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Role of blanket bog condition in stream dissolved organic carbon export

Muhammad Jehanzaib[1*], Raymond Flynn[1], Vicky Preece[1], Hannah Lehnhart-Barnett[2], Devin F. Smith[3], Oisín Leonard[2], Tiernan Henry[2], W. Berry Lyons[3], Anne E. Carey[3] and Peter Croot[2]

Abstract
The degradation of peatlands across the UK and Ireland has led to rising concentrations of dissolved organic carbon (DOC) in surface waters. This can have implications for the treatment of water supplies. While catchment management strategies to improve water quality, such as peatland restoration, aim to reverse these trends and thereby reduce treatment costs, relationships between DOC generation and land use require further clarification. DOC levels recorded in discharge from relatively intact areas can be used to establish realistic restoration targets. To investigate the relationships between DOC concentrations in streams draining intact areas and adjacent disturbed areas, a year-long integrated hydrological and water quality monitoring program was conducted along a 2.2 km stretch of a first-order stream draining a blanket peat-covered catchment in the Ox Mountains, Co. Sligo, Ireland. Groundwater level monitoring operated continuously at 15 catchment locations in contrasting hydrological settings. Combining the results of continuous stream discharge measurements with groundwater level monitoring permitted event-based water quality sampling at three locations along the stream's course; this allowed assessment of how changes in DOC concentrations and fluxes varied with land use, moving from the stream's headwaters, downstream. Data from five water quality sampling events distributed over the course of one-year (December 2023 to November 2024) revealed that DOC fluxes draining the 107 ha catchment of the stream's headwaters varied between 8.7 mg/m^2 and 144 mg/m^2. By contrast, DOC fluxes rose consistently going downstream. Results from the final 21 ha interval, (reflecting a substantially more degraded area) showed that fluxes from a formerly afforested peatland ranged from 27 mg/m^2 to 907 mg/m^2. The results indicated that DOC fluxes are affected by both peatland condition and seasonal variation.

Highlights

- DOC export from relatively undisturbed blanket bog ranges from 8.7 mg/m^2 to 144 mg/m^2
- Formerly afforested peatlands demonstrated markedly elevated DOC export, varying from 27 mg/m^2 to 907 mg/m^2
- Seasonal variation, coupled with degradation activities on blanket bogs, contributed to substantial increase in DOC export

Keywords Blanket bog, DOC, Clear-felling, Restoration baseline, Seasonal variability, Republic of ireland

*Correspondence:
Muhammad Jehanzaib
m.jehanzaib@qub.ac.uk
[1]School of the Natural and Built Environment, Queen's University Belfast, Belfast BT9 5AG, UK
[2]Earth & Ocean Sciences, School of Natural Sciences, University of Galway, Galway H91 TK33, Ireland
[3]School of Earth Sciences, The Ohio State University, Columbus, OH 43210- 1398, USA

Introduction

Peatlands occur in a variety of climatic settings from tropical regions to high latitudes, occupying roughly 3% of the Earth's surface (Yu et al. 2010). There is growing recognition of their importance, including for biodiversity and the provision of ecosystem services, such as carbon sequestration, water supply and recreational opportunities (Martino et al. 2022). Moreover, peatlands serve as vital reservoirs of water and soil carbon, holding an estimated 10% of the world's freshwater resources and up to one-third of global soil carbon (Nichols and Peteet 2019).

Peatlands across the Republic of Ireland cover approximately 17% of the land area and are estimated to store between 53% and 62% of the country's total soil carbon reserves (Koehler et al. 2009). Many of these contribute substantially to the country's water supply (Pschenyckyj et al. 2023). More generally, across the UK and Ireland, 70% of drinking water comes from catchments covered with peat (Van der Wal et al. 2011). Nonetheless, land use change can pose a threat to organic matter stores in bogs, potentially releasing significant amounts of sequestered organic carbon into water bodies. Elevated levels of dissolved organic carbon (DOC) in freshwater can prove problematic, for drinking water supplies, requiring supplemental water treatment. This can be complex and costly, particularly in peatland catchments (Armstrong et al. 2010; Ferretto et al. 2021). Moreover, incomplete removal of DOC can react with disinfectants and lead to the formation of disinfection by-products (DBPs), which are detrimental to human health (Davies and Mazumder 2003; Valdivia-Garcia et al. 2019). Furthermore, elevated DOC levels in raw water also raise coagulant demand, escalate disinfectant consumption, generate higher sludge volumes, and shorten filter lifespan in treatment plants, collectively drive-up operational costs (Eikebrokk et al., 2004; Ritson et al. 2014).

Storm events can play a significant role in carbon export, causing flushing of carbon-rich water from peatlands to downstream ecosystems (Hinton et al. 1997; Price 2003). Similarly, groundwater can play an important role, as drainage can lower water tables, enhancing peat decomposition and negatively affecting water quality (Holden 2005). This can include accelerated production of DOC, which may impact aquatic ecological receptors (Van Seters and Price 2002). Blodau (2002) stated that DOC concentrations typically range from 20 mg/L to 60 mg/L in northern peatlands, with elevated levels observed during low flow periods. Limpens et al. (2008) indicated that approximately 10–20% of carbon losses from peatlands could be attributed to DOC. Similarly, Murray et al. (2020) reported that the concentrations of DOC entering many British treatment facilities may now surpass 20 mg/L and are projected to increase further.

Intact blanket bogs help maintain water quality, being capable of removing suspended and dissolved constituents (organic matter, nitrate, ammonia, etc.), while also limiting the intrinsic generation of potentially problematic aqueous species, thereby preventing their transfer to surface water bodies (Holden et al. 2004). This includes reduction of DOC export and limiting heavy metal mobilization to enhance overall water quality stability (Lindsay 2010; Evans et al. 2012). However, many bogs have experienced degradation from a range of pressures, including threats ranging from climate change and anthropogenic activities (Artz et al. 2014). Projected climatic changes for the UK and Ireland include elevated temperatures and altered precipitation patterns, resulting in increased winter rainfall, diminished summer rainfall, and a higher frequency of extreme events impact peatland hydrology and DOC export (Manning et al. 2024). Tiwari et al. (2019) revealed that extreme climate events are likely to affect the biogeochemical processes that influence the production of DOC, as well as hydrological processes that influence the mobility and export of DOC in peatlands. Moreover, human activities such as drainage, afforestation, grazing, and burning all modify the hydrological and biogeochemical process of blanket bogs (Holden et al. 2004; Jehanzaib et al. 2025). Under these conditions, peatlands can be anticipated to experience additional stress, limiting, or potentially losing their ability to sequester carbon. For many blanket bogs disturbance to hydrological regimes through artificial drainage accentuates environmental degradation, leading to increased carbon loss, decreased biodiversity, increased fire frequency, land degradation, and enhanced vulnerability to soil erosion (Biancalani and Avagyan 2014).

Sustainable Catchment Management Programmes (SCAMP) and peatland restoration initiatives seek to alter hydrogeological regimes and reduce DOC concentrations in raw drinking water (Wallage et al. 2006; Barbier and Burgess 2021). Nordstrand (2025) demonstrates that restoring degraded peatlands might be one way to tackle climate change and improve water quality. Peatland restoration has been proposed as a catchment-scale strategy for reducing dissolved organic matter (DOM) concentrations in water draining from peatlands (IUCN Peatland Programme (IUCN 2025)). However, quantifiable metrics for restoration remain poorly defined. Water quality from relatively intact catchments can provide realistic restoration targets (Strack et al. 2015), although factors such as elevation and climate also influence conditions in intact systems. However, water quality in streams draining peatlands can vary substantially throughout the year, particularly across seasons and during more energetic hydrological events, which needs investigation in both intact and degraded peatland watersheds (Flynn et al. 2022). The drivers behind these issues remain poorly understood.

This study aims to compare DOC export from intact and degraded peatlands in runoff draining a low order stream. The key objectives are: (1) to investigate the spatial variation in DOC concentrations along the stream, from relatively intact headwaters to increasingly degraded downstream areas, and (2) to examine seasonal variations in DOC concentrations during sampling events over a hydrological year.

Materials and methods

Description of study area

The Letterunshin Blanket Bog Hydrology Research Catchment (Letterunshin) is located within the Ox Mountains Bogs, a designated Special Area of Conservation in County Sligo, Republic of Ireland (Latitude 54.185° and Longitude − 8.911°) **(**Fig. 1**)**. The site's total catchment area is 2.14 km^2, underlain by 1.08 km^2 of relatively intact blanket bog (W1), 0.85 km^2 of bog impacted by grazing, peat cutting, and burning (W2). An additional 0.21 km^2 of clear-felled plantation forestry (W3), planted on cutover blanket peat, occupies the lowermost part of the catchment. Letterunshin is part of a larger elevated blanket bog complex that forms part of the headwaters of the River Easkey. Ground elevations range from 107 m above mean sea level (AMSL) to 149 m AMSL, with the majority of the catchment situated between 130 m AMSL and 145 m AMSL (Fig. 1). The long-term (1991–2020) average annual rainfall at Letterunshin is approximately 1,503 mm (Curley et al. 2023). Table 1 provides a more detailed statistical description and seasonal variability of precipitation, temperature, and potential evapotranspiration.

The relatively flat upland portions of Letterunshin contain several dystrophic pool systems. Persistent flowing water in peat piping was observed at the headwaters of the Fiddanduff River; aerial imagery, coupled with ground observations suggest that the pipes extend away from the head waters for up to 1.3 km. Vertical shafts and swallow holes in the bog surface along lineaments revealing actively flowing water at depth confirm the presence of peat pipes (Flynn et al. 2022). Perrin et al. (2013) stated that although in downstream area there is evidence of previous burning, grazing and small-scale peat extraction at the catchment divide, yet the upland is free of artificial drainage and remains in reasonably intact state. Historical aerial image analysis revealed that coniferous forestry was planted in the early 1990s at the lower end of the watershed with ground prepared using a furrow-ridge plantation system (Google Earth (Google2024)). The forest was clear-felled between December 2022 and January 2023 (Jehanzaib et al. 2025). A recent wildfire occurred across much of W2 in April 2023 approximately 6 months before the event-based sampling program started. The fire was fast moving owing to high winds, predominantly affecting vegetation (heather), with no evidence of peat burning.

Data acquisition

A network of hydro-meteorological instrumentation, installed across the catchment as part of the current and previous studies (Flynn et al. 2022; Jehanzaib et al. 2025), aimed to record spatiotemporal meteorological, hydrological and hydrogeological variations (Fig. 1). A Vantage Pro-plus Weather Station (Davis Instruments, California, USA) installed at 142 m AMSL recorded rainfall, temperature and evapotranspiration at 30-minute intervals. A second rain gauge (EML ARG314, UK) was installed at 119 m AMSL for assessment of precipitation variability across the catchment (rainfall was recorded here at 15-minute intervals). Three customised unrated constant cross section flumes, having dimensions of 2.5 m length × 1.5 m width × 1.0 m depth, were installed along Fiddanduff River from its headwaters to river's outlet. These permitted continuous monitoring of stream flow at the outlets of three nested sub catchments, having varying topography/land use patterns. A CS451 0–2.0 m Pressure Transducer (Campbell Scientific, Loughborough, UK) (Resolution = 0.00035 m FS, accuracy = +/- 0.1% FS) was installed in a stilling well adjacent to flume near the W1 outlet, measuring stage at 15 min time interval. Similar stage measurements were made at the outlets of W2 and W3 using the same setup. Rating curves were developed by employing tracer injection technique, with stage measured using an OTT Hydromet (Kempten, Germany) sensor for each flume. (Data are provided in supplementary data file (Figure S1, S2, and S3). Due to the non-conventional configuration of the flumes, each rating curve was divided into three parts based on stage values (0–0.255 m, 0.256–0.61 m, > 0.61 m) and separate rating equations were formulated for each segment to convert stage into streamflow, while ensuring that increases in stage consistently corresponded to rises in discharge.

Stream water specific electrical conductance (SEC) was measured at the outlets of W1, W2, and W3 using Hobo U24-001 low range EC loggers (Onset Instruments, MA). Measurements at hourly intervals continuously recorded runoff temperature and electrical conductivity variations throughout the year, these were converted to SEC by in situ comparison against a calibrated YSI Pro plus electrical conductivity meter (Yellow Springs, OH, USA). Similarly, water-quality samples were collected during five hydrological events following intense rainfall (> 10 mm): December 2023 (41 mm), March 2024 (19.8 mm), June 2024 (14 mm), August 2024 (29.4 mm), and October 2024 (32.2 mm), using Teledyne ISCO autosamplers (Models 6712 and 3700; Lincoln, USA). Comparison of event data

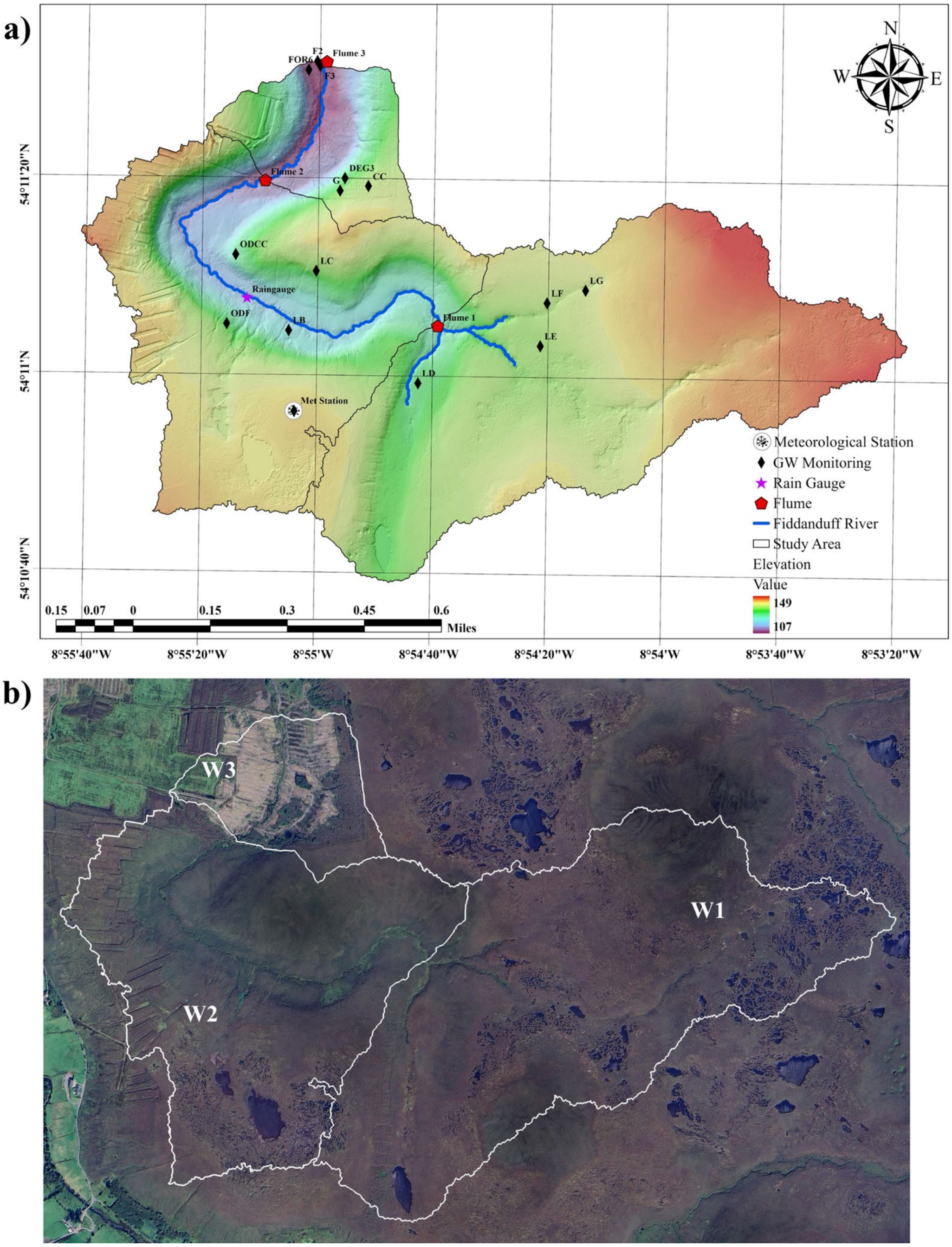

Fig. 1 **(a)** Map of study area showing elevation of the terrain and location of hydro-meteorological monitoring **(b)** Land use conditions in W1, W2, and W3

with continuously monitored stage data and water quality suggests that the December 2023 event is representative of winter, the March 2024 event represents spring, the June and August 2024 events correspond to summer, and the October 2024 event reflects autumn. The objective is to understand temporal variations in stream water quality during energetic (high stream flow) hydrological events. Autosamplers collected 24 samples at 2-hour intervals during each event for each sub catchment.

Groundwater level monitoring

Solinst Junior Edge Leveloggers® (5 m range; accuracy ± 0.1% or 0.5 cm) (Solinst, ON, Canada), installed at 15 representative locations across the catchment, aimed to reflect variations in hydrological setting, recorded groundwater levels on an hourly basis. A barometric logger (accuracy ± 0.1%, Solinst, ON, Canada) was deployed at the study site to measure atmospheric pressure for barometric correction of water level data. All

Table 1 Statistical description of meteorological variables and their seasonal distribution during studied period

Statistics	**Precipitation (mm)**	**Temperature (°C)**	**Potential Evapo-transpiration (mm)**
Mean	114.0	10.7	44.9
Standard Deviation	47.9	2.8	24.3
Kurtosis	2.9	−1.5	−1.7
Skewness	1.7	0.0	0.1
Range	171.6	8.3	61.2
Seasonal Variability	**Precipitation (mm)**	**Temperature (°C)**	**Potential Evapo-transpiration (mm)**
Winter	438	7	58
Spring	284	10	170
Summer	347	14	216
Autumn	299	11	96

logger measurements were validated with manual readings taken at least quarterly during the year to allow determination of water table depth and range of groundwater fluctuation (Mackin et al. 2024). Due to data gaps in groundwater measurements at certain locations, a complete 1-hour interval time series of water table levels for the research period was obtained from eight watershed sites (LD, LF, LG, LB, LC, ODF, DEG3, and FOR1).

Using data from water level loggers, summary water table depth statistics were calculated for December 2023 - November 2024. These statistics included comparisons of water table levels at the lower extreme (P10, or where the water table extended below this depth for 10% of the time), median (P50), upper extreme (P90) percentiles, and water table fluctuation (P99-P1).

DOC samples analysis

Sample aliquots, analysed for DOC concentrations, were filtered via a glass vacuum filtration through a 0.7 µm pore-size glass fibre into a 20 mL glass amber vial. The filtration set was rinsed three times with 18.2 MΩ deionized (DI) water and rinsed once with sample water prior to filtration. Glass amber vials had been washed with DI water and 10% HCl solution prior to combustion at 450 °C for 3 h. Samples for DOC concentration analysis were acidified to pH 3 and DOC concentrations were measured via a Shimadzu® TOC-V CPN. A standard curve of 1 to 25 mg/L C was created by dilution of a 1000 mg/L stock created in the lab with potassium hydrogen phthalate (KHP) A reference standard, TOC 1000 mg/L, was diluted to 10 mg/L to measure in-run accuracy. Standards were run with every sample set, and instrument accuracy and precision were each ≤ 4%.

Computation of DOC load, DOC mass and DOC flux

The DOC load, mass and flux were calculated from DOC concentration, flow rate and catchment area. DOC load is the product of DOC concentration and discharge which is calculated based on Eq. (1).

$$DOC\ Load\ (mg/s) = DOC\ conc.\ (mg/L) \times\ Discharge\ (L/s) \tag{1}$$

DOC mass for each event was calculated by integrating areas under each DOC load curve with time using Eq. (2) (Littlewood 1992). DOC mass for individual watershed was calculated by subtracting upstream watershed from downstream watershed.

$$DOC\ mass\ (kg) = \int_0^t (DOC\ Load)\, dt \tag{2}$$

Finally, DOC flux for a hydrological event was calculated by dividing the DOC mass from each watershed by its area using Eq. (3).

$$DOC\ Flux\ (mg/m^2) = DOC\ mass\ (mg)\,/Area\ \left(m^2\right) \tag{3}$$

Results

Weather station data suggest the annual precipitation for the study year was 1,368 mm, which fell principally as rain. This proved lower than the 30-year long-term average (1,503 mm). Stage data, recorded at 15-minute intervals in each watershed (W1, W2 and W3) were converted into runoff using the rating curves provided in Fig. S1-S3.

Impact of degradation on DOC export

The water quality analysis revealed that the DOC concentrations in water sampled from W1 was lower, overlapped with concentrations in samples collected from W2 and W3. Figure 2 provides an indication of variability in water quality, and how this varies with flow rate, between W1 and W3 during the March 2024 event. As in other events, background levels of stream water SEC, monitored prior to rainfall, show an increasing trend from W1 to W3, but these levels declined to comparable lower values as each event proceeded. Across all events, W1 showed consistently lower and more stable SEC, whereas conditions at W2 and W3 proved higher and more variable (Fig. 2; Figs S4-S7). By contrast, DOC levels increased progressively from W1 to W3 during events. Similarly, the flow peaks were lower in W1 than in W2 and W3. These patterns were consistent across all events (Figs. S4-S7).

The water-quality analyses showed that DOC load increased progressively from upstream to downstream for each event as shown in Fig. 3. It was observed that

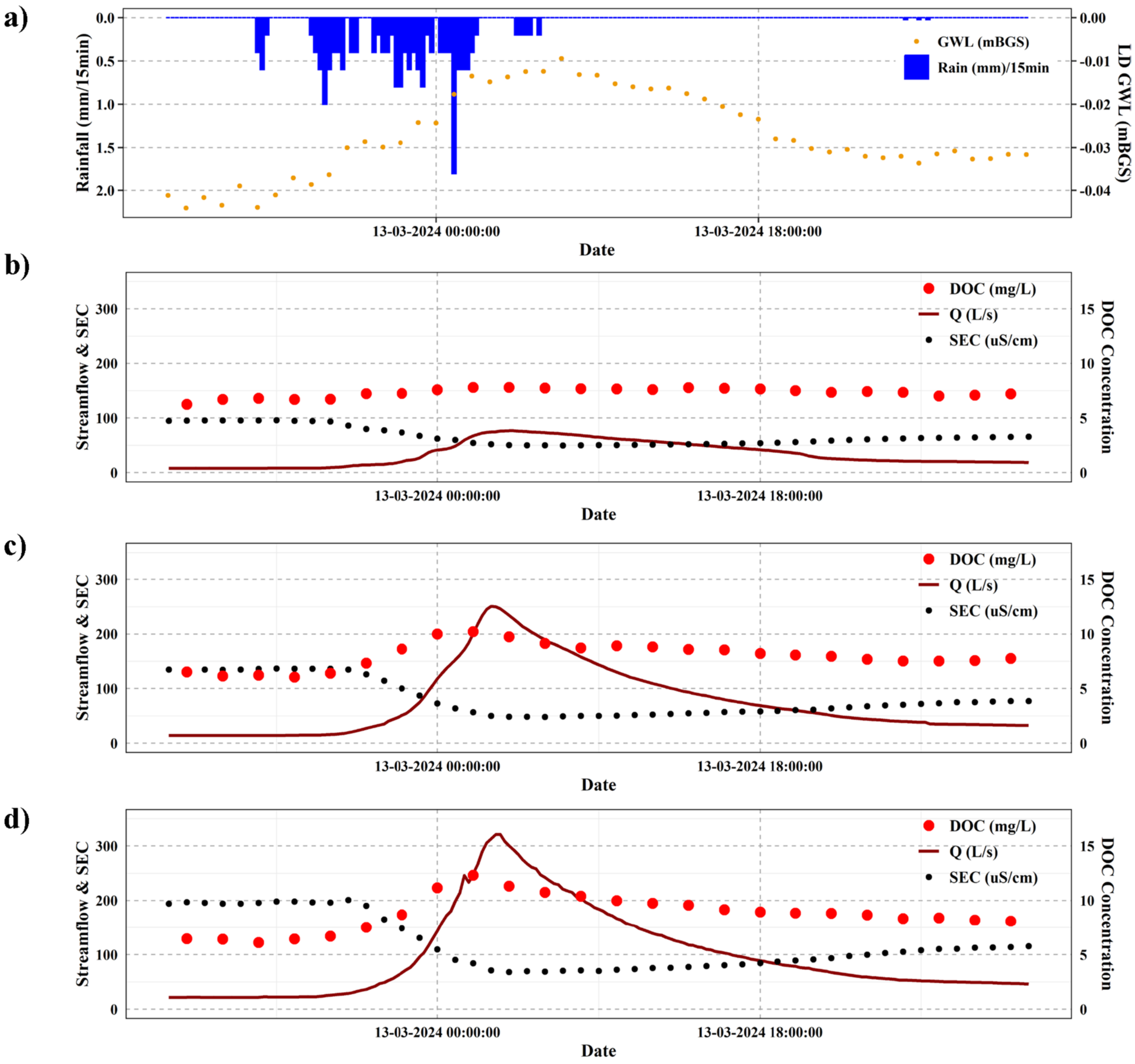

Fig. 2 Detailed representation of March 2024 event showing streamflow, specific electrical conductance (SEC) and dissolved organic carbon (DOC) variability: **(a)** Rainfall and groundwater level, **(b)** W1, **(c)** W2, and **(d)** W3

DOC load consistently correlated with runoff, with the strongest responses observed during high-runoff events (December 2023, August 2024, and October 2024) (see Fig. 2; Figs S4-S7). The peak DOC load recorded at the W3 outlet for the events in December 2023, August 2024, and October 2024 were 8,067 mg/s, 12,070 mg/s, and 7,778 mg/s, respectively. Additionally, export of DOC mass from each watershed for all five events is summarised in Table 2. The near-intact watershed (W1) exhibited high DOC mass export (155.6 kg and 145.4 kg) during the August 2024 and October 2024 events, while lower DOC mass export (36.4 kg and 9.4 kg) was observed in the March 2024 and June 2024 events. The DOC mass export from the near-intact watershed (W1) was highest during the August 2024 and October 2024 events, compared to the clear-felled watershed (W3), primarily due to its substantially larger catchment area (approximately five times greater).

Calculation of DOC fluxes permitted loads to be standardised for each catchment, with fluxes calculated for individual sub catchments by subtracting the load determined for the upstream monitoring points for W2 and W3. Table 2 shows that DOC fluxes in the degraded watersheds (W2 and W3) were consistently higher compared to the near-intact watershed (W1) for each of the events monitored. In the clear-felled watershed (W3), the highest DOC flux was observed during the December 2023 event (907.4 mg/m^2), followed by the October 2024

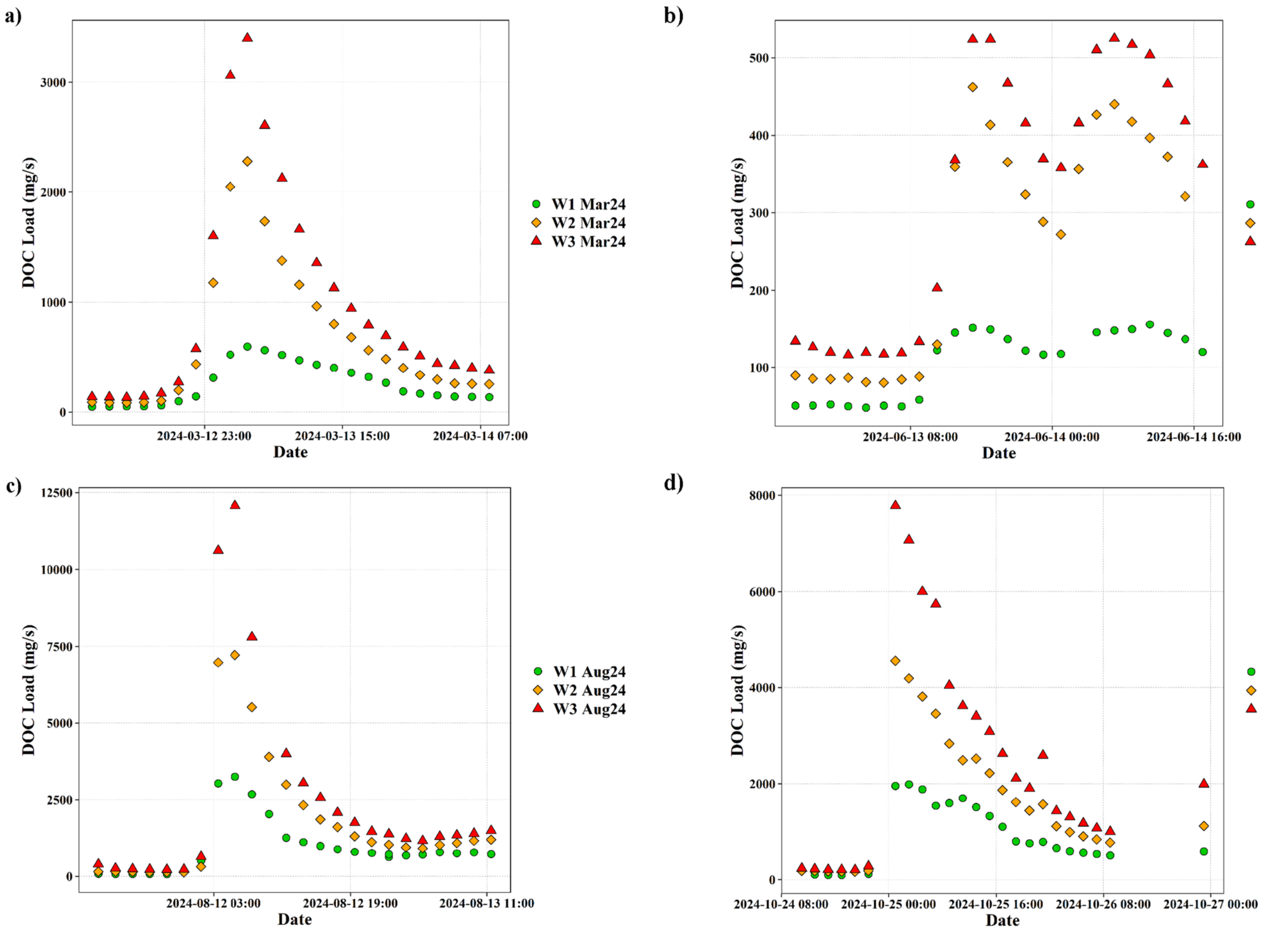

Fig. 3 Variability in DOC Load for 4 events from upstream to downstream (W1 to W3): **(a)** March 2024, **(b)** June 2024, **(c)** August 2024, and **(d)** October 2024

Table 2 Export of DOC from near-intact (W1) and degraded watersheds (W2 and W3) calculated over a 48-hour period for each event

DOC							
Sr. #	Date Period	W1		W2		W3	
		Mass (kg)	Flux (mg/m^2)	Mass (kg)	Flux (mg/m^2)	Mass (kg)	Flux (mg/m^2)
1	26th to 28th Dec 2023	NA	NA	280.42*	145.41*	191.32	907.37
2	12th to 14th Mar 2024	36.39	33.78	64.63	75.95	45.64	216.45
3	12th to 14th Jun 2024	9.38	8.70	19.39	22.79	5.81	27.54
4	11th to 13th Aug 2024	155.67	144.48	130.84	153.74	64.23	304.62
5	24th to 26th Oct 2024	145.45	135.01	99.53	116.95	129.06	612.06

[*] Combined DOC of watershed 1 and watershed 2. NA: Water quality data for December 2023 event was not recorded at W1 due to instrument failure

event (612.1 mg/m^2) and the August 2024 event (304.6 mg/m^2), while the June 2024 event resulted in the lowest flux (27 mg/m^2). Similarly, the degraded watershed (W2) exhibited a DOC flux trend similar to W3, except for the October 2024 event. Overall, the DOC flux proved consistently highest at W3 for all five events, followed by W2.

Comparison of near-intact and degraded watershed conditions

Rainfall, flow peaks and groundwater fluctuation during all five events in each watershed are shown in Figs. 4 and 5. Water table depth duration data for each groundwater monitoring point are provided in Table 3. These data indicate that groundwater levels in W1 remained consistently closer to the surface (0.02 to −0.16 m below ground surface (BGS) on average) throughout the year, whereas groundwater levels are relatively low (−0.03 to −0.36 m BGS on average) and (−0.04 to −0.48 m BGS on average) in W2 and W3, respectively. Spatial variability in groundwater levels is evident in each watershed, depending on hydrological setting. It is evident from Table 3 that the overall range of groundwater fluctuations (P99-P1) in

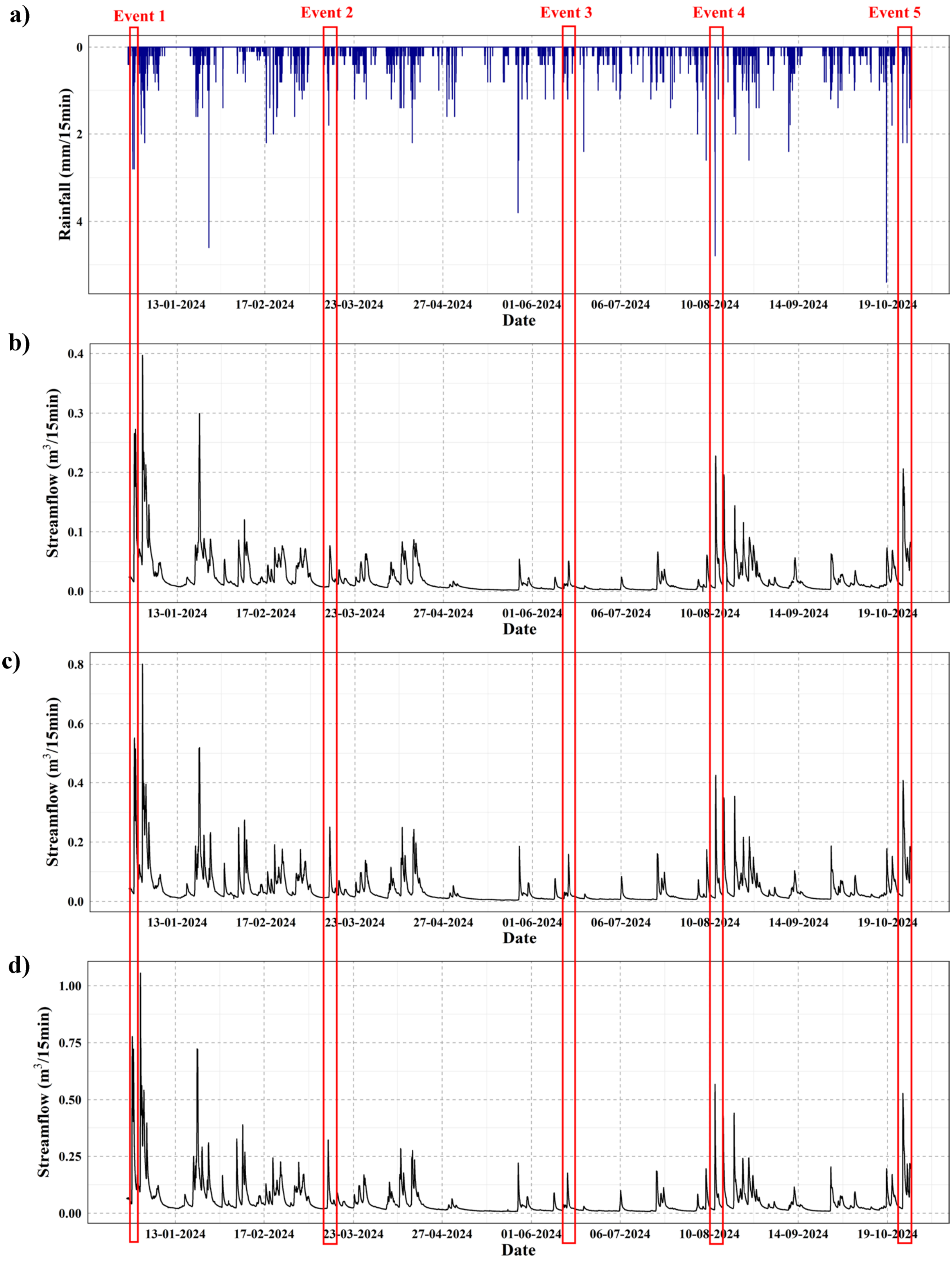

Fig. 4 Time series plot: **(a)** Rainfall, **(b)** Streamflow at W1, **(c)** Streamflow at W2, and **(d)** Streamflow at W3. Red strips show each event selected for water quality analysis

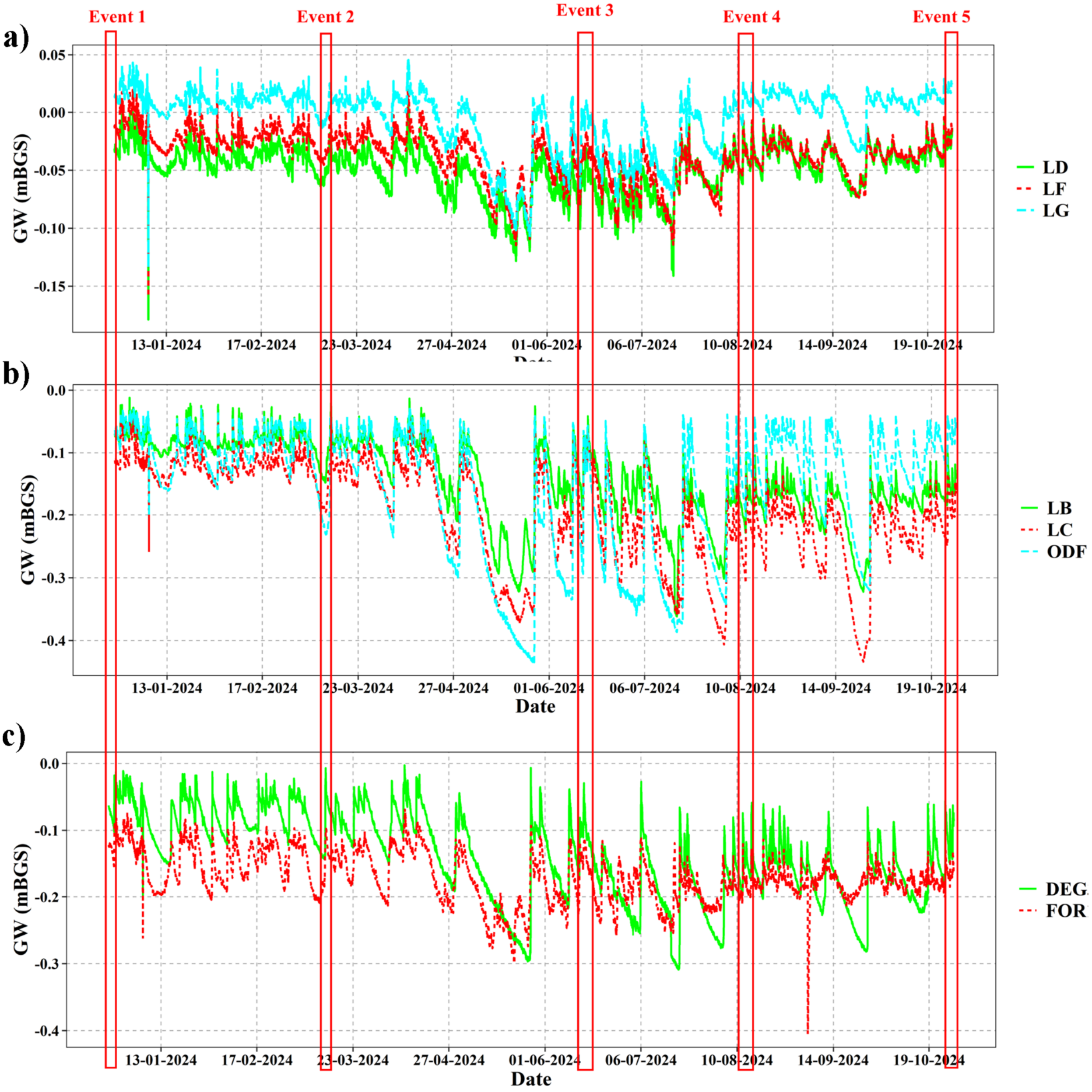

Fig. 5 Time series of groundwater level fluctuation (meter below ground surface): **(a)** W1, **(b)** W2, and **(c)** W3

W1 are lower (0.04 to 0.13 m BGS) as compared to W2 (0.08 to 0.39 m BGS) and W3 (0.11 to 0.27 m BGS). The 10th, 50th and 90th percentiles of groundwater levels in W1, W2, and W3 indicated spatial and temporal variability (Table 3). Duration curves permitted comparison of groundwater levels between the near-intact watershed (W1) and the degraded watersheds (W2 and W3) at each monitoring point over the study period, as presented in the supplementary material (Figures S8). An overall comparison of groundwater levels between the near-intact watershed (W1) and the degraded watersheds (W2 and W3) is shown in Fig. 6. A t-test confirmed that groundwater levels in W1 were significantly higher than those in W2 and W3 (p-value $< 2.2 \times 10^{-16}$).

DOC generation mechanisms and seasonal variability

To evaluate the relationship between streamflow, groundwater level, and DOC concentrations during individual events at each location, hysteresis plots were developed to characterise the non-linear processes governing DOC mobilisation (Fig. 7 and Fig. S9). In both the near-intact (W1) and degraded (W2 and W3) watersheds, DOC concentrations were generally highest when streamflow and groundwater levels peaked simultaneously. Moreover, the relationship between streamflow and DOC exhibited

Table 3 Comparison of percentiles of groundwater levels in intact and degraded watersheds for different time

Watershed	Piezometer	Percentile															
		Winter				Spring				Summer				Autumn			
		P10	P50	P90	P99-P1	P10	P50	P90	P99-P1	P10	P50	P90	P99-P1	P10	P50	P90	P99-P1
Near-Intact (W1)	**LD (mBGS)**	−0.05	−0.04	−0.02	0.04	−0.09	−0.05	−0.03	0.10	−0.09	−0.06	−0.03	0.09	−0.06	−0.04	−0.03	0.06
	LF (mBGS)	−0.03	−0.02	−0.01	0.05	−0.07	−0.03	−0.01	0.10	−0.08	−0.05	−0.03	0.09	−0.06	−0.04	−0.02	0.06
	LG (mBGS)	0.00	0.01	0.02	0.04	−0.07	0.00	0.02	0.13	−0.05	−0.02	0.02	0.09	−0.02	0.01	0.02	0.06
Degraded (W2)	**LB (mBGS)**	−0.10	−0.08	−0.05	0.08	−0.26	−0.09	−0.07	0.27	−0.24	−0.17	−0.11	0.28	−0.27	−0.17	−0.15	0.19
	LC (mBGS)	−0.14	−0.12	−0.08	0.10	−0.33	−0.15	−0.10	0.30	−0.33	−0.22	−0.14	0.30	−0.38	−0.23	−0.19	0.28
	ODF (mBGS)	−0.14	−0.09	−0.05	0.12	−0.38	−0.13	−0.06	0.39	−0.34	−0.20	−0.07	0.33	−0.25	−0.11	−0.06	0.27
Degraded (W3)	**DEG3 (mBGS)**	−0.12	−0.07	−0.04	0.13	−0.24	−0.10	−0.05	0.27	−0.25	−0.16	−0.11	0.24	−0.24	−0.17	−0.11	0.21
	FOR1 (mBGS)	−0.19	−0.14	−0.11	0.11	−0.24	−0.16	−0.12	0.19	−0.22	−0.19	−0.15	0.18	−0.20	−0.18	−0.16	0.13

m BGS means meter below ground surface. Negative values mean below ground surface and positive values mean above ground surface

a clockwise pattern in all events except the June 2024 event, which was a relatively small event and resulted in incomplete flushing of available DOC as shown in Fig. 7 and Fig. S9. During all events, the hysteresis loop magnitude increased systematically moving downstream from W1 to W3. Figure 7 and Figure S9 clearly demonstrates that each watershed exhibits an increasing trend in DOC concentration during each event moving downstream. The DOC concentration was higher in W2 and W3, compared to W1. The highest DOC concentration (14–18 mg/L) occurred during the August 2024 event, followed by the June 2024 (11.7–12.4 mg/L) and October 2024 (10–12 mg/L) events, while the lowest concentration increase (8–9.5.5 mg/L) was observed in the December 2024 event. Figure 8 demonstrates that average monthly groundwater levels and monthly streamflow were at their lowest, while mean monthly SEC peaked from May 2024 to July 2024 across all watersheds, until a significant rainfall event occurred in August 2024. During the period from December 2023 to April 2024 and August 2024 to November 2024, mean monthly groundwater levels were high, but mean monthly SEC values were diminished across all watersheds.

Discussion

Activities such as drainage, peat extraction, clear-felling of commercial forestry, and over-grazing can degrade blanket bogs and disrupt their hydrological functioning, leading to higher flood peaks and compromised water quality (Holden 2005; Gao et al. 2017).

This study examined the impact of peatland degradation on DOC export from a blanket bog site relative to a near-intact area. Although, the export of DOC mass was higher in W1 due to its catchment area being approximately five times larger than that of the clear-felled watershed (W3), DOC flux provided a more meaningful comparison. The elevated DOC flux observed in the degraded watershed W3 highlights the influence of peatland degradation on DOC export. Groundwater level data suggest that variations in DOC flux within the W2 and W3 sub-catchments are likely associated with contrasting groundwater level regimes resulting from blanket bog degradation. Monitoring data indicate that water tables in W1's catchment remain close to the ground surface (Fig. 6). By contrast W2 and W3 exhibit substantially lower and more variable water tables. Runoff water quality suggests that more variable water table regimes are associated with higher DOC fluxes; this is consistent with the findings of Pschenyckyj et al. (2023), who reported that increased groundwater variability enhances DOC export potential. The data collected from monitoring wells in W3 suggests its sub catchment has deeper groundwater levels than upstream sub catchments, which give rise to a higher DOC concentration in runoff.

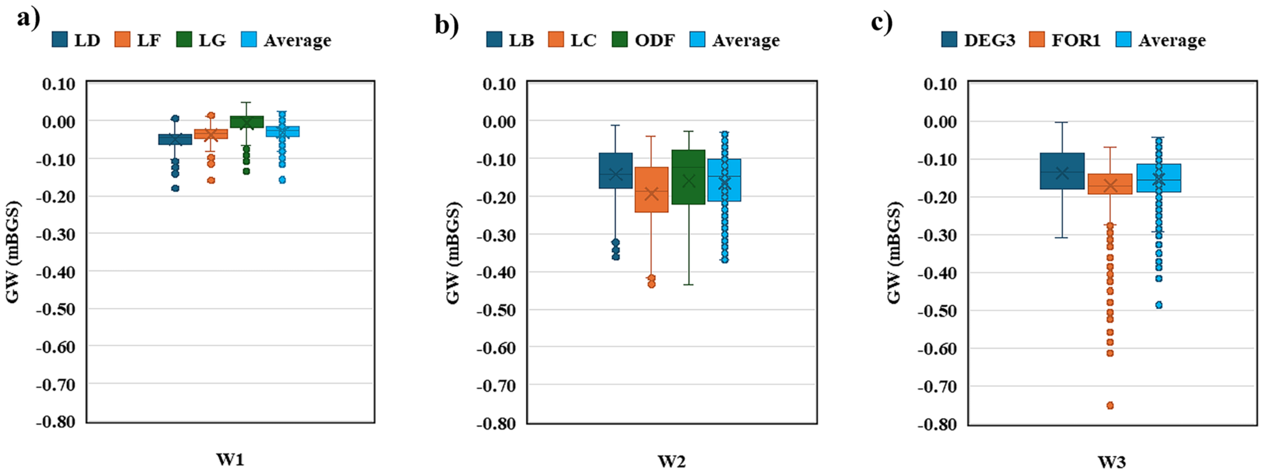

Fig. 6 Groundwater level variation in watersheds. **(a)** W1, **(b)** W2, and **(c)** W3. Groundwater level is expressed in meter below ground surface (mBGS), while legend represents groundwater monitoring location. T-test indicates a significant difference ($p\text{-value} < 2.2 \times 10^{-16}$) when comparing W1 with W2 and W1 with W3

These findings are consistent with the concept of deeper groundwater levels facilitating enhanced oxidation of peat through biochemical reactions (Holden et al. 2004). The introduction of oxygen into a naturally anaerobic setting accelerates peat decomposition and increase DOC release. Intense rainfall events further enhance DOC export. Heavy rainfall events, such as those in December 2023, August 2024, and October 2024, resulted in elevated DOC fluxes. These findings are in agreement with Clark et al. (2007), who demonstrated that variations in rainfall intensity and magnitude strongly influence DOC export.

Seasonal variations significantly influenced DOC export over the investigation period, with the highest DOC export occurring during August 2024 and June 2024 events (summer), followed by October 2024 event (autumn) (Fig. 7). This pattern likely reflects enhanced microbial activity under higher summer temperatures, promoting increased DOC production and mobilization. These findings are consistent with Koehler et al. (2009), who suggested that microbial activity rates are higher in summer, particularly during warm and dry conditions, when water tables decline more rapidly between rainfall events, allowing oxygen to enter the upper layers of peat. Moreover, summer runoff events for equivalent amounts of rainfall are smaller, due to the need to satisfy groundwater storage deficits (Fig. S5), i.e. some of the precipitation contributes to recharge groundwater rather than contributing directly to runoff. Data generated at Letterunshin suggest that much of the DOC produced during dry period remain stored until a significant rainfall event (August 2024) raises the water table and flushes the accumulated DOC (Fig. S6). In both the near-intact (W1) and degraded (W2 and W3) watersheds, DOC concentrations were generally highest when streamflow and groundwater levels peaked simultaneously. This behaviour is consistent with a flushing response, in which DOC stored in the upper peat layers is rapidly mobilised and transported to streams during elevated water table conditions when more permeable upper peat layers and/or shallow artificial drainage become hydraulically active. These findings are consistent with clockwise hysteresis plots presented in Fig. 7 and Figure S9. The increased size of hysteresis loops moving downstream from W1 to W3 (Fig. 7), is consistent with enhanced peatland degradation in more degraded sub catchments.

The clockwise hysteresis observed in the earlier and later parts of the monitoring period contrast with the anticlockwise orientation for the June 2024 event, which is believed to indicate partial flushing resulting from a more minor hydrological event, in which significant flushable DOC remained stored in the peat due to reduced hydraulic connection to the river. During the period from May to July 2024, streamflow remained at its lowest level, whereas SEC values were at their highest. This pattern indicates that groundwater discharging from the peat substrate was the dominant contributor to streamflow during these months (Fig. 8) (Flynn et al. 2022). Subsequently, a major rainfall event in August 2024 substantially increased streamflow and groundwater levels, enhancing hydrological connectivity and mobilising DOC accumulated during the preceding dry period. These findings are consistent with previous studies (Scott et al. 1998; Ferretto et al. 2021). Scott et al. (1998) reported high DOC production (8–20 mg/L) during summer and autumn, while lower DOC production (4–8 mg/L) in spring and winter. Ferretto et al. (2021) studied a reservoir system in a blanket peat covered catchment, supplying drinking water in Scotland, and observed a comparable DOC trend in summer and

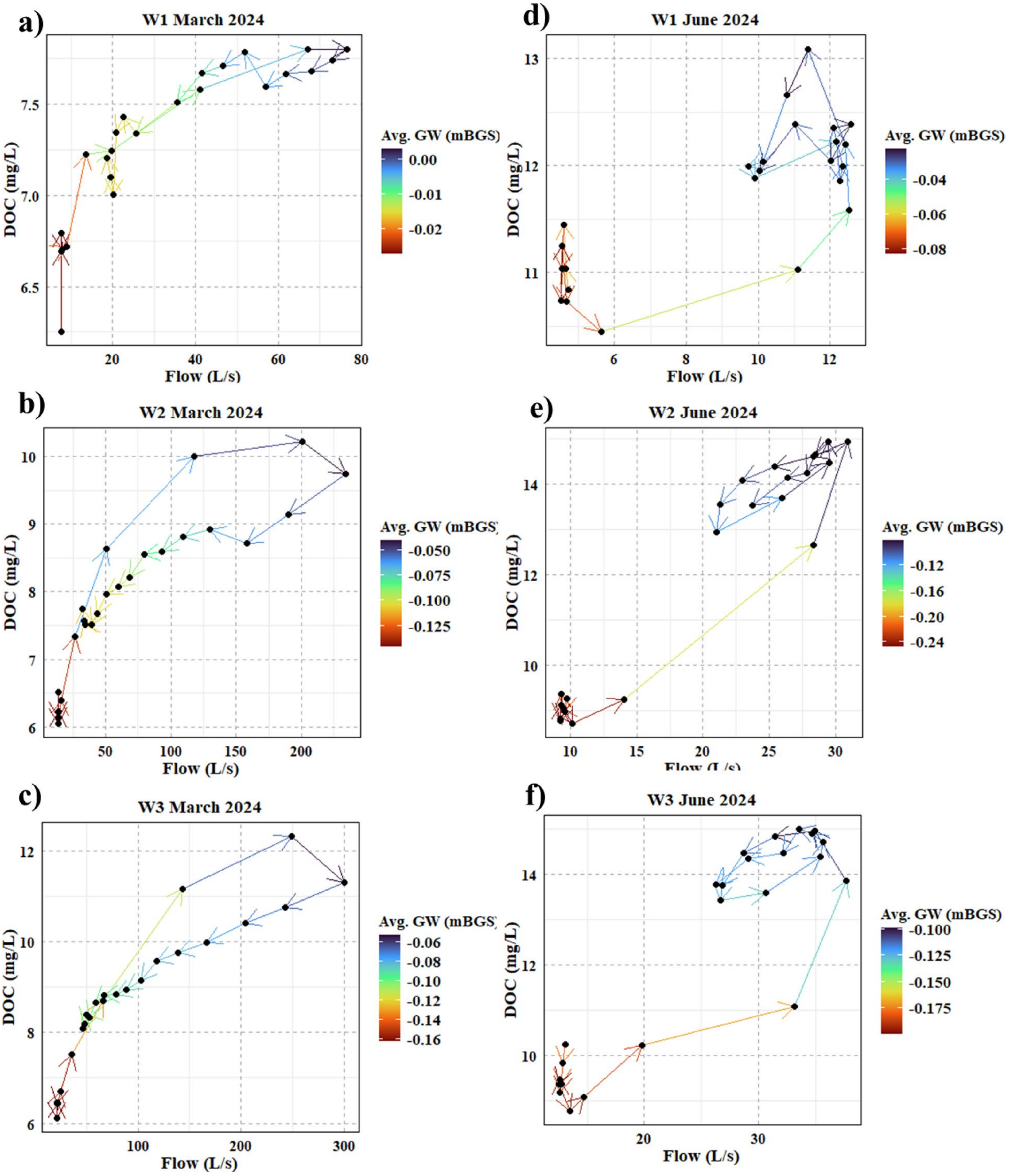

Fig. 7 Impact of seasonality and degradation on DOC variability and pathway of March 2024 (left) [**(a), (b), (c)**]and June 2024 (right) [**(d), (e), (f)**] event moving downstream from W1 (near-intact) to W3 (degraded)

autumn, suggesting that seasonal climatic variation may be an important driver underlying the responses observed. Overall, the findings of this study suggest that DOC production and export in blanket bog systems are strongly influenced by both peatland degradation (e.g. grazing, peat extraction, burning, drainage, and clear-felling) and seasonal hydrological variability.

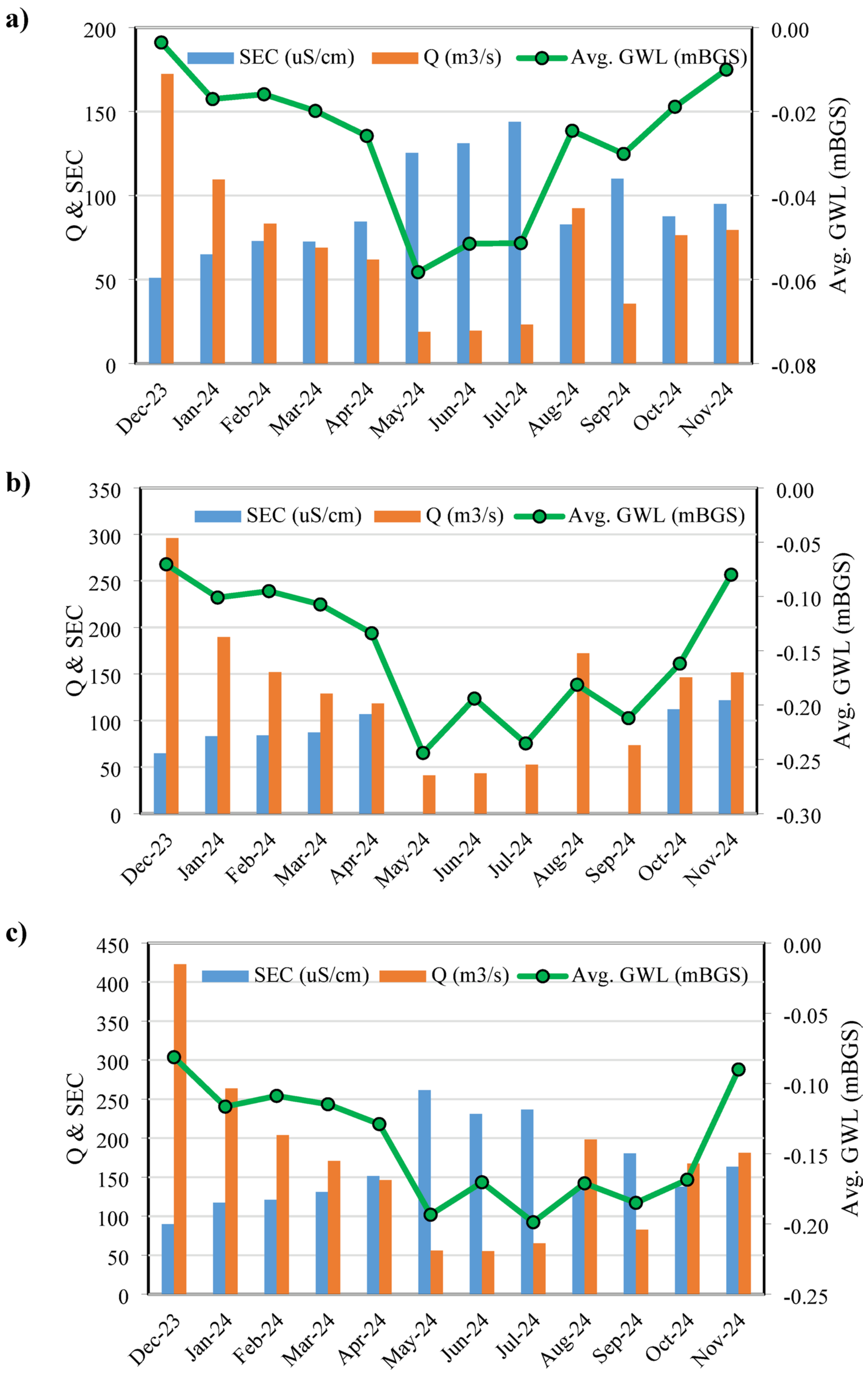

Fig. 8 Monthly comparison of streamflow, specific electrical conductance and average groundwater level: **(a)** W1, **(b)** W2, and **(c)** W3. SEC data at W2 is missing for three months due to instrument malfunctioning. Units of groundwater level are meters below ground surface (m BGS)

Conclusions

This study compared degraded blanket bog catchments with a relatively intact catchment and demonstrated that degradation leads to higher DOC fluxes, largely driven by lower groundwater levels. More specifically, key findings are summarized below:

1. DOC concentrations in the Fiddanduff River are significantly influenced by seasonal variation, as events collected in dry period showed high DOC concentration. Overall, the August 2024 event recorded the highest DOC concentration (14–18 mg/L), followed by the June 2024 (11.7–12.4 mg/L) and October 2024 (10–12 mg/L) events, while the lowest concentration (8–9.5.5 mg/L) was observed in the December 2024 event.
2. Seasonal variation in combination with blanket bog degradation give rise to consistently greater DOC export from degraded areas. For example, the August 2024 event resulted in DOC fluxes of 144 mg/m^2, 153.74 mg/m^2 and 304.6 mg/m^2 from W1, W2, and W3, respectively.

Study findings reveal that groundwater levels play a crucial role in controlling the variability of DOC export in runoff from blanket bogs. This is suspected to reflect seasonal processes; during summer, high evapotranspiration leads to a decline in groundwater levels within near-intact blanket bog catchments, while degraded areas exhibit substantially deeper groundwater levels. Lower groundwater levels allow greater oxygen penetration into the peat profile, stimulating microbial activity and enhancing DOC production. Moreover, during drier periods, most rainfall infiltrates to recharge groundwater, resulting in DOC accumulation within the peat until a major rainfall events raise water tables sufficiently to permit it to be flushed out. Due to consistently higher water tables in more intact areas, consistently lower, yet finite levels of DOC were observed in runoff. The DOC concentrations observed in discharge from these near-intact areas may therefore serve as a useful benchmark for restoration targets.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40068-025-00450-2.

Supplementary Material 1.

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Author contributions

Muhammad Jehanzaib: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization, Writing - review & editing. Raymond Flynn: Conceptualization, Validation, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition. Vicky Preece: Data curation. Hannah Lehnhart-Barnett: Data curation. Devin F. Smith: Investigation, Writing - review & editing: Oisín Leonard: Data curation. Tiernan Henry: Writing - review & editing. W. Berry Lyons: Project administration. Anne E. Carey: Project administration. Peter Croot: Writing - review & editing.

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Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Consent to publish was obtained from all individual participants included in the study.

Competing interests

The authors declare no competing interests.

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