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Upland grassland management influences organo-mineral soil properties and their hydrological function

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Abstract

Land-use change acts as a potential moderator of flood risk, affecting vegetation and soil properties and thus influencing the storage and flow of water across landscapes. This study, conducted in northwest England, investigated physical soil properties and their hydrological function using overland flow and soil moisture sensors, for five upland grassland habitats each created through management action. Overland flow was common, occurring up to 60% of the time with longer durations in grassland excluded from grazing with higher density vegetation. Soil moisture varied significantly between grassland habitats, but there was no clear soil moisture threshold for overland flow. Surface soil properties to 5-cm depth varied significantly between grassland types, with saturated hydraulic conductivity (K_s) ranging across several orders of magnitude from 1.3×10^{-3} to 1.5×10^{2} m day^{-1}. With shallow soils and a median K_s of 2.4 m day^{-1}, saturation-excess overland flow was determined as the main driver of flood risk. Landscape management was found to be a significant driver of soil physical and hydrological properties in upland grasslands and therefore should be strongly considered as part of flood management.

KEYWORDS
hydraulic conductivity, natural flood management, overland flow, soil moisture

1 | INTRODUCTION

As the occurrence of extreme weather events such as droughts and floods increase, landscape management is being considered to enhance resilience (Forbes et al., 2015). Land-cover is thought to be a key moderator for flood and drought risk by affecting the storage and transfer of water across landscapes (Archer, 2007; Gilman, 2002; Zope et al., 2017). However, recent reviews have suggested the evidence base for land-cover change impacts on hydrological functioning is still poorly formed (Burgess-Gamble et al., 2017; Dadson et al., 2017; Guzha et al., 2018; Rogger et al., 2017). Despite the lack of evidence, nature-based programmes to reduce flood and drought risk are now being funded. In the United Kingdom, for example, there is a programme of Natural Flood Management (NFM) that includes localised measures such as storage ponds and woody debris dams (Nicholson et al., 2020; Nisbet et al., 2015) and extensive measures such as woodland planting (Murphy et al., 2020), peatland restoration (Goudarzi et al., 2020; Shuttleworth et al., 2019) and reducing grazing intensity (Gao et al., 2015). Each initiative is designed to increase water storage or ‘slow the flow’ of run-off by enhancing roughness and decreasing the connectivity of the landscape. The influence of soil and vegetation properties on water storage and run-off generation for different habitats needs further research in order to support landscape-scale assessments of NFM (Burgess-Gamble et al., 2017; Environment Agency & CBEC, 2017; Forbes et al., 2015; Rogger et al., 2017; Strosser et al., 2015; WG POM, 2014; World Wildlife Fund, 2016).

In the United Kingdom, NFM initiatives are centred on headwater landscapes which typically have a cool, wet climate and are underlain by organo-mineral soils (OM soils). OM soils span multiple soil classification groups and are defined by the depth of surface organic material, generally <40 cm deep, and the organic content of that surface material, generally >20% (Forestry Commission, 2016; Holden et al., 2007; Joint Nature Conservation Committee, 2011; Smith et al., 2007). Very little is known globally about the hydrological function of OM soils, despite their common occurrence (Avery, 1990; Bol et al., 2011; Cranfield University, 2018; Hodgson, 1997; Mackney et al., 1983; Scotland's Soils, 2013). OM soils cover 30.5% of Europe, including 10.5% of England and Wales (of which 58.5% are in uplands), and 50% of Scotland and Ireland (Bol et al., 2011). While there are an increasing number of studies that recognise differences in soil properties between habitats and management types (Bogunovic et al., 2020; Carroll et al., 2004; Eze et al., 2020; Sun et al., 2018), and particularly reporting compaction effects (Clarke et al., 2008; Drewry, 2006; Wheater & Evans, 2009), there have been limited studies that have focussed on soil hydrological functioning and NFM, especially for OM soils. Thus, further work is required to understand how OM soils respond to rainfall events and whether their management can be used as part of NFM strategies by catchment managers.

OM soils are often not suitable for arable agriculture, particularly in headwater areas. Thus, such areas are often managed as grasslands to support livestock. Grasslands account for approximately 69% of global agricultural land (Wood et al., 2000), including 60% of the United Kingdom (of which 46% is 'semi-natural grassland'; DEFRA, 2016). Grasslands are the most common land use for OM soils in England and Wales, accounting for approximately 30% of total OM soil land cover (Bol et al., 2011). In upland England, 29% of all rough grassland, 35% of all bracken and 33% of all acid grasslands are underlain by OM soils (Bol et al., 2011). There are a range of grassland habitat types and management styles, each of which may influence soil hydrological function and run-off production through influences on soil compaction (Drewry, 2006), surface roughness (Bond et al., 2020), deposition of organic matter and root penetration into the soil (Soulsby, 1993), interception of precipitation by vegetation (Nisbet, 2005) and evapotranspiration. Each of these factors may contribute to regulation of water within grasslands, determining the antecedent conditions that drive rainfall–run-off response in a storm event. Within-grassland variation may also be important, influencing connectivity of hillslopes and streams.

This study seeks to investigate the hydrological function of five upland arable farm-based grassland types, henceforth referred to as habitat types, which are underlain by OM soil and subject to varying management conditions as part of the same heterogenous grassland landscape. Physical and hydrological soil properties are investigated including the hydrological function of each grassland management regime in response to storm events.

2 | METHOD

2.1 | Field site

Field measurements were conducted in Swindale, a 2.66-km^2 U-shaped valley in the Lake District of northwest England (Figure 1; 54°30′14.75″N, 2°45′56.91″W). Swindale has upland OM soils, predominantly Malvern 611a (Chromic Endoleptic Umbrisol) and Bangor 311e (Dystric Epileptic Histosol) soils, underlain by igneous shale and bedrock (Cranfield University, 2020). The U-shaped valley ranges between 270-m and 430-m elevation and forms part of a wider 15.3-km^2 catchment. In Shap, 5 km northeast of Swindale at 255 m

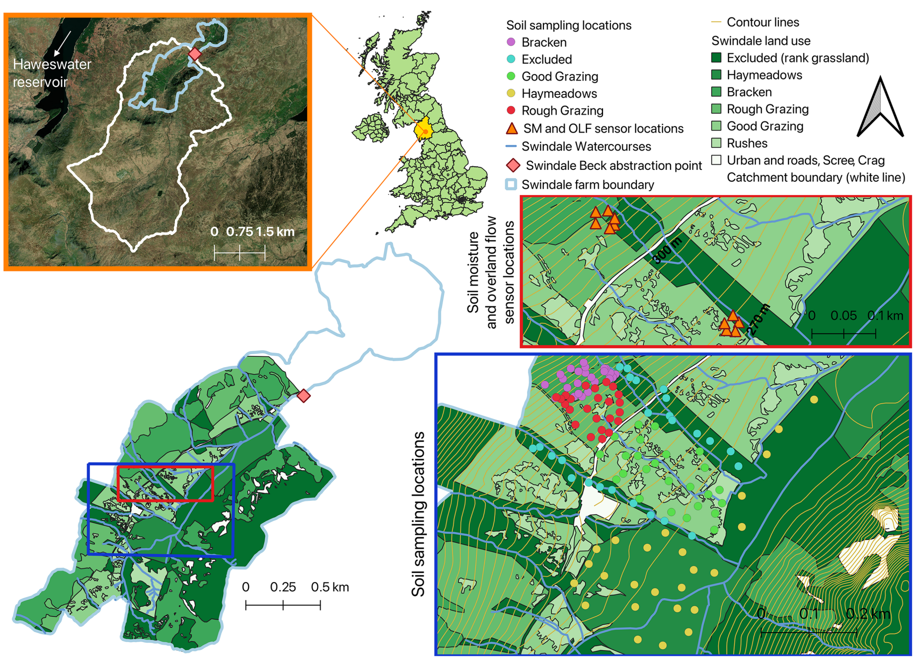

FIGURE 1 Swindale location and location of all physical soil sampling and soil moisture (SM in legend) and overland flow (OLF in legend) sensors. B = Bracken, E = Excluded (Rank Grassland), GG = Good Grazing, RG = Rough Grazing. For schematic diagram showing hydrological (soil moisture and overland flow) sensor locations, see Figure 2

above sea level, mean annual precipitation was 1779 mm between 1981 and 2010; mean of each daily maximum temperature at Shap was 11.5°C, and mean daily minimum was 4.1°C (Met Office, 2020). Swindale is part of a higher level stewardship scheme (HLS) that manages the upland grassland habitats as part of a working farm. HLS is an agri-environmental scheme in England that provides funding to land managers in return for environmentally conscious management (Natural England, 2012). This includes action such as creating and maintaining woodland, encouraging species-rich grassland or hay meadows, or protecting water quality.

Our sampling was conducted in a paired-plot comparison over one section of hillslope so that direct comparisons between adjacent habitats could be made, factoring in elevation, aspect, and making a reasonable assumption of similar climatic conditions (Figures 1 and 2). A section of hillslope was chosen representing five farm-based habitats that have the same Malvern 611a (Chromic Endoleptic Umbrisol) underlying soil type (Cranfield University, 2020) but represent different commonly occurring U.K. upland grassland types. These habitats were Good Grazing and Rough Grazing, Excluded (rank grassland not used for grazing), Hay Meadows and Bracken (Table 1); these habitats were also the most common habitat types within the farm boundary, each representing between 9.4% to 34% of the total land cover. When compared with the 2007 CEH U.K. land cover map (Morton et al., 2011), all sampled Swindale grassland types occur within the

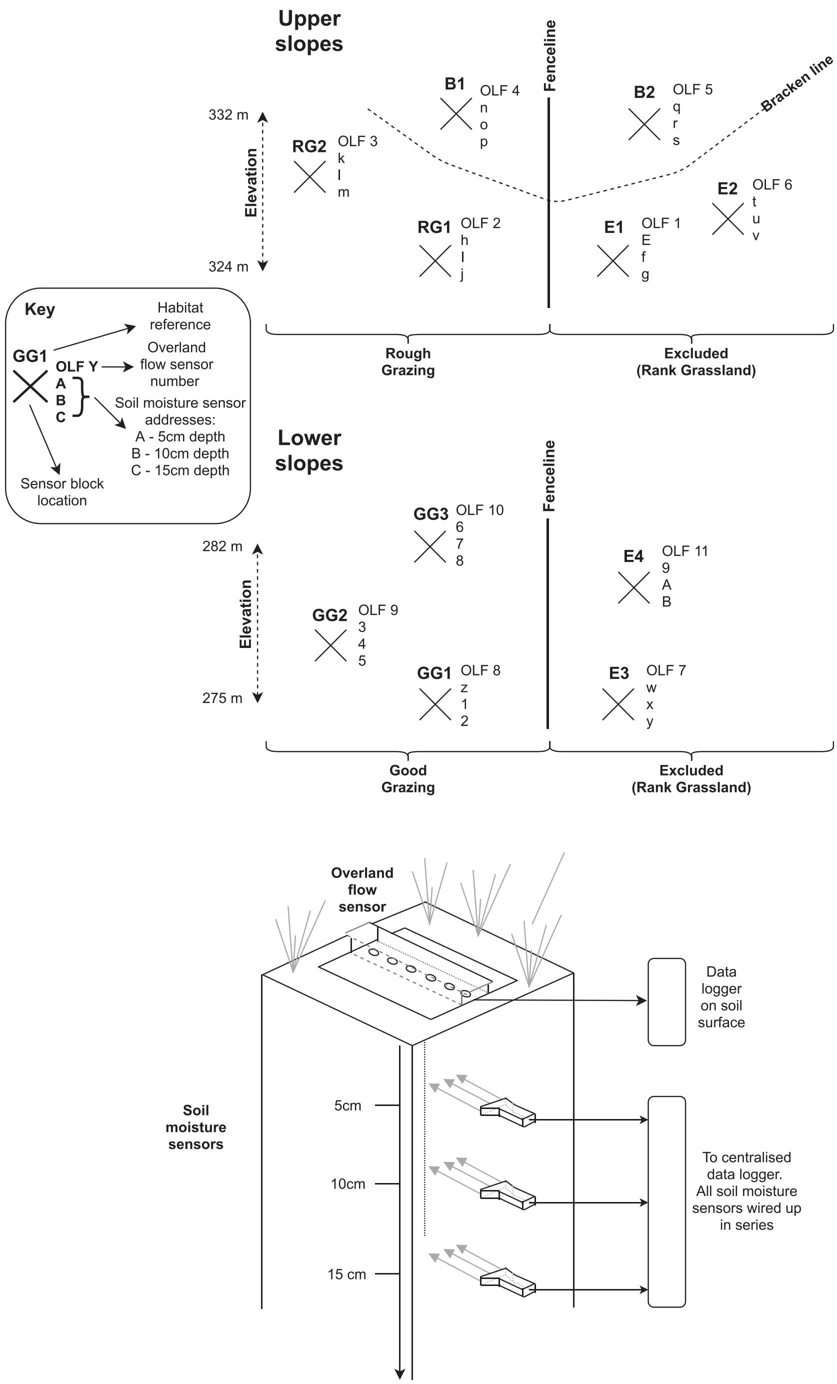

FIGURE 2 Schematic of the sensor installation. Above: the location of soil moisture and overland flow sensors in Swindale. Below: the configuration of soil moisture and overland flow sensors at each sensor block location

TABLE 1 Grassland habitats in Swindale

Study section	Habitat name		Elevation range (m) Average slope (degrees) Approx. land cover in Swindale (%)	Dominant species	Description and management	
Physical soil properties only	Hay Meadows		266–285 m 5.4° 9.5%	Grasses: *Holcus lanatus*, *Anthoxanthum odoratum* and *Cynosurus cristatus* Broadleaf species: *Rhinanthus minor*, *Trifolium dubium*, *Trifolium pratense* and *Plantago lanceolata*.	Hay Meadows are species-rich grasslands in which no single species dominates. Parts of Swindale represent a typical upland hay meadow: species rich with a SSSI[a] designation in parts of Swindale. Left ungrazed from March throughout the spring and summer months until cutting at the first opportunity after 25 July. After this, the Hay Meadows are lightly grazed through the winter months while sufficient fodder remains.	
Physical soil and soil hydrological properties	Bracken		330–355 m 22.4° 24.4%	Bracken: *Pteridium aquilinum*	Bracken is the largest, most common native fern species in the United Kingdom and grows in dense swathes favouring dry, acid soils (Wildlife Trust, 2020). In Swindale, Bracken grows within the 'Rough' Grazing and Excluded habitats on the upper slopes above 330-m elevation.	
	Low-density Grazing	Good 11.5% Rough	Grazing Maximum 2.66 ewes plus lambs per hectare	266–300 m 12.0° Grazing 335–340 m	Grasses: *Festuca ovina*, *Agrostis spp. and Cynosurus cristatus* Moss species: *Rhytidiadelphus squarrosus* Broadleaf species: *Trifolium repens*, *Luzula campestris and Rumex acetosella*	The definition of low-density grazing on upland pasture varies greatly. In Swindale, stock density is very variable throughout the year. Most stock spend bulk of summer months out of Swindale on common land, returning for short periods for treatments, shearing and separating lambs from ewes. Stock mostly sent away for winter months.
	16.2° 12.1%					
14.8° 34.0%	Excluded (Rank Grassland)		270–330 m	Grasses: *Dactylis glomerata*, *Holcus lanatus*, *Agrostis capillaris*, *Anthoxanthum odoratum*, and *Festuca spp*. Broadleaf: *Ranunculus repens*, *Lotus pedunculatus*, *and Ranunculus acris*	Typically species poor, Rank Grassland is dominated by tall, tussocky and coarse grass species and is produced in unmanaged, ungrazed grasslands. In Swindale, Rank Grassland is the result of grazed fields being fenced-off for a period of 7 years without cutting or grazing. No management currently applied in Swindale.	

Note: Elevation range refers to the range over which samples were taken and sensors placed as part of this study. Average slope and approximate land cover have been calculated using habitat cover over the Swindale Farm to the abstraction point (filled-in land use shown in Figure 1, left, bottom corner).

[a]SSSI is a Site of Special Scientific Interest, a conservation designation in the United Kingdom, which gives legal protection to land with features of particular interest such as its wildlife, geology or landforms.

three most populous land-use categories: Improved Grassland (the United Kingdom covers 23.60%, which includes Good Grazing, Rough Grazing and Hay Meadows), Rough Grassland (the United Kingdom covers 5.48%, which includes the Excluded habitat) and Acid Grassland (the United Kingdom covers 6.94%, which includes Bracken).

Good Grazing and Rough Grazing are both low-density habitats that have been given the grade of 'Good' or 'Rough' based on the quality of fodder and the extent to which the sward is allowed to grow before grazing. Rough Grazing is also situated on the higher, steeper hillslopes. Bracken, which dominates the upper hillslopes above 330-m elevation in Swindale, grows within the Rough Grazing and Excluded habitats. Each of these habitats have distinctive, but potentially adaptable, management strategies that may influence hydrological functions.

Seven years prior to this study, the Excluded habitat was created by fencing-off the watercourses from grazing using wide buffer strips throughout the catchment. Therefore, the Excluded habitat is relatively new and would have previously been subject to low-density grazing under the Good Grazing or Rough Grazing management.

Precipitation data were acquired from Mickleden, approximately 24 km southwest of Swindale (Middle Fell Farm telemetry, Station number 586820, Environment Agency, 2020). The rain gauge recorded 15-min interval data between May 2019 and March 2020. Flow gauge data for Swindale Beck were also recorded at 15-min intervals from the United Utilities Crump Weir located at the Swindale Beck abstraction point to Haweswater Reservoir (Figure 1).

2.2 | Soil properties

Soil properties were analysed over the five habitats, encompassing valley bottom (270 m) to steep upper slopes (330 m). Three soil pits per habitat were dug in the upper and lower slope plots to describe the OM soil horizons present. From the horizons identified, physical attributes that may influence soil hydrological function were assessed. Soil samples were then taken across the width and depth of each habitat in the hillslope, and all habitats had the same aspect. To prevent elevation bias, each habitat was divided into sections using 5-m contour lines, and the same number of samples were taken randomly along each line (Figure 1). In total, 125 intact soil samples were collected at 0- to 5-cm depth between November 2018 and May 2019, 25 for each habitat. Since bedrock was common below 5-cm depth, intact soil cores were collected as near-surface samples only.

Samples were analysed in the laboratory for saturated hydraulic conductivity (K_s) using an Eijkelkamp 25 place permeameter. Following K_s measurement, saturated intact soil cores were transferred to preweighed metal containers and dried overnight at 105°C to remove moisture and then reweighed to determine bulk density. Total organic matter (*TOM*, %) was calculated using loss on ignition at 550°C.

Shapiro–Wilkes tests showed that bulk density and *TOM* were normally distributed, whereas the K_s distribution was non-normal. As a result, bulk density and *TOM* were analysed using ANOVA and Tukey's post hoc tests, whereas K_s data were analysed using non-normal Kruskal–Wallis and Dunn's post hoc tests. The relationship between soil properties was investigated using Spearman's rank (Figure S1.1, Supporting Information S1).

2.3 | Hydrological monitoring

Hydrological monitoring occurred between May 2019 and March 2020 over four habitat types, using a paired-plot method. The paired-plot approach reduced spatial or temporal influences from factors such as elevation, underlying geology or storm event tracking. The Hay Meadows habitat was not included in the hydrological instrumentation because, being at the bottom of the hillslope, it did not have an equal-elevation comparison with another habitat and was known to collect water as part of the natural floodplain.

Two paired-plot sites were chosen, one on the 'upper slopes' incorporating Rough Grazing, Bracken and Excluded habitats, and one on the 'lower slopes' incorporating Good Grazing and Excluded (Figures 1 and 2 and Table 1). Although Bracken grew in both the Excluded and Rough Grazing habitat, it has been included as a separate habitat; Bracken is generally avoided by livestock, and its density precludes growth of the vegetation species otherwise found in the Excluded and Rough Grazing habitats. Each paired plot contained a series of 5TM Campbell Scientific soil moisture sensors at 5-, 10- and 15-cm depth, wired in series to an Arduino data logger that measured percentage soil moisture at 15-min intervals. Soil moisture sensors were calibrated using the method by METER Environment (2020). At the soil surface, an overland flow sensor, made following the design by Goulsbra (2011), measured the absence or presence of overland flow at 5-min intervals (Figure 2).

For clarity, when referring to the soil moisture and overland flow sensors, individual sensors henceforth are referred to by the location for which they were assigned (Figure 1) where E represents the Excluded habitat, RG represents Rough Grazing, B represents Bracken and GG represents Good Grazing. The number following each habitat abbreviation represents its position (Figure 2). A full list of abbreviations used in this manuscript can be found in Supporting Information S2 (Tables S2.1 and S2.2).

Some data gaps occurred during the operation of the soil moisture sensors due to power source and equipment failures and equipment tampering. Consequently, the period of time for which the soil moisture sensors were operational varied by location. The upper slope data ran for two periods, May 2019 to August 2019 and December 2019 to March 2020, during which all sensors were operational. The lower slope data were subject to more difficulties. Sensors for the habitats E4 and GG1 were operational May 2019 to October 2019 and mid-November to December 2019. All other sensors were operational mid-September to October 2019 and mid-November to December 2019 with occasional other scattered data points. The temporal distribution of soil moisture data is shown in Supporting Information S3 (Figures S3.1 and S3.2). The operation of the overland flow sensors and total time overland flow was present per habitat is shown in Table S4.1, Supporting Information S4.

Due to soil moisture sensors operating for different time periods (Supporting Information S3, Table S3.1), a matched-records approach was adopted, analysing data for time periods when all sensors were operational across each slope position.

For the upper slopes, 9526 matched records were available during which 808.4 mm rain fell; 9526 records accounted for 35.7% of the total possible records between May 2019 and March 2020. For the lower slopes, 3181 matched records were available during which 246.6 mm fell. This accounted for 11.9% of the total possible records. For both slope positions, periods of drought and large storm events were included in the matched-records data.

Since the matched records data were not normally distributed, a Kruskal–Wallis test was used to analyse difference in soil moisture between habitats within each slope position and by sensor depth. Tests were repeated to examine storm and drought conditions using the top and bottom 1% of soil moisture data.

Soil moisture was analysed using a general linear model for the sensors at 5-cm depth, where topsoil soil moisture is thought to be strongly connected to run-off production (Huza et al., 2014; Meißl et al., 2020). The model predicted soil moisture and cumulative rainfall by habitat per storm event, based on scaled variable data. Scaling is a process by which each variable entry for soil moisture and cumulative rainfall was subtracted from the mean and divided by the standard deviation, making both variables unitless, therefore comparable.

In combination with overland flow and rainfall data, we tested whether there was a soil moisture threshold at which overland flow occurred. Soil moisture thresholds ranging between 5% and 50% soil moisture were chosen for which the percentage overland flow presence was determined. The influence of seasonality on overland flow at different soil moisture thresholds was also tested.

3 | RESULTS

Results are split into three sections: soil profiling, soil properties and hydrological monitoring.

3.1 | Soil profile description

Soil pits were always less than 30 cm deep before reaching large pieces of underlying bedrock, which were impenetrable with hand tools (Figure 3). At depths greater than 5 cm, smaller pieces of shale up to approximately 5-cm diameter were present throughout the soil profile. The upper slopes had a more developed soil profile than the lower slopes. For the upper slopes, an O/A surface organic horizon, approximately 7 cm deep, overlays an eluviated (E) horizon, approximately 8 cm deep, which contained a higher clay content and leached mineral and organic material. Underlying the O/A and E horizons, a subsoil B horizon, approximately 9 cm deep, overlay the base shale (C) horizon. In comparison, the lower slope soil profiles consisted of one O/A horizon directly overlying the parent-material C horizon.

FIGURE 3 Representative soil profiles for the upper (left) and lower (right) slope sampling locations

3.2 | Soil properties

The relationships between K_s, bulk density and *TOM* are shown in Supporting Information S1. *TOM* and bulk density were found to be significant negatively correlated across the whole dataset ($R^2 = -0.82$, $p < 0.001$) and for individual habitats ($p < 0.05$). A significant negative correlation was also found between bulk density and K_s when examining all soil samples ($R^2 = -0.21$, $p = 0.019$); however, when this correlation was tested for individual habitats, only that for Bracken was significant ($R^2 = -0.69$, $p < 0.001$). No correlation was found between *TOM* and K_s.

Within the area sampled, elevation did not have a significant influence over any soil properties measured ($p > 0.05$). Mean *TOM* was highest in the Hay Meadow (24.6%) followed by Good Grazing (23.3%), Bracken (22.2%), Excluded (20.2%) and Rough Grazing (17.4%). Rough Grazing had significantly lower *TOM* than all other habitats, and Excluded *TOM* was significantly lower than that for Bracken, Good Grazing and Hay Meadows (Figure 4, $p < 0.05$). Good Grazing *TOM* was not significantly different to that of Bracken and Hay Meadows; however, Hay Meadows had significantly higher *TOM* to Bracken (Figure 4, $p = 0.047$). Variability in *TOM* was highest for Good Grazing, having an interquartile range of 7.0%, and lowest for Rough Grazing with an interquartile range of 3.6%.

Rough Grazing had significantly higher bulk density than all other habitats with a mean of 0.768 g cm^{-3}, followed by Excluded (0.654 g cm^{-3}), Bracken (0.618 g cm^{-3}), Hay Meadows (0.568 g cm^{-3}) and Good Grazing (0.562 g cm^{-3}) (Figure 4). The latter three were not significantly different to one another, while Excluded had significantly higher bulk density compared to Good Grazing and Hay Meadows (Figure 4, $p < 0.05$). The interquartile range was greatest for Good Grazing (0.208 g cm^{-3}).

K_s was high for all habitats, ranging across several orders of magnitude from 1.3×10^{-3} to 1.5×10^{2} m day^{-1} with a median of 2.4 m day^{-1}, suggesting that infiltration-excess overland flow was unlikely to occur across most of the landscape studied. Median K_s was highest in Bracken followed by Excluded, Good Grazing, Rough Grazing and Hay Meadows (Figure 4). K_s varied significantly between habitats, but within

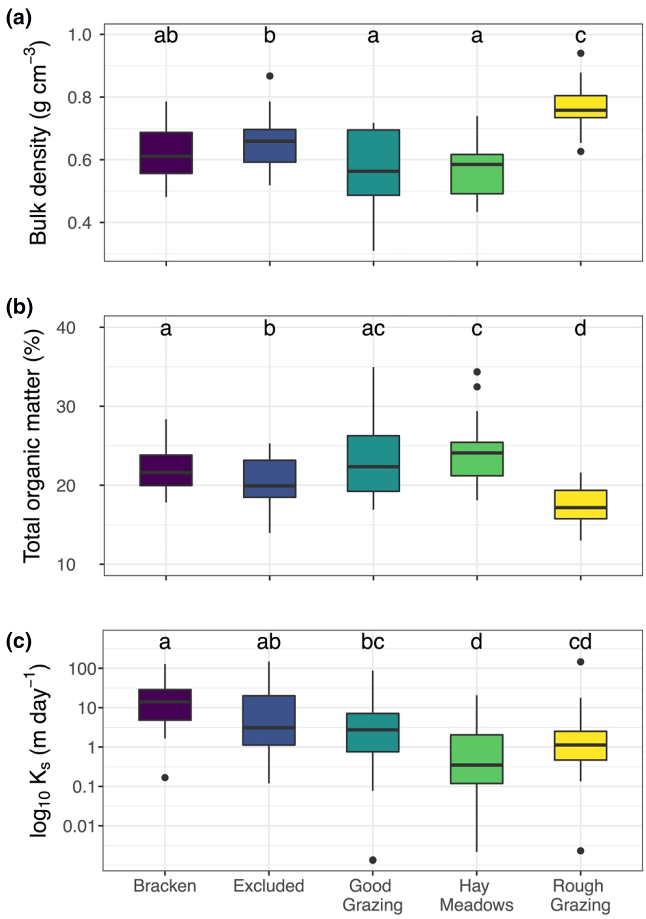

FIGURE 4 Soil properties for Bracken, Excluded (Rank Grassland), Good Grazing, Hay Meadows and Rough Grazing habitats. Boxplots show the range, quartiles and median data for each soil property: (A) bulk density, (B) total organic matter and (C) K_s. Statistical significance is shown by the letters above each boxplot (Tukey's post hoc test, $p < 0.05$) where a shared letter indicates no statistical significance

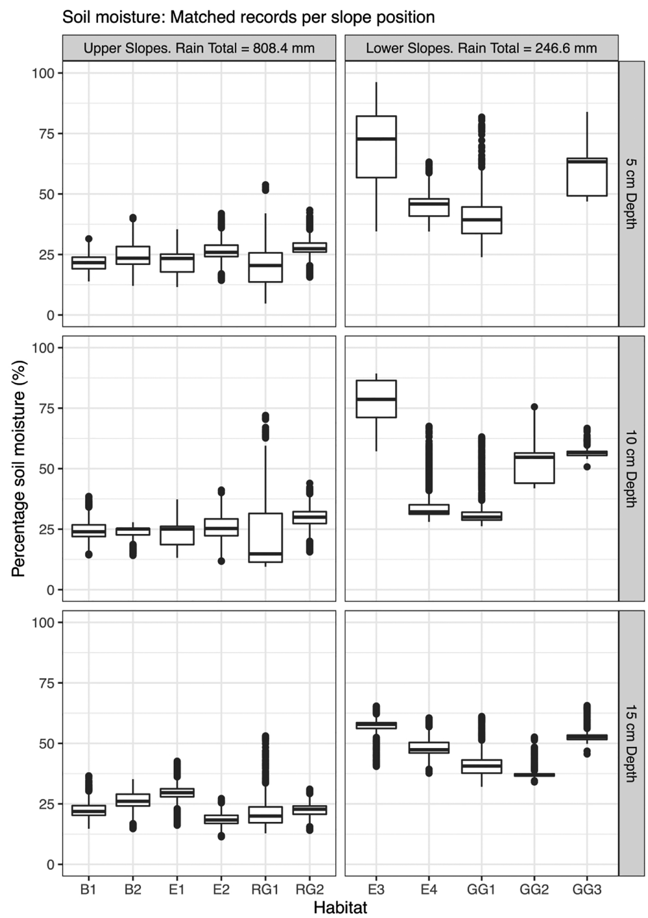

FIGURE 5 Soil moisture boxplots comparing habitats within each slope location by matched-records (i.e., the same time periods for each habitat within that Slope position). Direct statistical comparisons cannot be drawn between the upper and lower slope sites. Statistical significance is represented by the letters above each graph facet (Dunn's post hoc test, $p < 0.05$) where comparisons are made between habitats within each Slope position and sensor depth, and a shared letter indicates no statistical significance. Boxplots show the range, quartiles and median data for each habitat. Outlying data (data points greater than 1.5 * inter-quartile range) were retained because measurements of extreme soil moisture values related to antecedent conditions and storm events

habitats, there was up to three orders of magnitude variation. K_s for Bracken was significantly greater than that for Good Grazing, Hay Meadows and Rough Grazing while K_s for Excluded was significantly greater than that for Hay Meadows and Rough Grazing. K_s for Good Grazing was significantly greater than that for Hay Meadows (Figure 4).

3.3 | Hydrological monitoring

3.3.1 | Soil moisture

Mean soil moisture was found to significantly vary between all habitats, at all depths, subject to the same precipitation (Dunn's post hoc, $p < 0.05$), except for between RG1 and B1 in the upper slopes at 5-cm depth (Figure 5). Although soil moisture varied by depth, a Dunn's post hoc analysis of the whole dataset showed that, for the upper slopes, the driest habitat was RG1 followed by B1, E2, B2, E1 and RG2, the wettest habitat. However, when isolating the highest and lowest 1% of soil moisture data for each upper slope habitat, RG1 consistently had the highest soil moisture peaks, reaching a maximum 72%, and the lowest soil moisture, as low as 4.7%. Analysis of the top 1% of soil moisture data showed that, excluding Bracken, upper slope habitats were grouped; RG1 and RG2 were statistically similar to each other, as were E1 and E2 (Dunn's post hoc, $p < 0.05$). Otherwise, habitats were statistically different (top 1% data, Dunn's post hoc, $p < 0.05$). In comparison, for the bottom 1% of soil moisture data, all habitats except E1 and E2 were statistically different to each other (bottom 1% data, Dunn's post hoc, $p < 0.05$).

In the lower slopes, GG1 was the driest habitat, followed by E4, GG2, GG3 and E3, the wettest habitat. Looking at the top 1% of soil moisture data, E3 had the highest peaks, up to 96.2%, and GG1 had the lowest soil moisture (23.9%). Excluding GG1 and GG2, all lower slope habitats had significantly different soil moisture peaks (top 1% data, Dunn's post hoc, $p < 0.05$), and all habitats were significantly different from each other during the driest 1% period (Dunn's post hoc, $p < 0.05$).

Because of the nature of the matched-records analysis, slope positions were not comparable to each other using statistical tests. However, upper slope soil moisture was less variable (~25% moisture for all three depths) than lower slope soil moisture, which was more varied, and large peaks in soil moisture were reflected in towering 'whiskers' and outlying datapoints (Figure 5). Maximum soil moisture in the lower slopes was frequently 1.5 times greater than median soil moisture. Soil moisture was generally higher in the winter months (October to March) than summer (May to September).

3.3.2 | Overland flow

Overland flow occurred in all habitats between May 2019 and March 2020. In some habitats, overland flow was very frequent, occurring >60% of the time in habitat GG3, 57% of the time in habitat E3 and approximately 40% of the time in habitats E1, E2 and E4 (Table S4.1). Habitat GG2 had overland flow present for 32.7% of its operational timeframe and habitat B2 showed overland flow presence 19.8% of the time. All other habitats produced overland flow <9% of the time between May 2019 and March 2020.

Overland flow was consistently recorded more often in the lower slopes than the upper slopes and occurred more frequently in winter months than summer. Overland flow was also found to occur more often on the Excluded side of the hillslope than the grazed side, with the exception of habitat GG3 (Figure 6, Table S4.1). The Good Grazing habitat had the most varied overland flow occurrence within it, with 8–60% occurrence, despite the sensors' relatively close proximity to each other. In comparison, within habitat and slope position categories for Excluded and Rough Grazing sensors recorded similar values. For example, E1 and E2 were operational >90% of the time, recording overland flow presence 39% and 40% of the time respectively (Table S4.1).

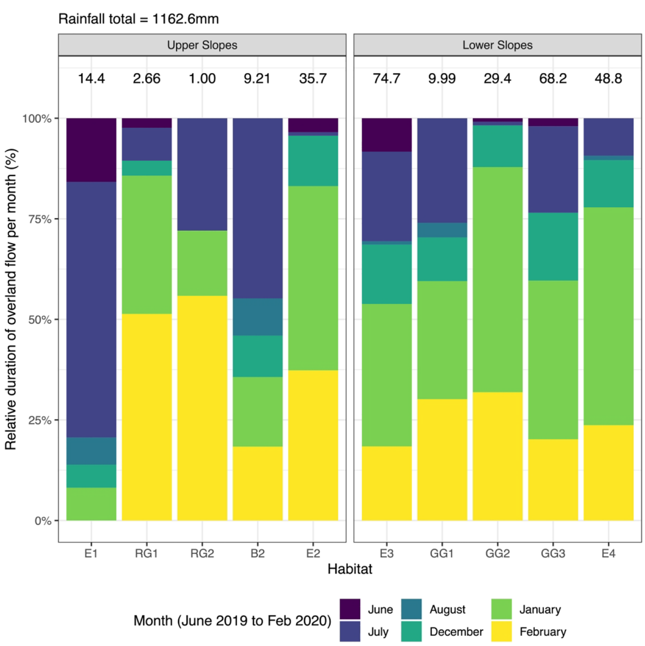

FIGURE 6 Relative overland flow presence per habitat per month. Calculated using a matched-records analysis including all sensor locations except B1. Above each stack the total duration of overland flow per habitat for all months is shown (%). Full details of the percentage overland flow and rainfall volume per month are shown in Supporting Information S4

The overland flow sensors were operational for the majority of the research period with most sensors recording data 65–99% of the time; only sensor B1 was operational for less time, working just 27% of the research period. Because of this, sensor B1 was excluded from a matched-record analysis that allowed direct comparison of habitats by monthly overland flow occurrence based on same-date, reliable records without bias towards seasonality or storm event (Figure 6).

Using the matched-records approach, with the exception of habitat E1, the majority of overland flow occurred in January and February, accounting for >50% in all lower slope habitats. January and February also account for the greatest rainfall volume with 434.6 mm and 326.8 mm, respectively, falling within the timesteps analysed. Winter overland flow, represented by December, January and February matched-records data, accounted for >70% overland flow presence in all habitats except E1 and B2, for which overland flow was most common in summer months. The third most common month in which overland flow occurred was July, accounting for >20% overland flow in habitats E1, RG2, B2, E3, GG1 and GG3. July also received the third highest volume of rainfall, 227.4 mm, which followed a drought period in June and early July.

There was no apparent soil moisture threshold at which overland flow occurred. Overland flow occurred at all soil moisture thresholds tested, even <5%, and was not more common within a particular soil moisture bin width. Although soil moisture was generally lower in the summer months than in winter months, and overland flow was recorded more often in the winter than summer, there was no soil moisture threshold influence on overland flow identified when analysis was undertaken for summer and winter periods independently.

3.3.3 | Storm events

Between May 2019 and March 2020, 68 storm events occurred, which had greater than or equal to 20-mm precipitation over a 24-h period. Figures 6 and 7 show two storm events that were representative of the hillslope response to rainfall in the summer and winter. These two events represent the largest storms for which soil moisture data were available at both upper and lower slope locations. For 5-cm depth, a general linear model indicated that soil moisture for all habitats significantly varied from each other for both the July and December storm events tested (Figures 7 and 8); both habitat type and the volume of cumulative rainfall were important in the model.

In both storm events, soil moisture was quick to respond to the onset of rain, rising almost immediately in response to rainfall. However, the summer response was more muted in comparison with the winter, gradually rising until peak rain and then falling gradually over

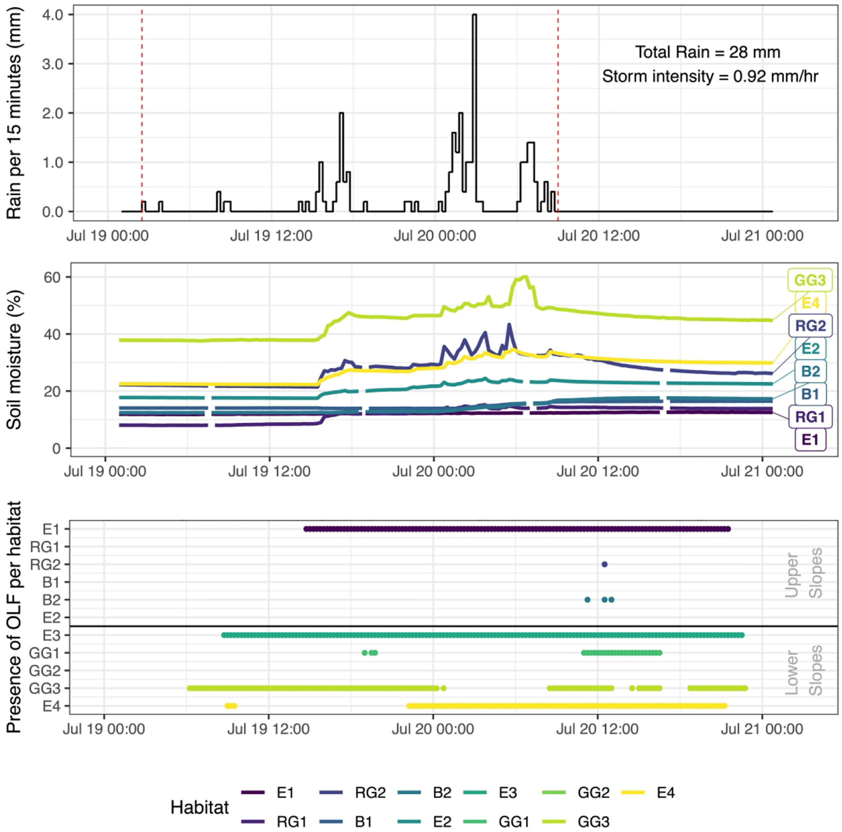

FIGURE 7 Rainfall, soil moisture (5-cm depth only) and presence of overland flow for a July 2019 storm

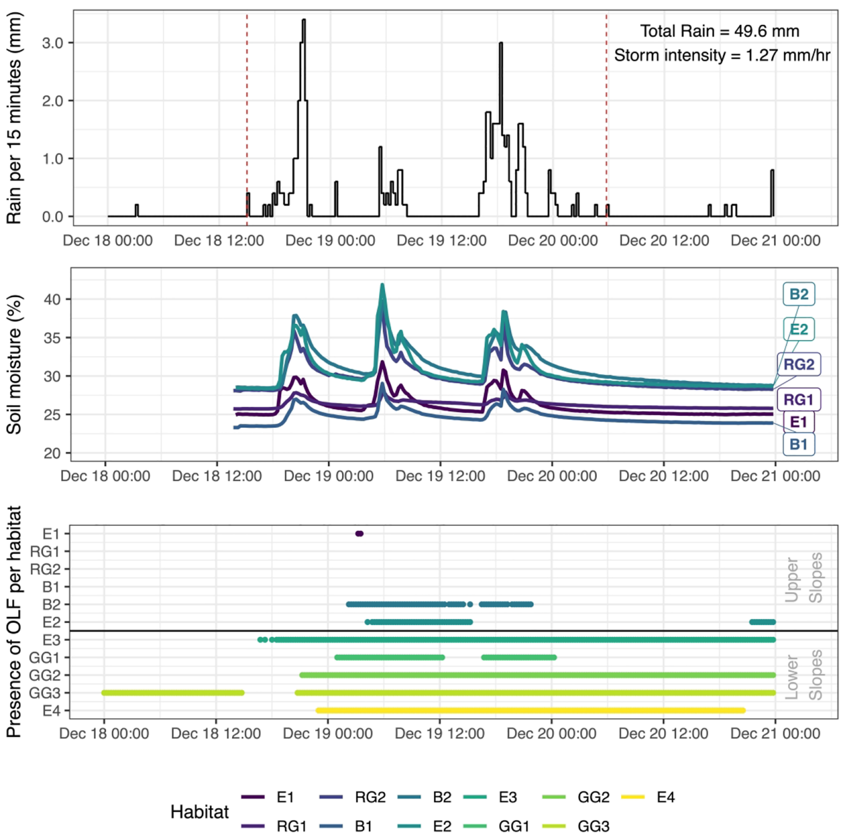

FIGURE 8 Rainfall, soil moisture (5-cm depth only) and presence of overland flow for a December 2019 storm

the following 12 h after which it had almost returned to the previous base-level moisture. The winter soil moisture was higher before the beginning of the storm than for the summer storm. However, soil moisture changes strongly in response to rainfall intensity, increasing soil moisture by up to 8% before falling rapidly after each rain event. After 12 h, soil moisture was at the pre-storm level again. Overland flow occurrence was more frequently recorded in the winter storm than the summer storm. However, both storms show a delay in overland flow response after rainfall and soil moisture rise, suggesting a saturation-excess overland flow response. For both storm events, habitat GG3 and E3 are the most sensitive to hydrological changes with overland flow occurrence quickly following any rainfall.

4 | DISCUSSION

Overland flow is an important feature in this upland OM soil system, frequently occurring in response to storm events. Results from this study recorded overland flow as being present or absent only; therefore, it is impossible to make comment about the volume of overland flow that occurred in each habitat. Many studies (Carroll et al., 2004; Jordon, 2020; Marshall et al., 2014) suggest that overland flow should be more prevalent in grazed habitats than ungrazed, and while the sensor location which recorded overland flow presence most often was GG3, a grazed habitat, overland flow occurred more frequently overall in Excluded habitats. The prevalence of overland flow in Excluded habitats may be a consequence of enhanced storage and slowing of flow in the more highly vegetated ungrazed habitats, through which surface water cannot flow downslope as readily and therefore the time for which overland flow lasts is longer. Confirmatory evidence for this hypothesis comes from Bond et al. (2020) who used overland flow velocity experiments in the Swindale catchment to show that surface roughness in Rank Grassland was associated with an overland flow velocity half that of the velocity in Hay Meadows. Thus, the Excluded habitat, the same habitat which Bond et al. (2020) called Rank Grassland, retained overland flow for longer which could be key for NFM implementation.

The common presence of overland flow in all habitats combined with high K_s (Figure 4), the shallow soil profiles (Figure 3) and the delayed overland flow onset after storm events (Figures 7 and 8), suggests a saturation-excess overland flow mechanism dominates in the upland grassland system studied. In many catchments, subsurface properties are thought to play a key influence on catchment hydrology (Anderson & Burt, 1990). In Swindale, we hypothesise that shallow soils and large pieces of underlying shale slow groundwater percolation allowing soil saturation to occur quickly, despite the high soil K_s values. The lower slope habitats were more susceptible to overland flow with net accumulation from upslope, and shallowest soils and higher soil moisture throughout the year, including soil moisture peaks up to 96.2% (Figure 5).

Despite the above, there was not an obvious soil moisture threshold at which overland flow occurred. Analysis of storm events produced some evidence to suggest that there was greater retention and slower release of water in the Excluded habitats than the grazed habitats, shown by prolonged overland flow presence. The difference between habitats may be related to both retention of water by the increased volume of vegetation in the ungrazed sections of the hillslope and to the physical soil properties, for which K_s was highest for the Excluded and Bracken habitats (where Bracken was 50% within the Excluded habitat and generally avoided by grazing livestock).

When compared on a matched-records basis, mean soil moisture was found to significantly vary between all habitats at all depths with the exception of habitats B1 and RG1 at 5 cm depth (Figure 5). The variation in soil moisture highlights strong heterogeneity within grassland habitats, even within those subject to the same management and weather conditions. Nevertheless, grouping was observed when comparing the top and bottom 1% of data where some sensor locations within a habitat type were statistically similar (RG1 and RG2, E1 and E2 and GG1 and GG2). Grouping suggests that management of grassland habitats may have a dominant influence over soil moisture extremes.

As expected, soil moisture was higher year-round in the lower slope habitats and higher in winter months compared with summer; however, significant within-habitat variation for both soil moisture and soil properties may be due to localised differences in compaction, rooting and micro-topography (Clarke et al., 2008; Ghestem et al., 2011; Hu et al., 2020). These localised differences may also account for the absence of anticipated grouping of grazed versus excluded habitats in terms of mean soil moisture, bulk density, *TOM* and K_s. It may be that rooting and compaction out-weigh each other in affecting infiltration and run-off for these habitats. Certainly, the higher overland flow frequency in the Excluded habitat does not translate to a higher soil moisture; this may also be a reflection of volume verses frequency of overland flow where both Low-density Grazing and Excluded habitats were subject to the same volume of rain which produced statistically similar soil moisture but differing durations of overland flow presence.

Bulk density, *TOM* and K_s were significantly different between most grassland types. The differences in soil properties are likely due to the influence of management which alter organic matter inputs through grazing and vegetation controls. Vegetation species present and grazing density are naturally heterogenous within each habitat type, explaining high within-habitat variability alongside micro-topographical influences. For example, high *TOM* in the Hay Meadows may be a consequence of floodplain deposition or waterlogging affecting breakdown of organic matter. Although, as expected, *TOM* and K_s were found to be significantly negatively correlated to bulk density (Figure S1.1), there was no strong association between management and soil properties, especially when comparing grazed and ungrazed habitats (Figure 4). Again, this may be the result of strong within-habitat heterogeneity, itself a partial consequence of low-density grazing and relatively newly-implemented exclusion zones. K_s had especially high variability, and the values recorded were similar to the highest found in temperate or high latitude peatlands: a literature summary of peat K_s by Branham and Strack (2014) suggests values between 8.64×10^1 m day^{-1} and 8.64×10^{-4} m day^{-1} across eight studies. This suggests that, for surface properties at least, OM soils have a similar hydrological response to peat, further supported by the dominance of saturation-excess overland flow.

Many studies compare land uses for which management has been separately applied for decades. In this study, the Excluded habitat had only been in operation for 7 years following grazing. If the Excluded habitat had the same soil properties as the low-density grazing habitats prior to being fenced-off, then we have evidence that changes in grassland management may quickly alter soil properties and hydrological conditions.

The prevalence of overland flow and the strong hydrological differences between habitats suggests that, at a hillslope scale, the largest influence on flood mitigation in these shallow, high K_s, OM-soil grassland systems is surface roughness. While soil properties are essential in controlling antecedent conditions and the rate at which habitats wet-up, once overland flow is produced, the primary control is vegetative roughness. Research by Bond et al. (2020) showed that overland flow velocity significantly varies between grassland habitats as a consequence of land management and seasonality, the primary controls affecting roughness. Since roughness changes occur in the short to medium term, land management may affect flood and drought mitigation on a shorter timescale than many studies suggest. Consequently, roughness may be important as a fast-acting land-use change which serves as initial NFM approach while long-term changes in soil properties more slowly accumulate further benefits. A mosaicked upland landscape can utilise NFM to produce multiple ecological and environmental benefits where they are most required, such as in a high overland flow-producing area, in addition to maintaining economic practices such as livestock management.

Since overland flow is clearly an important factor in upland OM soil landscapes at the hillslope scale, modelling research should explicitly include overland flow processes. Modelling is needed to upscale our findings to catchment and landscape scales, accounting also for soil property changes as a result of management practice. Where landscape heterogeneity is becoming an increasingly important part of upland management, modelling should account for spatial differences, investigating best placement of NFM and how future landscapes may respond hydrologically with shifting soil properties. Therefore, further studies could incorporate a long-term before-after-control-impact approach which monitors changes in hydrological function with management interventions, and funders should be encouraged to invest in such long-term monitoring.

5 | CONCLUSION

In this research, we investigated the hydrological function of upland OM soils under differing grassland management. Bulk density, *TOM* and K_s were significantly associated with grassland type, suggesting that management of grasslands is important to OM soil properties. Overland flow occurred frequently across the upland study site, being present for up to 60% of the research period and occurring more often in the Excluded habitat than under grazed conditions. Soil moisture was significantly different between habitats and between sensors within one habitat type; this was attributed to soil heterogeneity. Our research suggests that there is potential for upland grassland management on OM soils to be included as part of NFM, especially using surface roughness interventions. However, modelling is required to test the potential influence of grassland NFM techniques at a catchment scale.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available at the University of Leeds data repository at https://doi.org/10.5518/963, reference number 10.5518/963.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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