	4.4–5.28	4.2–5	4.2–5.4

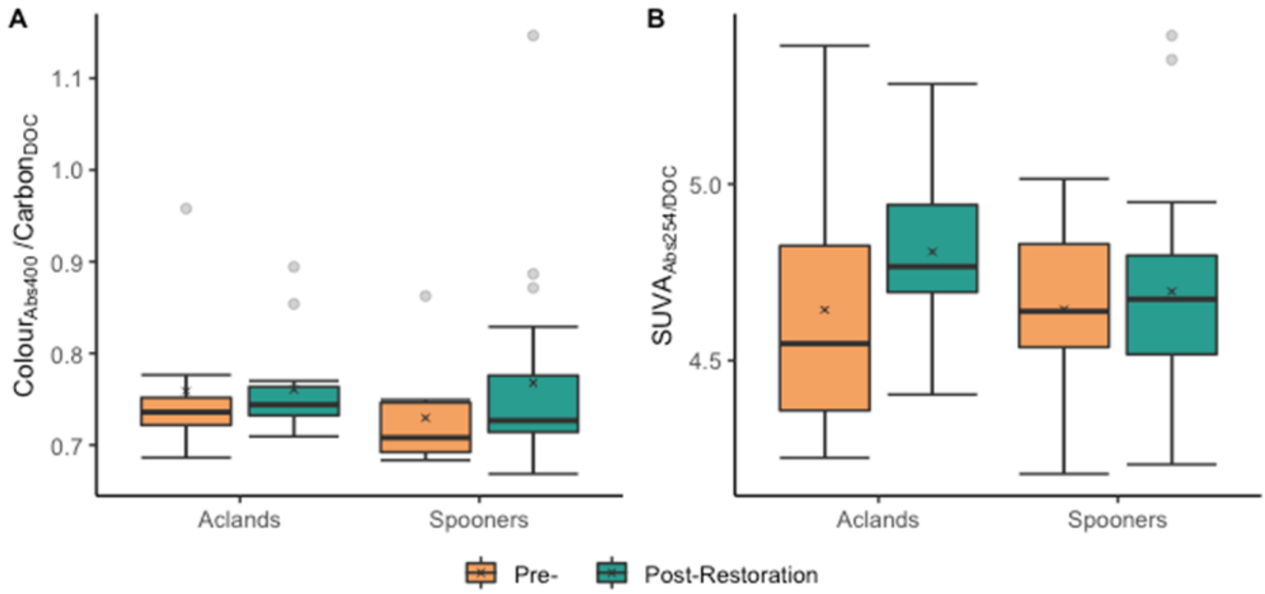

Figure 6. Colour/Carbon (A) and SUVA (B) for Aclands and Spooners pre- and post-restoration.

been observed after rewetting elsewhere (e.g., by Höll *et al.* 2009). Similar conclusions were reached following the restoration of cutaway peatland in Canada where the water table remained below the cutover layer and unconnected to the surface (McCarter & Price 2015, Strack *et al.* 2015). Additionally, temperature (Kirschbaum 1995, Freeman *et al.* 2001, Koehler *et al.* 2009, Dinsmore *et al.* 2013) and dryness (Glatzel *et al.* 2006) are established factors driving decomposition and DOC production, as confirmed by pre-rewetting analysis of DOC concentrations with a clear seasonal trend (Grand-Clement *et al*. 2014). The inter-annual variability in climatic variables could potentially compensate for, or accentuate, any change in the catchment, and therefore the effect of ditch blocking (Turner *et al.* 2013); such annual variability may be particularly important herein, where exceptional meteorological conditions have led to the occurrence of one particularly wet year (2012) before ditch blocking, followed by two consecutive dry years (2013 and 2014) following rewetting. It is therefore likely that low rainfall might have tempered the effect of ditch blocking at the catchment scale, and promoted the continuation of aerobic decomposition and the production of DOC.

H3: Ditch blocking will reduce the export of DOC at the headwater catchment scale during high flow events

Some studies examining DOC exports and loads post-restoration have shown a reduction in exports due to decreased flow rather than lowered concentrations (e.g. O'Brien *et al.* 2008, Gibson *et al.* 2009), whilst others have not observed any significant change (e.g. Evans *et al.* 2016, Gatis *et al.* 2023). The present results indicate the latter scenario, despite the fact that some of the hydrological functioning was restored at Spooners. It is worth noting, however, that the water quality analysis was based on a subset of events (n between 8 and 19) compared to the hydrological analysis (n between 158 and 439) which shows a larger, arguably more representative picture. Additionally, normalising by rainfall allows the changes in load to be considered irrespective of the high variation in rainfall for monitored events pre- and post-rewetting (Figure 2). Positively, this indicates that ditch blocking activities have not contributed to a significant increase in DOC concentrations downstream as found elsewhere (e.g. Worrall *et al.* 2007, Waddington *et al.* 2008, Wilson *et al.* 2011a, Gatis *et al.* 2023). It is likely that a longer post-intervention period might be needed to see reductions in DOC concentrations. However, the high variability in the change observed between studies highlighted by Evans *et al*. (2016) also confirms the increasing realisation that such outcomes should not be considered systematic (Evans *et al.* 2018). The investigation of DOC during rainfall/runoff would also benefit greatly from recent improvements in technology. For instance, the use of field-based continuous monitoring equipment measuring fDOM as a surrogate for DOC, would enable researchers to gain a more thorough understanding of change following the rewetting process and of the inter- and intra-event dynamics that characterise that change.

Progress so far and prospects for the future

Overall, these results offer an insight into what can be expected from the rewetting of shallow, climatically marginal peatlands that have been densely drained and degraded. On Exmoor, the process of ditch blocking has delivered some positive outcomes. Most notably, changes to the hydrology of the peat in one of the headwater catchments studied have been a success, altering the connectivity and the flow of water during some storm events, with reduced peak flows and total flows observed as a function of ditch blocking. However, this effect has not been uniform across the sites investigated. Moreover, ditch blocking does not seem to have fully restored the ecohydrological functioning of the peatland, five years on. In particular, ditch blocking has not led to a statistically significant reduction in DOC concentrations or to a reduction in loads leaving the headwater catchments. These results fit with the inconsistency in short-term water quality responses to restoration reported by different scientific studies, and would therefore particularly benefit from an additional monitoring period aiming to assess longer-term changes in water quality, as it may well be that more time is required before DOC concentrations and loads are lowered.

Although the general aim of restoration is to achieve a return to functioning, carbon accumulating peatlands, the improvement of water quality downstream of blanket bogs is also an important objective of the ditch blocking process and its funders, especially when located upstream of drinking water catchment areas. Overall, the results presented here suggest that ditch blocking alone may not be sufficient to alter the hydrological functioning of these shallow peatlands, or to bring the desired changes in water quality. Instead, other techniques such as *Sphagnum* reintroduction may be needed to lead to a significant change from *Molinia caerulea* dominated communities to the peat forming ones that were historically present on Exmoor, as evidenced by archaeological studies.

Even in the absence of these changes in the time considered, the benefits of ditch blocking on a number of other ecosystem services, such as flood alleviation and improved resilience, make it an essential process. Considering the uncertainty of the change brought by rewetting as well as current changes in climate, such benefits ensure that the investment in restoration of shallow, marginal peatlands is justified and worthwhile, and should actually become the aim of the process.

ACKNOWLEDGEMENTS

The Mires on the moors project was funded by South West Water Limited, Natural England and the Environment Agency.

AUTHOR CONTRIBUTIONS

EGC carried out field and lab work, data analysis and interpretation for the water quality part, and was the lead author of the manuscript. DJL carried out fieldwork and data analysis for the hydrology part, contributed to the interpretation and contributed to the writing of the manuscript. PB and JA carried out field and lab work, and contributed to the data analysis and interpretation; NG participated in field work and contributed to the interpretation. MA and DS provided the funding and access to site, as well as technical assistance in the peatland ditch blocking process. REB was the Principal Investigator for the project, and as such obtained the funding and conceptualised the experiment. All authors reviewed the manuscript and have contributed to revisions after submission.

REFERENCES

Alderson, D.M., Evans, M.G., Shuttleworth, E.L., Pilkington, M., Spencer, T., Walker, J., Allott, T.E.H. (2019) Trajectories of ecosystem change in restored blanket peatlands. *Science of The Total Environment*, 665, 785–796. https://doi.org/10.1016/j.scitotenv.2019.02.095

Allott, T., Evans, M.G., Lindsay, J.B., Agnew, C., Freer, J.E., Jones, A., Parnell, M. (2009) *Water Tables in Peak District Blanket Peatlands*. Moors for the Future Report No 17, Moors for the Future Partnership, Edale UK, 49 pp.

Allott, T.E.H., Auñón, J., Dunn, C., Evans, M.G., Labadz, J., Lunt, P., MacDonald, M., Nisbet, Thomas, Owen, R., Pilkington, M., Proctor, S., Shuttleworth, E.L., Walker, J. (2019) *Peatland Catchments and Natural Flood Management*. Report to the IUCN UK Peatland Programme's Commission of Inquiry on Peatlands Update, IUCN UK Peatland Programme, Edinburgh UK, 43 pp.

Armstrong, A., Holden, J., Kay, P., Francis, B., Foulger, M., Gledhill, S., McDonald, A.T., Walker, A. (2010) The impact of peatland drain-blocking on dissolved organic carbon loss and discolouration of water; results from a national survey. *Journal of Hydrology*, 381(1–2), 112–120. https://doi.org/10.1016/j.jhydrol.2009.11.031

Artz, R.E.E., Couwenberg, J., Evans, C.D., Moxey, A., Smyth, M.A. (2018) *Peatland Restoration - A Comparative Analysis of the Costs and Merits of Different Restoration Methods*. ClimateXChange, Edinburgh UK, 36 pp. Online at: https://www.climatexchange.org.uk/wp-content/uploads/2023/09/peatland-restoration-methods-a-comparative-analysis.pdf, accessed 25 Oct 2025.

Ashe, J. (2024) *Extracting Value from Patterns in Routinely Collected, High-Frequency Water Quality Data in Rivers Supplying Drinking Water Treatment Works*. PhD thesis, University of Exeter, Exeter UK, 59 pp.

Bain, C.G., Bonn, A., Stoneman, R., Chapman, S. and 21 others (2011) *IUCN UK Commission of Inquiry on Peatlands*, IUCN UK Peatland Programme, Edinburgh UK, 109 pp. ISBN 978-0-9570572-1-0

Billett, M.F., Charman, D., Clark, J.M., Evans, C. D., Evans, M.G., Ostle, N.J., Worrall, F., Burden, A., Dinsmore, K., Jones, T., McNamara, N., Parry, L., Rowson, J.G., Rose, R. (2010) Carbon balance of UK peatlands: Current state of knowledge and future research challenges. *Climate Research*, 45, 13–29. https://doi.org/10.3354/cr00903

Blier-Langdeau, A., Guêné-Nanchen, M., Hugron, S., Rochefort, L. (2022) The resistance and short-term resilience of a restored extracted peatland ecosystems post-fire: An opportunistic study after a wildfire. *Restoration Ecology*, 30(4), e13545. https://doi.org/10.1111/rec.13545

Blodau, C., Siems, M. (2012) Drainage-induced forest growth alters belowground carbon biogeochemistry in the Mer Bleue bog, Canada. *Biogeochemistry*, 107(1), 107–123. https://doi.org/10.1007/s10533-010-9535-1

Bonn, A., Holden, J., Parnell, M., Worrall, F., Chapman, P.J., Evans, C.D., Termansen, M., Beharry-Borg, N., Acreman, M.C., Rowe, E., Emmett, B.A., Tsuchiya, A. (2010) *Ecosystem Services of Peat - Phase 1*. Report on CEH Project

Number CO3758 T1, Defra, London, 140 pp. Online at: https://nora.nerc.ac.uk/id/eprint/9360, accessed 25 Oct 2025.

Bowes, A.C. (2006) *Exmoor Blanket Bog Inventory and Restoration Plan for English Nature*. Master's degree project submitted to the Faculty of Environmental Design, University of Calgary AB, Canada, 163 pp.

Brazier, R.E., Angus, M., Benaud, P., Gatis, N., Luscombe, D.J., Anderson, K., Ashe, J., Barrowclough, C., Carless, D., Freeman, G., Gillard, M., Grand-Clement, E., Hand, A., Malone, E., McAleer, A., Smith, D. (2020) *Mires on the Moors: Science and Evidence Report 2020*. University of Exeter, Exeter UK, 47 pp.

Caporn, S.J.M., Rosenburgh, A.E., Keightley, A.T., Hinde, S.L., Riggs, J.L., Buckler, M., Wright, N. A. (2018) *Sphagnum* restoration on degraded blanket and raised bogs in the UK using micropropagated source material: A review of progress. *Mires and Peat*, 20, 09. https://doi.org/10.19189/MAP.2017.OMB.306

Carey, C., White, H., Macphail, R., Bray, L., Scaife, R., Coyle McClung, L., Macleod, A. (2020) Analysis of prehistoric brown earth paleosols under the podzol soils of Exmoor, UK. *Geoarchaeology*, 35, 772–799. https://doi.org/10.1002/gea.21789

Chambers, F.M., Mauquoy, D., Todd, P.A. (1999) Recent rise to dominance of *Molinia caerulea* in environmentally sensitive areas: new perspectives from palaeoecological data. *Journal of Applied Ecology*, 36(5), 719–733. https://doi.org/10.1046/j.1365-2664.1999.00435.x

Clark, J.M., Lane, S.N., Chapman, P.J., Adamson, J.K. (2007) Export of dissolved organic carbon from an upland peatland during storm events: Implications for flux estimates. *Journal of Hydrology*, 347(3–4), 438–447. https://doi.org/10.1016/j.jhydrol.2007.09.030

Clutterbuck, B., Yallop, A.R. (2010) Land management as a factor controlling dissolved organic carbon release from upland peat soils 2: Changes in DOC productivity over four decades. *Science of The Total Environment*, 408(24), 6179–6191. https://doi.org/10.1016/j.scitotenv.2010.08.038

Deasy, C., Quinton, J.N., Silgram, M., Bailey, A.P., Jackson, B., Stevens, C.J. (2009) Mitigation options for sediment and phosphorus loss from winter-sown arable crops. *Journal of Environmental Quality*, 38, 2121–2130. https://doi.org/10.2134/jeq2009.0028

de Wit, H., Stoddard, J.L., Monteith, D.T., Sample, J.E., Austnes, K., Couture, S., Fölster, J., Higgins, S.N., Houle, D., Hruška, J., Krám, P., Kopáček, J., Paterson, A.M., Valinia, S., Van Dam, H., Vuorenmaa, J., Evans, C.D. (2021) Cleaner air reveals growing influence of climate on dissolved organic carbon trends in northern headwaters. *Environmental Research Letters*, 16, 104009. https://doi.org/10.1088/1748-9326/ac2526

Dinsmore, K.J., Billett, M.F., Dyson, K.E. (2013) Temperature and precipitation drive temporal variability in aquatic carbon and GHG concentrations and fluxes in a peatland catchment. *Global Change Biology*, 19(7), 2133–2148. https://doi.org/10.1111/gcb.12209

Drewitt, A.L., Manley, V.J. (1997) *The Vegetation of the Mountains and Moorlands of England: National Assessment of Significance*. English Nature Research Reports (ENNR) 218, Uplands Team, English Nature, Peterborough UK, 32 pp. plus Appendices. Online at: https://publications.naturalengland.org.uk/publication/129033, accessed 26 Oct 2025.

Edzwald, J.K., Tobiason, J.E. (1999) Enhanced coagulation: US requirements and a broader view. *Water Science and Technology*, 40(9), 63–70. https://doi.org/10.2166/wst.1999.0444

Evans, C.D., Monteith, D.T., Cooper, D.M. (2005) Long-term increases in surface water dissolved organic carbon: Observations, possible causes and environmental impacts. *Environmental Pollution*, 137(1), 55–71. https://doi.org/10.1016/j.envpol.2004.12.031

Evans, C.D., Renou-Wilson, F., Strack, M. (2016) The role of waterborne carbon in the greenhouse gas balance of drained and re-wetted peatlands. *Aquatic Sciences*, 78(3), 573–590. https://doi.org/10.1007/s00027-015-0447-y

Evans, C.D., Peacock, M., Green, S.M., Holden, J., Chapman, P.J., Lebron, I., Callaghan, N., Grayson, R., Baird, A.J. (2018) The impact of ditch blocking on fluvial carbon export from a UK blanket bog. *Hydrological Processes*, 32(13), 2141–2154. https://doi.org/10.1002/hyp.13158

Frank, S., Tiemeyer, B., Gelbrecht, J., Freibauer, A. (2014) High soil solution carbon and nitrogen concentrations in a drained Atlantic bog are reduced to natural levels by 10 years of rewetting. *Biogeosciences*, 11(8), 2309–2324. https://doi.org/10.5194/bg-11-2309-2014

Freeman, C., Evans, C.D., Monteith, D.T., Reynolds, B., Fenner, N. (2001) Export of organic carbon from peat soils. *Nature*, 412(6849), 785. https://doi.org/10.1038/35090628

Gallego-Sala, A.V., Clark, J.M., House, J.I., Orr, H.G., Prentice, I.C., Smith, P., Farewell, T., Chapman, S.J. (2010) Bioclimatic envelope model of climate change impacts on blanket peatland distribution in Great Britain. *Climate Research*, 45, 151–162. https://doi.org/10.3354/cr00911

Gatis, N., Luscombe, D.J., Grand-Clement, E., Hartley, I. P., Anderson, K., Smith, D., Brazier, R. E. (2015) The effect of drainage ditches on vegetation diversity and CO_2 fluxes in a *Molinia caerulea*-dominated peatland. *Ecohydrology*, 9, 407–420. https://doi.org/10.1002/eco.1643

Gatis, N., Grand-Clement, E., Luscombe, D.J., Hartley, I. P., Anderson, K., Brazier, R.E. (2019) Growing season CO_2 fluxes from a drained peatland dominated by *Molinia caerulea*. *Mires and Peat*, 24, 31. https://doi.org/10.19189/MAP.2019.OMB.STA.1812

Gatis, N., Luscombe, D.J., Benaud, P., Ashe, J., Grand-Clement, E., Anderson, K., Hartley, I.P., Brazier, R.E. (2020) Drain blocking has limited short-term effects on greenhouse gas fluxes in a *Molinia caerulea* dominated shallow peatland. *Ecological Engineering*, 158, 106079. https://doi.org/10.1016/j.ecoleng.2020.106079

Gatis, N., Benaud, P., Anderson, K., Ashe, J., Grand-Clement, E., Luscombe, D.J., Puttock, A., Brazier, R.E. (2023) Peatland restoration increases water storage and attenuates downstream stormflow but does not guarantee an immediate reversal of long-term ecohydrological degradation. *Scientific Reports*, 13(1), 15865. https://doi.org/10.1038/s41598-023-40285-4

Gibson, H.S., Worrall, F., Burt, T.P., Adamson, J.K. (2009) DOC budgets of drained peat catchments: Implications for DOC production in peat soils. *Hydrological Processes*, 23, 1901–1911. https://doi.org/10.1002/hyp.7296

Glatzel, S., Lemke, S., Gerold, G. (2006) Short-term effects of an exceptionally hot and dry summer on decomposition of surface peat in a restored temperate bog. *European Journal of Soil Biology*, 42(4), 219–229. https://doi.org/10.1016/j.ejsobi.2006.03.003

Glendell, M., Extence, C., Chadd, R., Brazier, R.E. (2014) Testing the pressure-specific invertebrate index (PSI) as a tool for determining ecologically relevant targets for reducing sedimentation in streams. *Freshwater Biology*, 59(2), 353–367. https://doi.org/10.1111/fwb.12269

Glenk, K., Faccioli, M., Martin-Ortega, J., Schulze, C., Potts, J. (2021) The opportunity cost of delaying climate action: Peatland restoration and resilience to climate change. *Global Environmental Change*, 70, 102323. https://doi.org/10.1016/j.gloenvcha.2021.102323

Goulsbra, C., Evans, M., Lindsay, J. (2014) Temporary streams in a peatland catchment: Pattern, timing, and controls on stream network expansion and contraction. *Earth Surface Processes and Landforms*, 39(6), 790–803. https://doi.org/10.1002/esp.3533

Graham, H.A., Puttock, A.K., Elliott, M., Anderson, K., Brazier, R.E. (2022) Exploring the dynamics of flow attenuation at a beaver dam sequence. *Hydrological Processes*, 36(11), e14735. https://doi.org/10.1002/hyp.14735

Grand-Clement, E., Anderson, K., Smith, D.M., Luscombe, D., Gatis, N., Ross, M., Brazier, R.E. (2013) Evaluating ecosystem goods and services after restoration of marginal upland peatlands in south-west England. *Journal of Applied Ecology*, 50, 324–334. https://doi.org/10.1111/1365-2664.12039

Grand-Clement, E., Luscombe, D.J., Anderson, K., Gatis, N., Benaud, P., Brazier, R.E. (2014) Antecedent conditions control carbon loss and downstream water quality from shallow, damaged peatlands. *Science of The Total Environment*, 493, 961–973. https://doi.org/10.1016/j.scitotenv.2014.06.091

Grand-Clement, E., Anderson, K., Smith, D., Angus, M., Luscombe, D.J., Gatis, N., Bray, L.S., Brazier, R.E. (2015) New approaches to the restoration of shallow marginal peatlands. *Journal of Environmental Management*, 161, 417–430. https://doi.org/10.1016/j.jenvman.2015.06.023

Haapalehto, T.O., Vasander, H., Jauhiainen, S., Tahvanainen, T., Kotiaho, J.S. (2010) The effects of peatland restoration on water-table depth, elemental concentrations, and vegetation: 10 years of changes. *Restoration Ecology*, 19(5), 587–598. https://doi.org/10.1111/j.1526-100X.2010.00704.x

Haapalehto, T.O., Kotiaho, J.S., Matilainen, R., Tahvanainen, T. (2014) The effects of long-term drainage and subsequent restoration on water table level and pore water chemistry in boreal peatlands. *Journal of Hydrology*, 519, Part B, 1493–1505. https://doi.org/10.1016/j.jhydrol.2014.09.013

Hinton, M.J., Schiff, S., English, M.C. (1997) The significance of storms for the concentration and export of dissolved organic carbon from two Precambrian Shield catchments. *Biogeochemistry*, 36(1), 67–88. https://doi.org/10.1023/A:1005779711821

Holden, J., Burt, T.P. (2003) Hydrological studies on blanket peat: The significance of the acrotelm-catotelm model. *Journal of Ecology*, 91, 86–102. https://doi.org/10.1046/j.1365-2745.2003.00748.x

Holden, J., Wallage, Z.E., Lane, S.N., McDonald, A. T. (2011) Water table dynamics in undisturbed, drained and restored blanket peat. *Journal of Hydrology*, 402, 103–114. https://doi.org/10.1016/j.jhydrol.2011.03.010

Höll, B.S., Fiedler, S., Jungkunst, H.F., Kalbitz, K., Freibauer, A., Drösler, M., Stahr, K. (2009) Characteristics of dissolved organic matter following 20 years of peatland restoration. *Science of The Total Environment*, 408(1), 78–83. https://doi.org/10.1016/j.scitotenv.2009.08.046

Hugron, S., Guêné-Nanchen, M., Roux, N., LeBlanc, M.-C., Rochefort, L. (2020) Plant reintroduction in restored peatlands: 80% successfully transferred - Does the remaining 20% matter? *Global Ecology and Conservation*, 22, e01000. https://doi.org/10.1016/j.gecco.2020.e01000

Joosten, H., Tapio-Biström, M.L., Tol, S. (eds.) (2012) *Peatlands - Guidance for Climate Change Mitigation through Conservation, Rehabilitation and Sustainable Use*. Second edition, Mitigation of Climate Change in Agriculture (MICCA) Programme, Food and Agriculture Organization of the United Nations (FAO) and Wetlands International, Rome IT, 100 pp.

Kalbitz, K., Geyer, S. (2002) Different effects of peat degradation on dissolved organic carbon and nitrogen. *Organic Geochemistry*, 33(3), 319–326. https://doi.org/10.1016/S0146-6380(01)00163-2

Kirschbaum, M.U.F. (1995) The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage. *Soil Biology and Biochemistry*, 27(6), 753–760. https://doi.org/10.1016/0038-0717(94)00242-S

Koehler, A.-K., Murphy, K., Kiely, G., Sottocornola, M. (2009) Seasonal variation of DOC concentration and annual loss of DOC from an Atlantic blanket bog in South Western Ireland. *Biogeochemistry*, 95(2), 231–242. https://doi.org/10.1007/s10533-009-9333-9

Ladson, A.R., Brown, R., Neal, B., Nathan, R. (2013) A standard approach to baseflow separation using the Lyne and Hollick filter. *Australasian Journal of Water Resources*, 17(1), 25–34. https://doi.org/10.7158/13241583.2013.11465417

Lindsay, R. (2010) *Peatbogs and Carbon: A Critical Synthesis to Inform Policy Development in Oceanic Peat Bog Conservation and Restoration in the Context of Climate Change*. Report, Royal Society for the Protection of Birds (RSPB) Scotland, Edinburgh UK, 315 pp.

Littlewood, I.G. (1992) *Estimating Contaminant Loads in Rivers: A Review*. Report No. 117, Institute of Hydrology, Wallingford UK, 81 pp. Online at: https://nora.nerc.ac.uk/id/eprint/7353/, accessed 28 Nov 2025.

Loisel, J., Gallego-Sala, A. (2022) Ecological resilience of restored peatlands to climate change. *Communications Earth & Environment*, 3(1), 208. https://doi.org/10.1038/s43247-022-00547-x

Luscombe, D.J. (2014) *Understanding the Ecohydrology of Shallow, Drained and Marginal Blanket Peatlands*. PhD thesis, University of Exeter, Exeter UK, 191 pp.

Luscombe, D.J., Anderson, K., Gatis, N., Grand-Clement, E., Brazier, R.E. (2014) What does airborne LiDAR really measure in upland ecosystems? *Ecohydrology*, 8(4), 584–594. https://doi.org/10.1002/eco.1527

Luscombe, D.J., Anderson, K., Gatis, N., Grand-Clement, E., Brazier, R.E. (2015) Using thermal airborne imagery to measure near surface hydrology in upland ecosystems, *Hydrological Processes*, 29(6), 1656–1668. https://doi.org/10.1002/hyp.10285

Luscombe, D.J., Anderson, K., Grand-Clement, E., Gatis, N., Ashe, J., Benaud, P., Smith, D., Brazier, R.E. (2016) How does drainage alter the hydrology of shallow degraded peatlands across multiple spatial scales? *Journal of Hydrology*, 541, 1329–1339. https://doi.org/10.1016/j.jhydrol.2016.08.037

Mander, Ü., Espenberg, M., Melling, L., Kull, A. (2024) Peatland restoration pathways to mitigate greenhouse gas emissions and retain peat carbon. *Biogeochemistry*, 167(4), 523–543. https://doi.org/10.1007/s10533-023-01103-1

McCarter, C.P.R., Price, J.S. (2015) The hydrology of the Bois-des-Bel peatland restoration: Hydrophysical properties limiting connectivity between regenerated *Sphagnum* and remnant vacuum harvested peat deposit. *Ecohydrology*, 8(2), 173–187. https://doi.org/10.1002/eco.1498

Menberu, M.W., Marttila, H., Tahvanainen, T., Kotiaho, J.S., Hokkanen, R., Kløve, B., Ronkanen, A.-K. (2017) Changes in pore water quality after peatland restoration: Assessment of a large-scale, replicated before-after-control-impact study in Finland. *Water Resources Research*, 53(10), 8327–8343. https://doi.org/10.1002/2017WR020630

MetOffice (2025) *Location-Specific Long-Term Averages. Station: Liscombe*. Web page, Met Office, Exeter UK. Online at: https://www.metoffice.gov.uk/research/climate/maps-and-data/location-specific-long-term-averages/gcj6tuher, accessed 05 Mar 2025.

Natural England (2025) *England Peat Map Project: Final Report*. Research Report 149 (NERR149), Natural England, York UK, 84 pp. Online at: https://publications.naturalengland.org.uk/publication/5075614867128320, accessed 27 Oct 2025.

Nava, V., Patelli, M., Rotiroti, M., Leoni, B. (2019) An R package for estimating river compound load using different methods. *Environmental Modelling & Software*, 117, 100–108. https://doi.org/10.1016/j.envsoft.2019.03.012

O'Brien, H., Labadz, J.C., Butcher, D.P., Billett, M.F., Midgley, N.G. (2008) Impact of catchment management upon dissolved organic carbon and stream flows in the Peak District, Derbyshire, UK. In: *Sustainable Hydrology for the 21st Century*, Proceedings of the 10th BHS National Hydrology Symposium, Exeter, 15–17 Sept 2008, British Hydrological Society, London UK, 178–185.

Phillips, I.D., McGregor, G.R. (2001) The relationship between synoptic scale airflow direction and daily rainfall: A methodology applied to Devon and Cornwall, South West England. *Theoretical and Applied Climatology*, 69(3–4), 179–198. https://doi.org/10.1007/s007040170024

Pickard, A.E., Branagan, M., Billett, M.F., Andersen, R., Dinsmore, K.J. (2022) Effects of peatland management on aquatic carbon concentrations and fluxes. *Biogeosciences*, 19(5), 1321–1334. https://doi.org/10.5194/bg-19-1321-2022

Puttock, A., Graham, H.A., Ashe, J., Luscombe, D.J., Brazier, R E. (2021) Beaver dams attenuate flow: A multi-site study. *Hydrological Processes*, 35(2), e14017. https://doi.org/10.1002/hyp.14017

Quinty, F., Rochefort, L. (2003) *Peatland Restoration Guide*. Second edition, Canadian Sphagnum Peat Moss Association and New Brunswick Department of Natural Resources and Energy, St Albert AB and Fredericton NB, Canada, 107 pp.

Richardson, S.D., Plewa, M.J., Wagner, E.D., Schoeny, R., DeMarini, D.M. (2007) Occurrence, genotoxicity, and carcinogenicity of regulated and emerging disinfection by-products in drinking water: A review and roadmap for research. *Mutation Research / Reviews in Mutation Research*, 636(1–3), 178–242. https://doi.org/10.1016/j.mrrev.2007.09.001

Riley, H. (2014) *Turf Cutting on Exmoor: An Archaeological and Historical Study*. Report, Exmoor Mires Project, Dulverton UK, 58 pp.

Ritson, J.P., Bell, M., Brazier, R.E., Grand-Clement, E., Graham, N.J.D., Freeman, C., Smith, D., Templeton, M.R., Clark, J.M. (2016) Managing peatland vegetation for drinking water treatment. *Scientific Reports*, 6, 36751. https://doi.org/10.1038/srep36751

Ritson, J.P., Croft, J.K., Clark, J.M., Brazier, R.E., Templeton, M.R., Smith, D., Graham, N.J.D. (2019) Sources of dissolved organic carbon (DOC) in a mixed land use catchment (Exe, UK). *Science of The Total Environment*, 666, 165–175. https://doi.org/10.1016/j.scitotenv.2019.02.228

Ritson, J.P., Lees, K.J., Hill, J., Gallego-Sala, A., Bebber, D.P. (2025) Climate change impacts on blanket peatland in Great Britain. *Journal of Applied Ecology*, 62, 701–714. https://doi.org/10.1111/1365-2664.14864

Ritzema, H., Limin, S., Kusin, K., Jauhiainen, J., Wösten, H. (2014) Canal blocking strategies for hydrological restoration of degraded tropical peatlands in Central Kalimantan, Indonesia. *Catena*, 114, 11–20. https://doi.org/10.1016/j.catena.2013.10.009

Rodwell, J.S. (ed.) (1991) *British Plant Communities Volume 2: Mires and Heaths*. Cambridge University Press, Cambridge UK, 628 pp.

Roulet, N., Moore, T.R. (2006) Environmental chemistry: Browning the waters. *Nature*, 444(7117), 283–284. https://doi.org/10.1038/444283a

Schiff, S., Aravena, R., Trumbore, S., Hinton, M.J., Elgood, R., Dillon, P.J. (1997) Export of DOC from forested catchments on the Precambrian Shield of Central Ontario: Clues from ^{13}C and ^{14}C. *Biogeochemistry*, 36, 43–65. https://doi.org/10.1023/A:1005744131385

Schumann, M., Joosten, H. (2008) *Global Peatland Restoration Manual*. Institute of Botany and Landscape Ecology, Greifswald University, Greifswald DE, 64 pp. Fifth download in list at: https://www.imcg.net/pages/publications/papers.php, accessed 27 Oct 2025.

Schwieger, S., Kreyling, J., Couwenberg, J., Smiljanić, M., Weigel, R., Wilmking, M., Blume-Werry, G. (2021) Wetter is better: Rewetting of minerotrophic peatlands increases plant production and moves them towards carbon sinks in a dry year. *Ecosystems*, 24(5), 1093–1109. https://doi.org/10.1007/s10021-020-00570-z

Shantz, M.A., Price, J.S. (2006) Hydrological changes following restoration of the Bois-des-Bel Peatland, Quebec, 1999–2002. *Journal of Hydrology*, 331(3–4), 543–553. https://doi.org/10.1016/j.jhydrol.2006.06.002

Shuttleworth, E.L., Evans, M.G., Pilkington, M., Spencer, T., Walker, J., Milledge, D., Allott, T.E. H. (2019) Restoration of blanket peat moorland delays stormflow from hillslopes and reduces peak discharge. *Journal of Hydrology X*, 2, 100006. https://doi.org/10.1016/j.hydroa.2018.100006

Skjelkvåle, B.L., Mannio, J., Wilander, A., Andersen, T. (2001) Recovery from acidification of lakes in

Finland, Norway and Sweden 1990–1999. *Hydrology & Earth System Science*, 5, 327–338. https://doi.org/10.5194/hess-5-327-2001

Strack, M., Waddington, J.M., Bourbonniere, R.A., Buckton, E.L., Shaw, K., Whittington, P., Price, J.S. (2008) Effect of water table drawdown on peatland dissolved organic carbon export and dynamics. *Hydrological Processes*, 22(17), 3373–3385. https://doi.org/10.1002/hyp.6931

Strack, M., Zuback, Y., McCarter, C., Price, J. (2015) Changes in dissolved organic carbon quality in soils and discharge 10 years after peatland restoration. *Journal of Hydrology*, 527, 345–354. https://doi.org/10.1016/j.jhydrol.2015.04.061

Turner, E.K., Worrall, F., Burt, T.P. (2013) The effect of drain blocking on the dissolved organic carbon (DOC) budget of an upland peat catchment in the UK. *Journal of Hydrology*, 479, 169–179. https://doi.org/10.1016/j.jhydrol.2012.11.059

Urban, N.R., Bayley, S.E., Eisenreich, S.J. (1989) Export of dissolved organic carbon and acidity from peatlands. *Water Resources Research*, 25, 1619–1628. https://doi.org/10.1029/WR025i007p01619

von Post, L., Granlund, E. (1926) *Södra Sveriges Torvtillgågar 1* (*Peat Resources in Southern Sweden I*). Sveriges Geologiska Undersökning Series C, Volume 335 (Årsbok 19:2), Swedish Geological Survey, Stockholm, 127 pp. (in Swedish).

Waddington, J.M., Tóth, K., Bourbonniere, R. (2008) Dissolved organic carbon export from a cutover and restored peatland. *Hydrological Processes*, 22(13), 2215–2224. https://doi.org/10.1002/hyp.6818

Wallage, Z.E., Holden, J. (2010) Spatial and temporal variability in the relationship between water colour and dissolved organic carbon in blanket peat pore waters. *Science of The Total Environment*, 408(24), 6235–6242. https://doi.org/10.1016/j.scitotenv.2010.09.009

Wallage, Z.E., Holden, J., McDonald, A.T. (2006) Drain blocking: An effective treatment for reducing dissolved organic carbon loss and water discolouration in a drained peatland. *Science of The Total Environment*, 367(2–3), 811–821. https://doi.org/10.1016/j.scitotenv.2006.02.010

Walling, D.E., Webb, B.W. (1985) Estimating the discharge of contaminants to coastal waters by rivers: Some cautionary comments. *Marine Pollution Bulletin*, 16, 488–492. https://doi.org/10.1016/0025-326X(85)90382-0

Wickham, H., Averick, M., Bryan, J., Chang, W. and 20 others (2019) Welcome to the Tidyverse. *Journal of Open Source Software*, 4(43), 1686. https://doi.org/10.21105/joss.01686

Williamson, J., Evans, C., Spears, B.M., Pickard, A., Chapman, P.J., Feuchtmayr, H., Leith, F.I., Monteith, D. (2020) Will UK peatland restoration reduce dissolved organic matter concentrations in upland drinking water supplies? *Hydrology & Earth System Science Discussions* [preprint]. https://doi.org/10.5194/hess-2020-450

Wilson, D., Farrell, C., Mueller, C., Hepp, S., Renou-Wilson, F. (2013) Rewetted industrial cutaway peatlands in western Ireland: A prime location for climate change mitigation? *Mires and Peat*, 11, 01. https://doi.org/10.19189/001c.128473

Wilson, L., Wilson, J., Holden, J., Johnstone, I., Armstrong, A., Morris, M. (2011a) Ditch blocking, water chemistry and organic carbon flux: Evidence that blanket bog restoration reduces erosion and fluvial carbon loss. *Science of The Total Environment*, 409(11), 2010–2018. https://doi.org/10.1016/j.scitotenv.2011.02.036

Wilson, L., Wilson, J., Holden, J., Johnstone, I., Armstrong, A., Morris, M. (2011b) The impact of drain blocking on an upland blanket bog during storm and drought events, and the importance of sampling-scale. *Journal of Hydrology*, 404(3–4), 198–208. https://doi.org/10.1016/j.jhydrol.2011.04.030

Worrall, F., Armstrong, A., Holden, J. (2007) Short-term impact of peat drain-blocking on water colour, dissolved organic carbon concentration, and water table depth. *Journal of Hydrology*, 337(3–4), 315–325. https://doi.org/10.1016/j.jhydrol.2007.01.046

Xu, J., Morris, P.J., Liu, J., Holden, J. (2018) Hotspots of peatland-derived potable water use identified by global analysis. *Nature Sustainability*, 1(5), 246–253. https://doi.org/10.1038/s41893-018-0064-6

Yallop, A.R., Clutterbuck, B. (2009) Land management as a factor controlling dissolved organic carbon release from upland peat soils 1: Spatial variation in DOC productivity. *Science of The Total Environment*, 407(12), 3803–3813. https://doi.org/10.1016/j.scitotenv.2009.03.012

Submitted 07 Mar 2025, revision 25 Sep 2025
Editor: Gerald Jurasinski

Author for correspondence:
Dr Emilie Grand-Clement, Centre for Resilience, the Environment, Water and Waste, University of Exeter, CREWW building, North Park Road, Exeter EX4 4TA. E-mail: e.grand-clement@exeter.ac.uk.

Appendix

The relationship between colour (Abs_{400}) and DOC (measured by the spectroscopic method) was explored (Figure A1A). This showed, in particular, a different relationship for the 2017 calendar year, likely to be due to a difference in the laboratory equipment used to measure DOC. However, the relationships remained linear for both time periods (R^2 = 0.96 for 2017 and R^2 = 0.82 for all other years combined). Linear regressions were therefore applied to recalculate DOC values, as presented in Figure A1B.

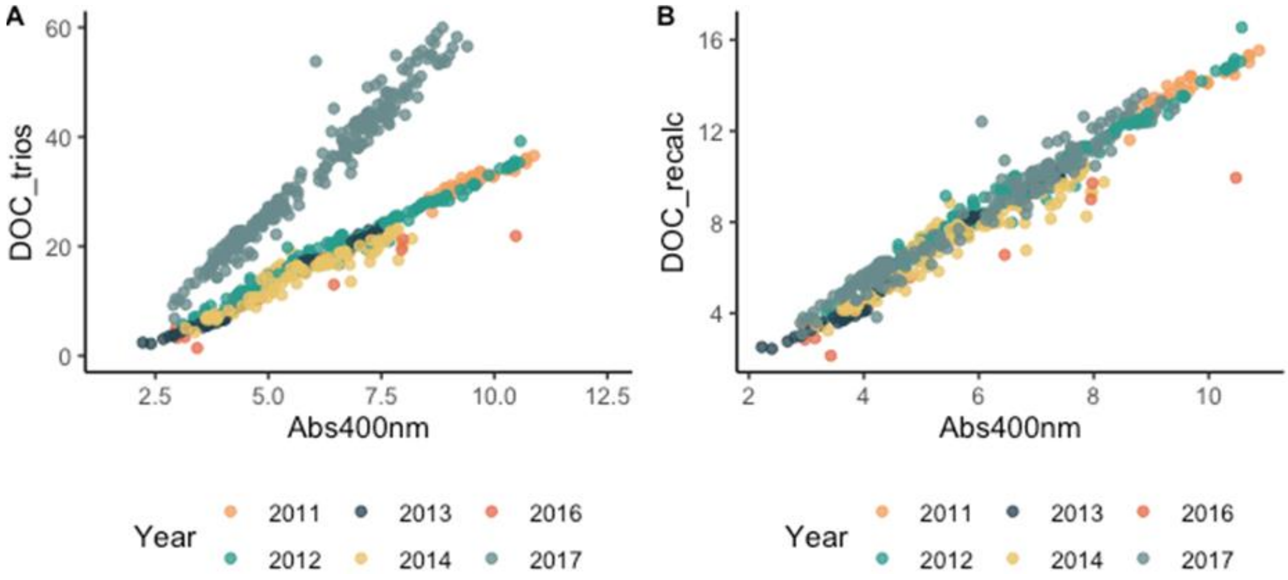

Figure A1. Relationships between Colour (Abs_{400}) and measured DOC concentrations (mg L^{-1}) (A) and corrected DOC concentrations (mg L^{-1}) (B), with individual monitoring years distinguished by differently coloured symbols.