Received: 6 April 2020 | Accepted: 28 May 2020
DOI: 10.1002/hyp.13842

RESEARCH ARTICLE

WILEY

Seasonal vegetation and management influence overland flow velocity and roughness in upland grasslands

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Funding information
Natural England, Grant/Award Number: NE/P009085/1 (CASE Partner to NERC studentship); Natural Environment Research Council, Grant/Award Number: NE/P009085/1

Abstract
There is considerable interest in how headwater management may influence downstream flood peaks in temperate humid regions. However, there is a dearth of data on flow velocities across headwater hillslopes and limited understanding of whether surface flow velocity is influenced by seasonal changes in roughness through vegetation cycles or management. A portable hillslope flume was used to investigate overland flow velocities for four common headwater grassland habitats in northern England: Low-density Grazing, Hay Meadow, Rank Grassland and *Juncus effusus* Rush pasture. Overland flow velocity was measured in replicate plots for each habitat, in response to three applied flow rates, with the experiments repeated during five different periods of the annual grassland cycle. Mean annual overland flow velocity was significantly lower for the Rank Grassland habitat (0.026 m/s) followed by Low-density Grazing and Rushes (0.032 and 0.029 m/s), then Hay Meadows (0.041 m/s), which had the greatest mean annual velocity (examples from 12 L/min flow rate). Applying our mean overland flow velocities to a theoretical 100 m hillslope suggests overland flow is delayed by >1 hr on Rank Grassland when compared to Hay Meadows in an 18 mm storm. Thus grassland management is important for slowing overland flow and delaying peak flows across upland headwaters. Surface roughness was also strongly controlled by annual cycles of vegetation growth, decay, grazing and cutting. Winter overland flow velocities were significantly higher than in summer, varying between 0.004 m/s (Rushes, November) and 0.034 m/s (Rushes, June); and velocities significantly increased after cutting varying between 0.006 m/s (Hay meadows, July) and 0.054 m/s (Hay meadows, September). These results show that seasonal vegetation change should be incorporated into flood modelling, as cycles of surface roughness in grasslands strongly modify overland flow, potentially having a large impact on downstream flood peak and timing. Our data also showed that Darcy-Weisbach roughness approximations greatly over-estimated measured flow velocities.

KEYWORDS
Darcy–Weisbach, natural flood management, organo-mineral soils, runoff, surface roughness

1 | INTRODUCTION

The frequency and intensity of flooding in many parts of the world is increasing, and climate change is a significant driver (Feyen, Barredo, & Dankers, 2008; Hirabayashi et al., 2013; Middelkoop et al., 2001; Wingfield, Macdonald, Peters, Spees, & Potter, 2019). However, land-use change can act as a moderator of flood risk, affecting the storage and flow connectivity of water across landscapes (Schilling et al., 2014; Wheater & Evans, 2009). There is a lack of information, at a range of scales, about how some types of land-cover change and land-use management practices may influence downstream flood risk (Rogger et al., 2017). Despite this lack of data, a number of initiatives are now being undertaken that seek to use "nature-based solutions" to flooding, including the sponge-city concept in some Chinese cities (Li, Ding, Ren, Li, & Wang, 2017; Liu, Jia, & Niu, 2017), and the use of Water Sensitive Urban Design in Australia (Sharma et al., 2016). In the UK, funding has been provided to trial Natural Flood Management (NFM) initiatives which are primarily focussed on upper catchment areas that can support schemes such as woodland planting, woody debris dams, farm storage ponds, and peatland restoration (Nicholson, Wilkinson, O'Donnell, & Quinn, 2012; Nisbet, Marrington, Thomas, Broadmeadow, & Valatin, 2011; Short, Clarke, Carnelli, Uttley, & Smith, 2019; Shuttleworth et al., 2019). Much of the UK uplands is covered by managed grasslands, both above and below the moorland line, used for sheep grazing. There have been suggestions that increased grazing intensities in UK upland grasslands may influence flood risk downstream (e.g., Meyles, Williams, Ternan, Anderson, and Dowd (2006), Lane (2001)) but recent assessments of the literature have shown that there are few datasets that can demonstrate the effectiveness of grassland management or other NFM measures (Burgess-Gamble et al., 2017; Dadson et al., 2017). Therefore, it is important to collect new data. In environments where overland flow is common, vegetative surface roughness may be particularly important in slowing water flow and impacting downstream flood peak magnitude and timing.

The role of riparian roughness has been well studied for its effects on slowing channel and out-of-bank flood flows (Medeiros, Hagen, & Weishampel, 2012). For example, Chien (1957) measured Manning's *n* calculated from flood stages for different floodplain covers: for a flood between 30–60 cm depth, roughness varied from 0.05 in pasture, to 0.08 in meadows and 0.11 in "brush and waste". Chow (1959) produced a table containing simplistically-calculated Manning's *n* roughness values for floodplain channels, including vegetation types ranging from pasture to trees. These values, still commonly used as an estimate for roughness (Burgess-Gamble et al., 2017; Manandhar, 2010; Phillips & Tadayon, 2006), showed riparian trees have a channel roughness of up to five times that of grassland, and grassland double that of bare earth.

While several studies have suggested surface runoff volume can be reduced by altering the vegetation cover (Macleod et al., 2013; O'Connell, Ewen, O'Donnell, & Quinn, 2007; Schafer, 1986), and such principles are used in sustainable urban drainage systems (Green, 2019), the surface roughness processes have generally not been disentangled from potential interception (Macleod et al., 2007; Marshall et al., 2009), plant uptake (Yoshikawa, Overduin, & Harden, 2004), and rooting (Bodner, Leitner, & Kaul, 2014; Soulsby, 1993) storage processes. The presence and management of differing vegetation species may influence soil properties and therefore the volume of surface runoff present. Grassland management such as aeration (Wallace & Chappell, 2019), ploughing (Douglas & Goss, 1987; Wallace & Chappell, 2020), grazing (Meyles et al., 2006) and underdrainage (Burt, 2001) all influence soil permeability and moisture regime, which, in turn, partially control antecedent conditions leading up to storm events and therefore potential overland flow occurrence.

While Emmett (1970) recognised vegetation as "an extreme influence on resistance to flow over natural hillslopes", hillslope measurements of roughness are much less common than channel roughness measurements and have so far centred on investigating rills (Gómez & Nearing, 2005; Roels, 1984), farming processes such as ploughing (Mwendera & Feyen, 1994), and the relationship between roughness coefficients and the Reynolds number (Gilley, Kottwitz, & Wieman, 1991; Wu, Shen, & Chou, 1999). Surfaces studied include single-species vegetated slopes (Roels, 1984), bare soil (Gilley & Finkner, 1991), minimally vegetated desert environments (Abrahams & Parsons, 1991; Abrahams, Parsons, & Luk, 1986), (laboratory-based) agricultural crop environments (Gilley & Kottwitz, 1994; Gilley & Kottwitz, 1995; Gilley, Kottwitz, & Wieman, 1992) and artificial horsehair 'vegetation' environments (Wu et al., 1999). All of these studies showed that vegetation roughness is important to overland flow, although there are some types of crop cover that appear to have a minimal effect (Gilley & Kottwitz, 1994). A hillslope flume used by Holden et al. (2008), established a set of roughness parameters for *Sphagnum*, *Eriophorum*, *Sphagnum-Eriophorum* mix and bare surfaces on blanket peat. Holden et al. (2008) found that vegetation significantly influenced overland flow velocity which was 10 times faster over bare peat surfaces than for surfaces covered with a *Sphagnum* understory. Such data would be useful in other environments and for other types of vegetation cover that can be influenced by management.

Recently, slowing the flow of water across hillslopes by altering the surface roughness has been seen as a potentially important factor that could be used by land managers who seek to reduce downstream flood peaks (Gao, Holden, & Kirkby, 2016, 2017; Grayson, Holden, & Rose, 2010; Shuttleworth et al., 2019), particularly in the temperate-humid zone where saturation-excess overland flow is common (Burt, 1996). As the need for flood mitigation has increased, hydrological modelling has been used to demonstrate the potential importance of vegetative surface roughness on the timing of flood peaks from upland peatland systems (Ballard, McIntyre, Wheater, Holden, & Wallage, 2011; Gao et al., 2016, 2017; Lane & Milledge, 2013). These studies all suggest that overland velocity and surface roughness data made from local observations could be very important when modelling downstream flood hydrographs. It is also widely agreed that there are more sensitive areas of the landscape for which surface cover change could cause the largest shifts in peak flow and timing. As such, this is important evidence that suggests spatially-targeted management interventions on surface roughness could reduce downstream flood peaks as part of NFM. Thus, data is urgently needed on overland flow velocities from non-peatland areas to inform hydrological modelling.

NFM initiatives in the UK are primarily focussed on headwater areas which typically have a cool, wet climate with organo-mineral soils (58.5% of UK uplands are underlain by organo-mineral soils [Bol et al., 2011]). However, the extent of storage and flow velocity reduction is dependent on catchment characteristics including factors such as geology, antecedent conditions, vegetation type and land use. Previous surface roughness evaluations have focussed on peatlands (Gao et al., 2016, 2017; Holden et al., 2008) and cropland (Gilley & Kottwitz, 1994), but grassland covers approximately 46% of the total UK land area (DEFRA, 2016) and 69% of global agricultural land (Wood, Sebastian, & Scherr, 2000), of which much is used for grazing. Since vegetation composition and its spatial distribution is strongly associated with grazing (Clarke et al., 2008; Davies & Bodart, 2015; Martin, Fraser, Pakeman, & Moffat, 2013; Merriam, Markwith, & Coppoletta, 2018), how grassland roughness varies between grazing and other land management regimes is important. In addition, altering grazing regimes is possibly more achievable for many landowners worldwide than other NFM interventions. Therefore, it is important to measure overland flow velocities and calculate roughness values from such environments and to understand how they vary with vegetation in these upland systems.

An important factor that needs to be considered in land management interventions that seek to influence surface roughness, is that of seasonality—the surface roughness and consequent retardation of overland flow may change during the year with vegetation growth cycles. However, such an effect has rarely been studied and is generally not incorporated into flood models. Nevertheless, seasonality has long been recognised as a potential factor influencing channel roughness. For example, Chien (1956) studied the effect of vegetation to drainage channel roughness and found a seasonal variation in Manning's *n* ranging from 0.033, when the channel was clear of vegetation, 0.055 when bushy willows grew on the side slopes, 0.115 after a thick growth of cattails on the channel bed, and 0.072 after the cattails were washed out by a storm. Where hillslope vegetation seasonality has been used within flood modelling, studies have typically focussed on woodland coverage and interception changes (De Roo, Odijk, Schmuck, Koster, & Lucieer, 2001; De Roo, Schmuck, Perdigao, & Thielen, 2003; Jackson et al., 2008) or impacts of sudden vegetation removal (such as through cutting) which Kourgialas and Karatzas (2013) suggested (based on predicted Manning's *n* values from Chow (1959) and Sturm (2001)), could significantly alter predicted flood area. However, no field-based hillslope roughness studies have yet investigated seasonal changes in vegetation or coupled these changes to flood risk.

This paper aims to:

1. Expand the range of vegetation characterised for hillslope surface roughness, particularly to grassland upland environments which are subject to land management such as grazing and cutting.
2. Calculate any seasonal variation in roughness to improve understanding of vegetation impacts on surface flow.
3. Assess the appropriateness of the Darcy–Weisbach coefficient for hillslope surface roughness measures
4. Provide roughness parameter values which could be used in the future to model how flood response may vary under different grassland cover types and seasons.

2 | METHODS

2.1 | Study site

Field measurements were conducted in the Swindale catchment, Lake District, UK (54° 30′14.75″N, 2° 45′ 56.91″W). The Lake District is a mountainous region in the northwest of England designated as a UNESCO World Heritage site. Swindale comprises a 2.66 km^2 *U*-shaped valley between 270 and 430 m elevation, with upland organo-mineral soils, predominantly Malvern 611a (Chromic Endoleptic Umbrisol) and Bangor 311e (Dystric Epileptic Histosol) soils (Cranfield University, 2020). Between 1981 and 2010 mean annual precipitation was 1,779 mm in the nearby village of Shap, 5 km northeast of Swindale at 255 m above sea level; 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 managed as a working grassland farm under a higher-level stewardship (HLS) scheme. HLS is an agri-environmental scheme in England which 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 through buffer strips. Four farm-based habitats were chosen in Swindale to represent commonly occurring UK upland grassland types which have distinctive, but potentially adaptable, management strategies. These were Hay Meadows, Low-density Grazing, Rushes and Rank Grassland (Table 1). A full description of species presence and abundance, and the survey method used, can be found in Appendix S2.

2.2 | Flume design

A portable and durable hillslope flume (Figure 1), for measuring vegetative roughness subject to overland flow, was constructed based on designs of a miniature flume for interrill overland flow by Parsons and Abrahams (1989), and a hillslope flume for vegetative roughness measurements in peatlands by Joseph Holden et al. (2008). Bounded plots measuring 0.4 m by 2.0 m were established using aluminium panels hammered into the ground. Immediately downslope of each plot, a z-shaped aluminium panel 0.4 m wide with three 0.2 m long faces angled at 60° to form a z-shape, also bound on either side with aluminium panels, was dug into the ground so that the upper surface was level with the soil surface. To ensure a seal between the ground

TABLE 1 Upland grassland habitats studied in Swindale

Habitat name	Location within Swindale	Dominant species	Average vegetation height (cm)	Description and management
Hay meadows	Valley floor on either side of the Swindale Beck (river)	Grasses: *Holcus lanatus*, *Anthoxanthum odoratum* and *Cynosurus cristatus* Broadleaf species: *Rhinanthus minor*, *Trifolium dubium*, *Trifolium pratense* and *Plantago lanceolata*.	April: 3.4 June: 18.8 July: 35.5 Sept: 1.1 Nov: 2.2	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 25th July. After this, the hay meadows are lightly grazed through the winter months while sufficient fodder remains.
Low-density grazing	On the slopes immediately above the Hay meadows	Grasses: *Festuca ovina*, *Agrostis spp*. and *Cynosurus cristatus* Moss species: *Rhytidiadelphus squarrosus* Broadleaf species: *Trifolium repens*, *Luzula campestris* and *Rumex acetosella*.	June: 10.6 July: 4.2 Sept: 8.9 Nov: 2.8	The definition of low-density grazing on upland pasture varies greatly. In Swindale, low-density grazing represents a maximum 2.66 ewes plus lambs per hectare, but 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.
Rushes	Found in large swathes throughout the catchment	Soft rushes: *Juncus effusus*	Not recorded	*Juncus effusus* rush swathes only. Most of these areas fall within areas managed as Low-density Grazing (as above) but the rushes are unpalatable and are generally avoided by grazing animals. No specific management is applied at Swindale. However, rush is commonly removed in the UK under some forms of management (Gilley et al., 1992; Pinches, 2013; Wolton, 2000)
Rank grassland	Within sections of the catchment fenced-off from grazing	Grasses: *Dactylis glomerata*, *Holcus lanatus*, *Agrostis capillaris*, *Anthoxanthum odoratum*, *Festuca spp*. Broadleaf: *Ranunculus repens*, *Lotus pedunculatus*, and *Ranunculus acris*	April: 13.0 June: 31.9 July: 37.7 Sept: 10.1 Nov: 8.8	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 6 years without cutting or grazing. No management currently applied in Swindale

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

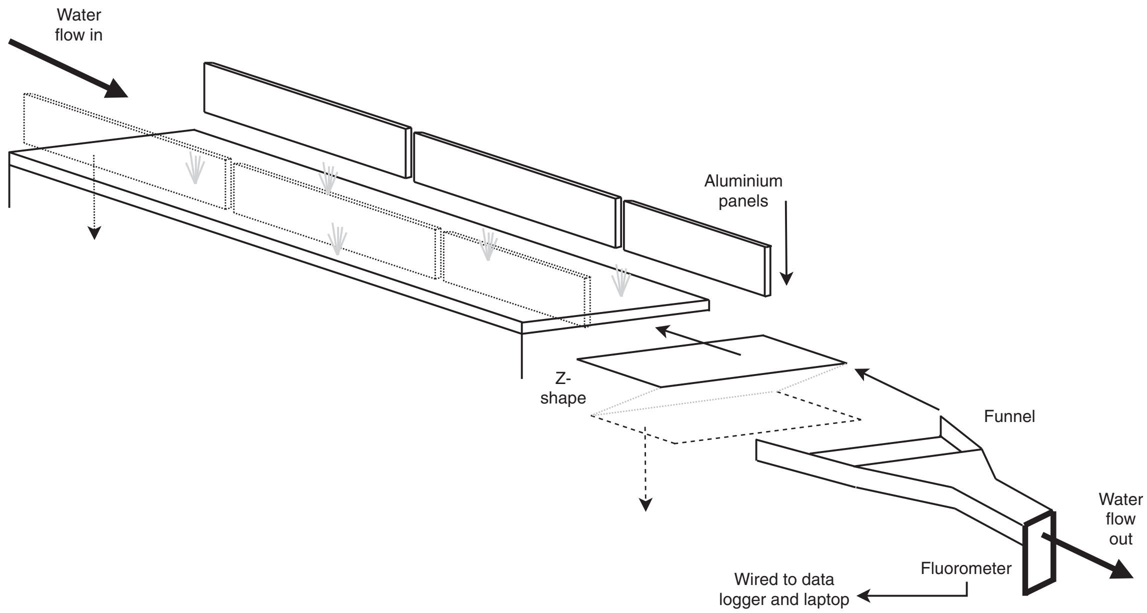

FIGURE 1 Overland flow hillslope flume design

surface and z-shape, the z-shape was driven into the soil face by approx. 2 cm. Onto the opposite surface-edge of the z-shape, a plastic funnel was fitted level with the *Z* surface. The funnel was attached and made water-tight using tape and petroleum jelly. The funnel was designed to collect water travelling through the flume and channel it into and through a fluorometer, attached to the funnel, without disrupting water flow rate. A fluorometer was used to measure the fluorescence at the outlet after slugs of tracer were added in low-concentrations at the inlet, enabling automated velocity measurements. The Z-shape, funnel and fluorometer were dug into the ground in such a way as to provide a continuity of the slope angle for the hillslope bounded plot. A Seapoint Rhodamine fluorometer was wired to a CR220X data logger and laptop, capable of recording changes in fluorescence every 1 s.

To provide water, a 180 L portable "bowser" water tank was positioned at the top of each flume and filled from nearby streams using pumps. Flow from the bowser was controlled using a Mariotte tube to provide a uniform flow rate. Three separate applied flow rates were investigated; 12, 6 and 1.2 L/min. If applied over a 100 m slope, these flow rates reflect rainfall intensities of 18, 9 and 1.8 mm/hr respectively and were chosen to reflect a range of realistic rainfall intensities for storm events in the UK uplands (e.g., Holden & Burt, 2002).

2.3 | Data collection

Sampling locations were chosen using a stratified approach based on a visual assessment of habitat representativeness and practicality of access. Data was collected over five field campaigns between April and November 2019. This time period was chosen to reflect the course of one growing season, over which the Rank Grassland and Rushes habitats were subject to natural growth and decay only, and the Low-density Grazing and Hay Meadow habitats were subject to additional management (Table 1). Ewes and lambs on the Low-density Grazing habitat were separated between July and September data collections, reducing grazing pressure with up to two-thirds fewer sheep grazing in the studied fields. Almost all sheep were off-wintered (transferred out of the catchment) before the November collection. For the Hay Meadow habitat, vegetation was cut between the July and September data collections. Visual habitat change over selected months throughout the growing season is shown in Figure 2.

Flumes were set-up in locations considered visually representative of the habitat type, and away from field boundaries to reduce edge effects. New locations were chosen for each flume study (i.e., the same point was not revisited during each field campaign) in order to be representative of the whole habitat and to eliminate any influence on vegetation from the flume structure. For example, it was thought that natural grazing patterns could be disturbed by in situ equipment. One flume per habitat was established for April and November data collections and, with the exception of the 1.2 L/min July flow data for Rushes and Rank Grassland for which overland flow could not be generated in the dry conditions, two flumes per habitat were established in all other months. Across all field campaigns, a total of eight flumes were set-up for each of the Hay Meadow and Low-density Grazing habitats and seven flumes for each of the Rank Grassland and Rushes habitats. For each flume established, a minimum of five Rhodamine injections were recorded for each flow rate.

Vegetative surface roughness was measured using Rhodamine WT dye at a concentration detectable for all three flow rates. The flume concentration range observed and fluorometer breakthrough curves are discussed in Appendix S3. The length of vegetation over which flow occurred varied per flume depending on habitat and conditions. Most often, flume length measured approximately 2 m for the 12 and 6 L/min flow rates, and approx. 1.1 m for the 1.2 L/min flow rate. This shorter flume length was chosen for the lowest flow rate due to the long time period required to saturate the ground at that flow rate. Similar flume lengths between locations and across seasons ensured habitat comparability.

2.4 | Calculating surface roughness

Downslope flow velocity was used as a proxy measurement for vegetative surface roughness, where recorded velocity varied as the result of friction between the vegetation and overland flow. Mean velocity, $\bar{V}$, was calculated using an inverse time method, where:

$$\bar{V} = \frac{\sum_{i=1}^{n} \frac{l}{t_i Vq_i}}{\sum_{i=1}^{n} Vq_i} \tag{1}$$

and

$$Vq_i^n = \mathrm{SEVolt}_i - \mathrm{LoQ} \tag{2}$$

where l is the vegetated flume length (m); t is the time difference in seconds from the point of Rhodamine injection; and Vq is the SEVolt above limit of quantification (LoQ). Fluorescence was measured in SEvolts. Further information about these calculations, including a list of abbreviations and examples of breakthrough curves, can be found in Appendices S1 and S3.

Darcy Weisbach roughness, f, was calculated as a commonly used measure of roughness:

$$f = \left(\frac{8g\bar{d}S}{\bar{V}^2}\right) \tag{3}$$

and

$$\bar{d} = \frac{Q}{w\bar{V}} \tag{4}$$

where g is the gravitational acceleration constant, $\bar{d}$ is mean flow depth (m), S is the slope (α), $\bar{V}$ is the mean velocity (m/s), Q is the flow rate (m^3/s) and w is the flume width (m).

Mean flow depth was calculated based on the Rhodamine response curve, flume dimensions and fixed flow rate. Given this, the Rhodamine response curve could not be used to calculate a lower-flume flow rate. Therefore, flow rate was assumed to be equal at the top of the flume as at the bottom, where saturation, once reached, sufficiently impedes water percolation so that infiltration losses compared to overland flow rates are negligible. Instrumentation to accurately measure flow rate at the bottom of the flume was too bulky for a portable flume, and, over two metres, a saturation assumption was considered reasonable.

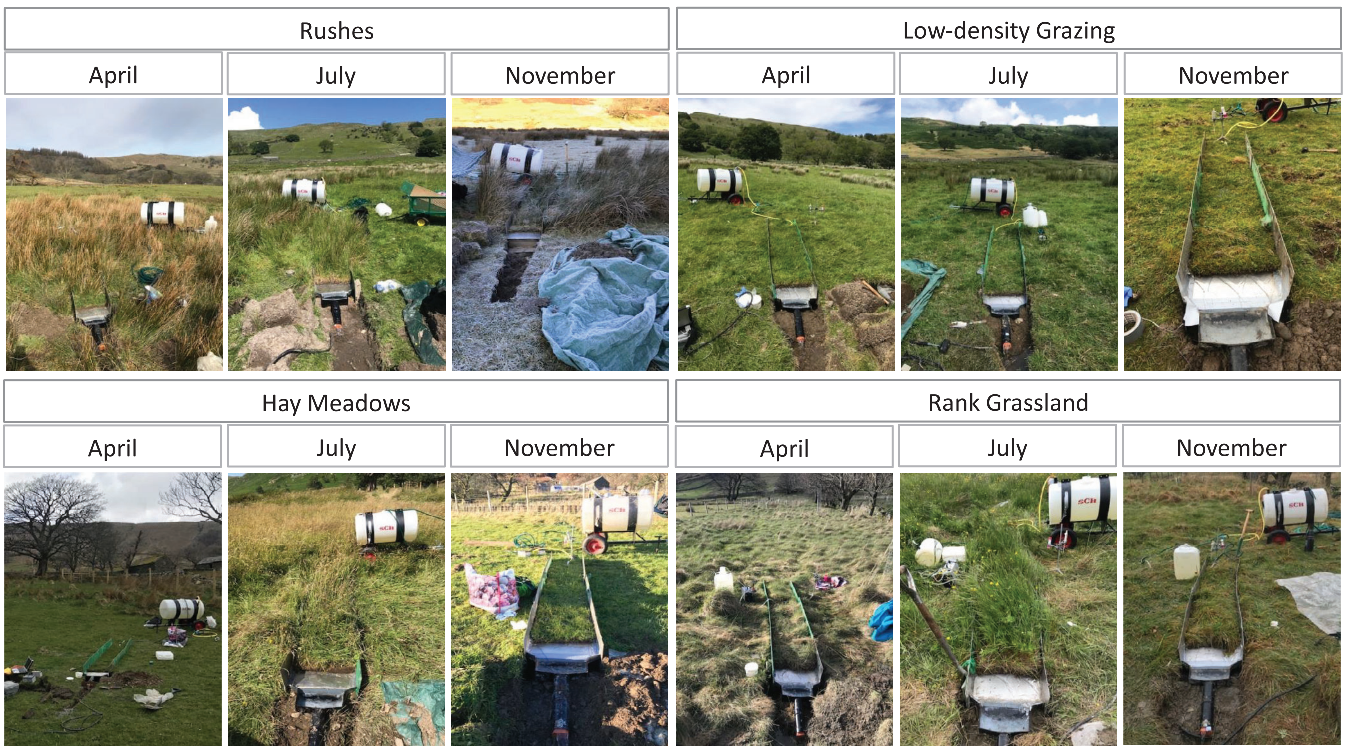

FIGURE 2 Flume set up showing visual habitat change seasonally. Average slope angles for each habitat are shown in Table 2

2.5 | Modelling expected roughness

Traditionally, roughness has been calculated using either Manning's n or Darcy–Weisbach roughness (f) coefficients. While both of these methods are valid forms of measuring roughness within channel contexts, there is debate about whether they are transferable to hillslope environments. f has been applied in both laminar and turbulent flow regimes, while n is most relevant in turbulent flows where roughness elements are very fully submerged by the flowing water. However, since both roughness coefficients are commonly used in catchment-scale hydrological modelling, it is essential that field roughness observations are suitably transferrable to modelling scenarios. Both f and n coefficients generally make the assumption that the measured roughness elements are comparable to grains on a riverbed. This differs from most overland flow scenarios, for which vegetation stems are only partially submerged and may be subject to flow forces which drag them downwards. To test the appropriateness of roughness measurements in vegetated hillslope contexts, the properties of flow were investigated with respect to expected roughness. The Darcy–Weisbach equation describes resistance to flow (Equation 3) which can also be related, for fully turbulent flow, to the ratio of flow depth, d, to equivalent grain roughness, k:

$$f^{-0.5} = A + B\,log_{10}(d/k) \qquad (5)$$

where A and B are empirically derived constants. Equation (5) implies that as the ratio of depth to roughness (d/k) increases, so the Darcy–Weisbach friction factor, f, should decrease ($f^{-0.5}$ increase), as long as k remains roughly constant. In order to investigate the expected relationship between discharge and velocity for a fixed k, a Constant Grain Roughness Model was produced as described below.

Using regularly-spaced f values $0.01 < f < 1{,}000$, depth, d, was calculated from Equation (5). Following this, velocity was calculated using Equation (6), rearranged from Equation (3), and discharge (m^3/s) from Equation (7):

$$V = \sqrt{\frac{8gdS}{f}} \qquad (6)$$

$$d = \frac{Q}{wV} \qquad (7)$$

This model assumed fixed slope, S; width, w; A and B constants (Myers, 2002); and a fixed equivalent grain roughness where $S = 0.17$, $w = 0.40$, $A = 1.14$, $B = 2.00$ and $k = 0.01$ and 0.001. The Reynolds number, Re, was calculated for each iteration:

$$Re = \frac{Vd}{v} = \frac{Q}{w\nu} \qquad (8)$$

where v is the kinematic viscosity, 1.307×10^{-6} m^2/s at 10°C. Fully turbulent flow was assumed where $Re > 2000$, and laminar flow where $Re < 500$.

For laminar flow conditions, Equation (5) no longer applies, and the friction factor is related to the Reynolds number by the relationship (9):

$$f = 64/Re \qquad (9)$$

Following modelling using the Constant Grain Roughness Model, Relative Roughness, k^*, was calculated to investigate the relationship between k^* and seasonality using calculated V and applied Q values from field data collection. If

$$V = \frac{8gd^2S}{k^*v} \qquad (10)$$

then, using Equation (7):

$$V = \left[8gSQ^2/\left(k^*\nu w^2\right)\right]^{1/3} \qquad (11)$$

and

$$k^* = \frac{48Q^2}{V^3} \qquad (12)$$

for the experimental flume width and gradient at 10°C.Using the Darcy–Weisbach equation form for wide channels (Equation (10), Myers (2002)), k^* was calculated for each habitat using Equation (12).

3 | RESULTS

Surface cover exerts a strong influence over overland flow. A Kruskall–Wallis test showed significant differences in mean flow velocity between all habitats ($p < .05$) except between Low-density Grazing and Rushes. Mean overland flow velocity across all times of the year (hereafter "mean annual overland flow velocity") was consistently lowest for the Rank Grassland habitat, followed by Low-density Grazing and Rushes habitats, then Hay Meadows, which had the highest mean velocity (Table 2). In response to the same applied flow event, overland flow velocity for the Hay Meadows habitat was up to double that recorded for Rank Grassland (Table 2, Figure 3). Slope was dissimilar between all habitats except Low-density Grazing and Rushes. However, there was no correlation between velocity and slope. Hay Meadows, with the shallowest slopes, produced the fastest velocities. Therefore, slope was not a significant influence over velocity for the habitats studied.

Within each habitat, the seasonal pattern of growth, decay and management is visible, shown by the striking "U-shaped" nature of the 6 and 12 L/min response curves for individual habitat types (Figure 3). The U-shaped pattern appears to represent an annual cycle for which there are low velocities during the summer months and higher velocities during spring and autumn. Although mean annual flow velocity had a clear habitat "roughness order" (Table 2), Rank Grassland did

TABLE 2 Count, velocity, flow depth, Darcy–Weisbach roughness, slope and relative roughness summary table for all flume data

	Count, *n*	Velocity, *V* (m/s)		Flow depth, *d* (m)		Darcy–Weisbach roughness, $1/\sqrt{f}$		Slope (rad)	Relative roughness, k^*	
Habitat type	*n*	μ	σ	μ	σ	μ	σ	μ	μ	σ
1.2 L/min										
RG	23	0.00506	0.000817	0.0108	0.00182	0.0129	0.00303	0.19	7.48	1.26
R	31	0.00674	0.00291	0.00916	0.00335	0.0216	0.0124	0.17	6.34	2.32
LDG	41	0.00589	0.00149	0.00975	0.00299	0.0180	0.00751	0.17	6.75	2.07
H	35	0.00851	0.00237	0.00669	0.00187	0.0345	0.0136	0.13	4.69	1.32
6 L/min										
RG	42	0.0170	0.00488	0.0179	0.00472	0.0355	0.0143	0.19	7.10	1.87
R	32	0.0223	0.00753	0.0143	0.00503	0.0558	0.0238	0.17	5.60	2.02
LDG	41	0.0209	0.00360	0.0140	0.00230	0.0514	0.0175	0.17	5.54	0.91
H	43	0.0271	0.00550	0.0111	0.00289	0.0820	0.0228	0.13	4.39	1.15
12 L/min										
RG	52	0.0257	0.00590	0.0227	0.00712	0.0471	0.0154	0.19	7.23	2.27
R	38	0.0320	0.0100	0.0188	0.00593	0.0696	0.0277	0.17	5.98	1.89
LDG	44	0.0289	0.00581	0.0200	0.00669	0.0608	0.0232	0.17	6.37	2.14
H	43	0.0414	0.00891	0.0141	0.00503	0.113	0.0334	0.13	4.55	1.63

Note: Count represents the number of Rhodamine injections, therefore data points per habitat. Habitats are represented by abbreviation where RG is Rank Grassland, LDG is Low-density Grazing, H is Hay Meadows, and R is Rushes. For velocity, flow depth, Darcy–Weisbach roughness and relative roughness, the mean (μ) and standard deviation (σ) of the data is given. For Slope, the mean (μ) slope in radians is shown.

not always have the lowest flow velocity. During April and November, for all flow rates except the 1.2 L/min in November, Low-density Grazing velocity was equal to, or had a significantly lower recorded overland flow velocity, than the Rank Grassland habitat (Dunn's post-hoc, $p < .05$, Figure 3). In comparison, for the 6 and 12 L/min flow rates during June, July and September, Rank Grassland and Rushes habitats had the joint lowest flow velocity, with the exception of 6 L/min September for which Rank Grassland had the lower velocity (Figure 3; Table 2).

Seasonal roughness change in managed habitats was strongly centred on management events (Figure 3). Whereas Rank Grassland and Rushes habitats demonstrated a *U*-shaped roughness curve which increased and then diminished through the growing season, the managed habitats exhibited a clear response to interventions. The Hay Meadows were cut between the July and September data collections, between which there was a significant increase in mean overland flow velocity for all three flow rates (Dunn's post-hoc, $p < 0.05$); 43.7% increase in mean flow velocity for the 1.2 L/min applied flow rate, 28.4% increase for the 6 L/min flow rate, and 19.1% increase for 12 L/min flow rate (Figure 3).

In comparison, the mean flow velocity for Low-density Grazing decreased significantly in response to reduced grazing pressures (Dunn's post-hoc, $p < 0.05$); between July and September data collections, flow velocity decreased by 20.9% for the 6 L/min applied flow rate and 26.6% for the 12 L/min rate (Figure 3). In response to a second reduction in grazing pressure between September and November, a time of year in which vegetation dieback also occurs, no statistical change in flow velocity was recorded for the 6 L/min flow rate; however a significant increase in flow velocity of 18.8% was recorded for the 12 L/min flow rate (Figure 3).

Flow velocity was greatest in response to the highest applied flow rate, which also produced the most varied velocity between habitats. For the 12 L/min applied flow rate, recorded velocity for all habitats varied by 0.45 m/s across the growing season, in comparison to 0.025 m/s for the 6 L/min flow rate, and just 0.0082 m/s for the 1.2 L/min rate (Figure 3; Table 2). This strongly suggests that vegetative roughness exerts a higher influence on overland flow velocity during larger storm events than smaller events. In comparison to higher flows, seasonal differences in velocities in response to 1.2 L/min flows were more muted. This is most clearly demonstrated by the flow velocity response in the Low-density Grazing habitat, within which there were no significant seasonal differences for the 1.2 L/min flow rate (Figure 3).

Mean flow depth was calculated using Equation (4) and across all applied flow rates and habitats ranged between 0.004 and 0.058 m with a mean of 0.015 m. Depth was consistently greatest for the Rank Grassland vegetation across all applied flow rates, and shallowest for the Hay Meadows habitat. Low-density Grassland and Rushes habitats had very similar mean flow depths (Table 2). As with velocity, depth also varied seasonally, increasing into the summer months for all habitats, and decreasing toward winter.

Produced from outputs of the Constant Grain Roughness Model (Equations 5–9), Figure 4 shows discharge against velocity for both turbulent (k = 0.001 and k = 0.01) and laminar flows, plotted beside calculated Swindale data, which is categorised as laminar. As expected, the modelled *V-Q* relationship has a slope of 0.67, for which

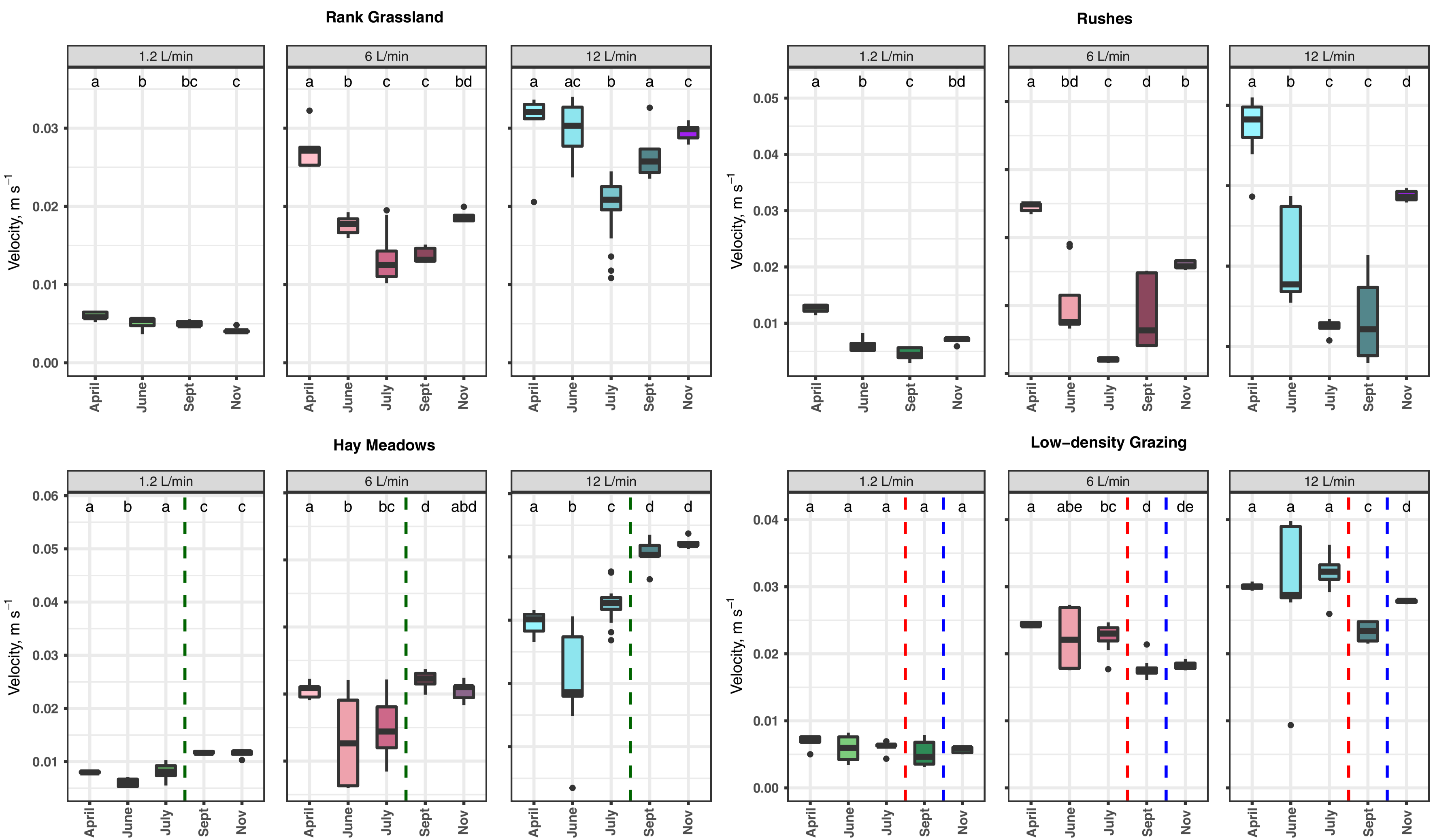

FIGURE 3 Seasonal overland flow velocity for Rank Grassland, Rushes, Hay Meadows and Low-density Grazing. Boxplots show the range, quartiles and median data for each sampling period and flow rate for each habitat. Statistical significance is shown by the letters above each graph facet (Dunns post-hoc test, $p < .05$) where comparisons are made between months within each facet, and a shared letter indicates no statistical significance. Dotted lines represent management interventions occurring. Hay Meadows: green dotted lines indicate cutting between July and September data collections. Low-density Grazing: red dotted line indicates separation of lambs from ewes between July and September data collection; blue dotted lines indicate off-wintering of sheep, occurring in October before final data collection

the Swindale data best fit line is almost parallel; however Swindale data show a velocity approximately 10 times less than modelled for a laminar flow. This is thought to be primarily due to the increased roughness from vegetated surfaces which behave differently to the grain-bed river channels, for which Darcy–Weisbach roughness is most appropriate. The influence of *k* on flow velocity is shown by the varying *k* inputs for turbulent flow.

Annually, k^* is similar between flow rates (Table 2). However, Figure 5 shows how k^* changes between April and November, reflecting seasonal changes in growth and management of grasslands as discussed previously. The change in k^* seasonality also shows the importance of relative roughness between habitats and calls into question the appropriateness of the Darcy–Weisbach *f* as a measure of roughness within which *k* should remain constant with increasing depth.

4 | DISCUSSION

4.1 | Impact of grassland type on overland flow velocity

We found striking differences in overland flow velocity between grassland habitats within the same catchment, showing that the condition of the grassland can strongly influence overland flow and its associated roughness. Rank Grassland was shown to have the most influence in slowing overland flow across the year, followed by Low-density Grazing, Rushes and Hay Meadows (Table 2). These velocity differences have potentially large implications for flood management in upland farming systems. The strong difference in overland flow velocity provides empirical evidence which supports the use of grassland manipulation as a NFM method for "slowing the flow". In the UK, rainfall is often frontal with low intensities maintained over several hours leading to saturation-excess overland flow. Frontal or convective storms with rainfall intensities over 12 mm/hr for short durations are relatively rare, typically occurring in the uplands ∼10 times per year for a few minutes in duration (e.g., Holden and Burt (2002)). If theoretically applied over a continuous 100 m hillslope, the difference in roughness we found is such that, for a 12 L/min applied flow rate (equivalent to an 18 mm/hr rainfall event), the mean time for flow to reach the bottom of the slope ranges between 40 min for the Hay Meadows habitat in comparison to 64 min for the Rank Grassland habitat. For the 1.2 L/min flow rate (1.8 mm/hr rainfall event) this delay is even larger; over a 100 m slope, overland flow in the Rank Grassland may take 5 hr 29 min to reach the bottom in comparison to 3 hr 15 min in the Hay Meadows habitat. However, to understand the influence of such roughness variation on flow peak arrival and delay under different grassland habitats during storm events requires hydrological modelling.

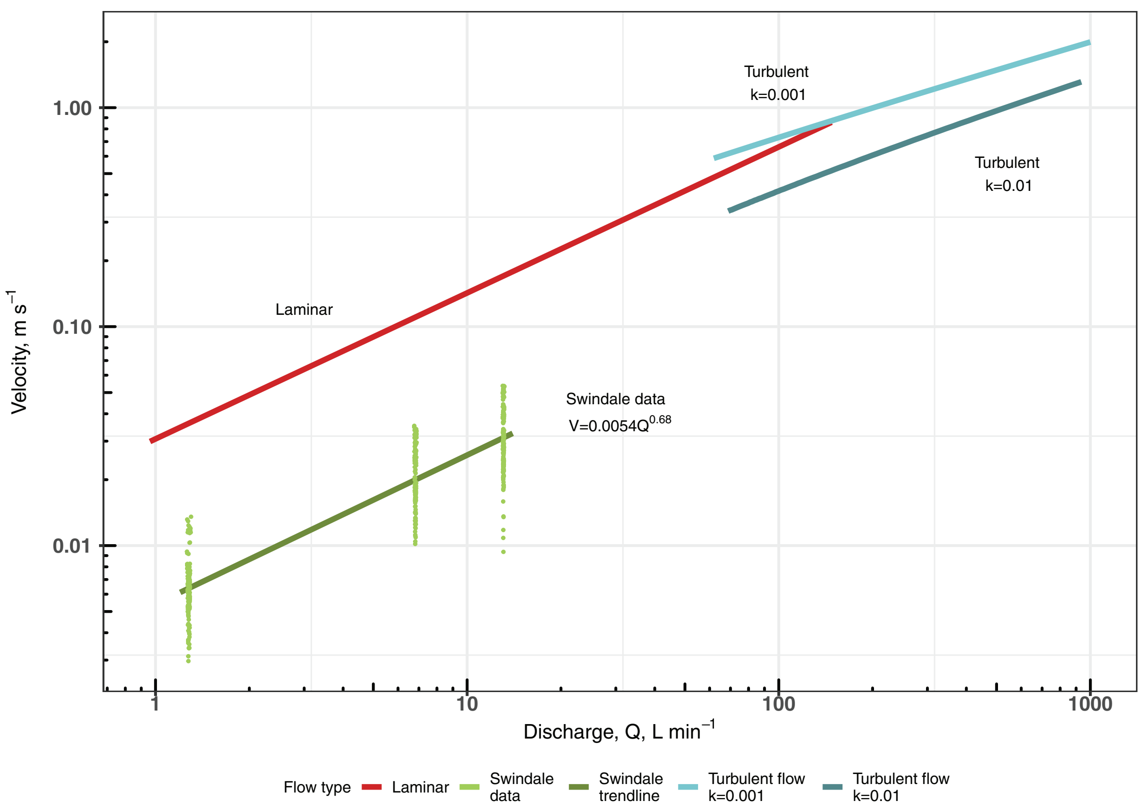

FIGURE 4 The relationship between discharge and velocity, comparing theoretical to calculated Swindale values

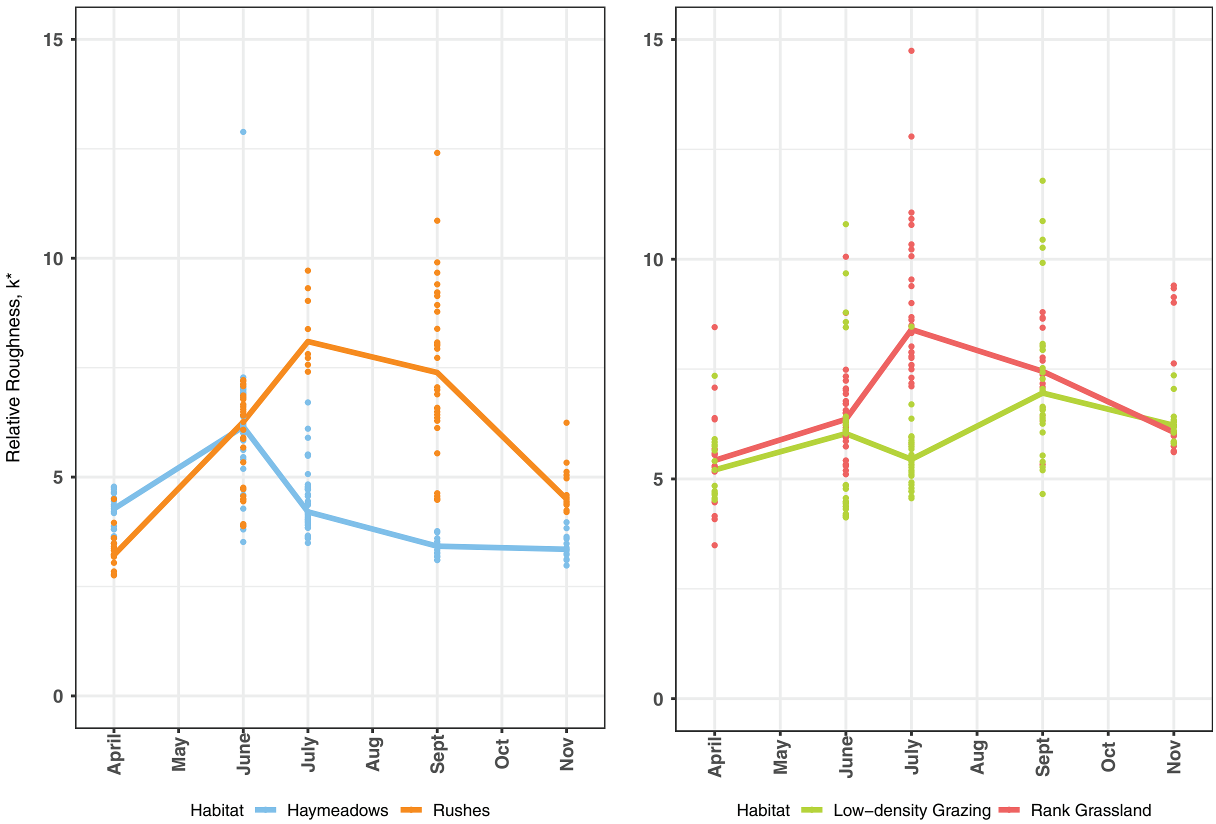

FIGURE 5 Calculated relative roughness (k^* in Equation 12), showing seasonality for Swindale

4.2 | Seasonal influences on overland flow

The seasonal impact of vegetation within habitat types was clearly visible from the "*U*-shaped" mean velocity response curves. This is doubtless a strong reflection of the growth and decay of vegetation within those habitats throughout the year where flow velocity decreases with vegetation growth and increases with decay. Results suggest that Low-density Grazing may be more effective than Rank Grassland in reducing flow velocity over winter months (represented by April and November); and Rank Grassland and Rushes were more effective during summer months. This shows that seasonality of vegetation is important in controlling overland flow velocity, and therefore must be related to both vegetation species and to vegetation management; most important is the portion of vegetation in direct contact with overland flow, which for this study was between 0 and 6 cm above the surface.

The vegetation species present on the Low-density Grazing areas included common grasses such as *Festuca ovina* and *Agrostis spp.* underlain by *Rhytidiadelphus squarrosus* moss throughout, and broadleaf species such as *Trifolium repens*, *Luzula campestris* and *Rumex acetosella*. Due to grazing, these species remain close to ground level. The mossy understorey in particular has a coarse structure with a broad-leaf base, which is evergreen, maintaining structure throughout the year. In the flume investigations by Holden et al. (2008) and subsequent modelling by Gao et al. (2017), *Sphagnum* mosses were shown to have a significant influence on downslope velocity, reducing modelled downstream flood peak by up to 15% compared to a baseline unrestored peat catchment which included some areas of bare peat and grazing. Although the vegetation within the Low-density Grazing habitat remained short, the presence of *Rhytidiadelphus squarrosus* moss may be the reason for such high roughness during winter months.

Rank Grassland and Rushes habitats, whilst both equally 'rough' through the summer months, probably have very different methods of detaining overland flow. Rank Grassland contained grass species such as *Dactylis glomerata*, *Holcus lanatus*, *Agrostis capillaris*, *Anthoxanthum odoratum*, *Festuca spp*., and broadleaf species such as *Ranunculus repens*, *Lotus pedunculatus*, and *Ranunculus acris*. Together these species are thickly-stemmed and dense at the base, forming clumps and root-mats. They are also able to grow tall, "folding over" in the height of summer, whereas in winter leaf litter dominates the Rank Grassland habitat. The strong seasonal growth and decay likely alters the structure of the flow-influencing vegetation portion, therefore explaining the increase in measured overland flow velocity during the winter months. In comparison, *Juncus effuses* rushes are clumped together in dense swathes which force water to flow around the base of each plant; this can also cause pools to form in depressions between clumps. It is therefore likely that overland flow velocity in Rushes is decreased through storage and re-routing of water, as opposed to a direct consequence of friction with the vegetation itself. The Hay Meadows, which are species rich, had a lesser effect on overland flow velocity than the other habitats. Although Hay Meadows had more species, and the species present were tall, growing up to 35.5 cm in July, and the species tended to have thinner basal stems and did not "fold over". Visually, basal vegetation here was also much less dense, and this likely influenced the portion of vegetation which impacted upon overland flow.

Grassland management interventions were shown to have strong effects on overland flow velocity. For the Hay Meadows habitat, there was a significantly greater velocity in September compared to July (Figure 3). This is highly likely to be a direct response to hay cutting after which vegetation was set back to almost bare soil in many places, with a very sparse covering of green shoots up to 1.1 cm height. Compaction of the soil from farm vehicles may also influence the roughness of the underlying soil, although flume locations were established away from visible track marks. Changes away from agricultural systems that involve cutting vegetation (for hay or silage) toward those that retain greater vegetation density could therefore result in significant improvements to summer overland flow resistance. However, where hay cutting has long been established, the cutting and post-cut grazing of the Hay Meadow environment helps to maintain the high species diversity found in this ecosystem (Jefferson, 2005). Hay and silage are also important crops required to feed livestock in the winter. An alternative to wholesale change from hay or silage to extensive pastures would be to manage vegetation conditions through field-rotation, reducing the impact of grazing on specific parts of the catchment. With reduction in summer grazing pressure, we found a decrease in flow velocity between management stages; in winter, changes to grazing pressure had a lesser effect, likely due to vegetation dieback.

While Rushes and Rank Grassland habitat were "non-managed" habitats, their presence and, for Rank Grassland, position in the catchment can be managed. Rushes typically occur in poorly-drained soils and are frequently removed in uplands to improve grassland grazing quality and, in some cases, aid soil drainage (Wolton, 2000). Therefore, whilst Rushes have a high roughness which was shown to slow overland flow in this study, the effect of their removal on overland flow, and its occurrence in the first instance, is likely to be dependent on factors such as soil permeability and surrounding-habitat roughness. This demonstrates the importance of whole-environment considerations when implementing NFM strategies.

Six years prior to this study, Rank Grassland habitat was created in Swindale through the introduction of buffer zones which fenced-off sections of the Low-density Grazing habitat in order to improve water quality. This management intervention, in addition to its original purpose, has also significantly altered the roughness of the vegetation, thus contributing to overland flow management. This demonstrates how NFM can be used to generate whole-ecosystem benefits (Wingfield et al., 2019).

Whereas vegetation species and management are essential in controlling the height and density of vegetation, the ultimate impact of vegetative roughness is also dependent on the applied flow rate. Flow velocity and depth were found to vary most with the highest applied flow rate, 12 L/min, and least with the lowest rate, where depth and velocity are the combined outcome of applied flow rate, and roughness provides friction to overland flow. This variation shows that larger storm events are more influenced by vegetative roughness, and this is likely to be related to the structure and height of the hillslope vegetation which determines roughness extent. At the lowest flow rate, 1.2 L/min, for which the maximum depth was 0.018 m, recorded flow velocity varied by only 0.0082 m/s between habitats (Table 2). This suggests that the vegetation characteristics which control overland flow velocity are more similar at this flow depth/vegetation height. In comparison, the highest applied flow rate, 12 L/min, had a maximum depth of 0.058 m and mean flow velocity varied by 0.45 ms. Since higher flow rates have greater flow depth and therefore more contact with the taller portion of vegetation present, they are subject to a relatively greater variation in vegetation roughness, density and possible flow pathways.

4.3 | Implications for modelling and NFM

It is widely known that roughness influences overland flow velocity and that vegetation characteristics change over the course of the year (Chien, 1956; Medeiros et al., 2012). Our study clearly demonstrates that headwater grassland vegetation, and its associated roughness, is intrinsically linked to seasonal cycles and management. Consequently, seasonal influences to vegetation may be essential for understanding the benefits and impacts of NFM initiatives. In upland temperate regions, flood events generally occur during winter months when the ground is more liable to saturation, and in summer months when ground is dry but there is increased rainfall intensity (Burt & Ferranti, 2012). Therefore, vegetation types and management chosen to reduce flood risk should be those with most influence during high-risk periods. This may include temporally-driven management, or spatially-driven management, both of which can be explored with modelling using the calculated f coefficient values, for the four grassland habitats studied. Indeed, spatially-distributed modelling such as that by Hankin et al (2019), who modelled the Swindale catchment using predicted roughness values, might be refined further by applying the roughness parameter values presented in this paper. For example, for a slope with a proportion p of roughness k^*_p and the rest (q = 1−p) or roughness k^*_q, the combined average roughness, from Equation (12) is $k^* = (p.k^{*\,1/3}_p + q.k^{*\,1/3}_q)^3$. Thus, for example, for a slope which is 20% of roughness k^* = 1,000 and 80% of roughness k^* = 1, the combined average roughness $k^* = (0.2 \times 10 + 0.8 \times 1)^{1/3} = 22$. This indicates the importance of rough buffer strips in slowing the flow.

With our field data which specifically measured vegetative roughness, we recommend modelling now be undertaken to upscale our results to examine the influence on downstream flood peaks and to incorporate seasonal vegetation change. The location and scale of intervention can be modelled to investigate the best placement of NFM interventions. Studies such as that by Gao et al. (2016) and Blanc, Wright, and Arthur (2012) demonstrated that the location of NFM may be as vital to reducing flood risk as the type of intervention.

We used flow velocity as a proxy for surface roughness where it is assumed that changes in vegetation characteristics, especially vegetation density, are the primary cause of flow velocity response. Despite strong seasonal relationships between habitat type, management, and overland flow depth and velocity, the portion of the vegetation which impacts overland flow (approx. 0–6 cm) is difficult to survey. Therefore, although roughness is theoretically a good proxy for vegetation density, further research is required to understand any quantitative relationship. This may also determine whether roughness could be approximated by empirical measures of vegetation.

5 | CONCLUSIONS

Overland flow velocity was found to significantly vary between the four upland grassland types studied, showing that differences in surface roughness across one type of landscape can be very important in modifying flows. Rank Grassland was associated with the lowest overland flow velocities while overland flow across Hay Meadows occurred at up to twice that in Rank Grassland. Within each habitat, recorded flow velocity also varied seasonally with vegetation growth and as a result of grazing and cutting management. Our results suggest that upland grassland management and the types of grassland that managers decide to adopt in headwater systems may be crucial for flood management due to the large differences in overland flow velocity we observed. The effects of grassland cover on downstream flood risk may also be seasonally dependent and such seasonal effects need to be incorporated into future spatially-distributed flood models. Until better methods of quickly surveying near-surface vegetation roughness are devised, these models should be driven by empirical velocity data where possible.

ACKNOWLEDGEMENTS

This research was funded by a UK Natural Environment Research Council Industrial CASE PhD studentship awarded in national competition to JH and AC, and held by SB (grant reference: NE/P009085/1), with support from Natural England as CASE partner. We thank United Utilities, RSPB Haweswater and Boddington Playing Fields (University of Leeds), especially John Gorst, Lee Schofield, Spike Webb and Martin Roscoe, for granting access, permissions and equipment storage. Technical support from David Ashley and Anthony Parsons is acknowledged in constructing the flume. We also thank members of the River Basins Processes and Management cluster (School of Geography, University of Leeds) and other volunteers, for assisting with field measurements.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in the University of Leeds data repository at https://doi.org/10.5518/794, reference number 10.5518/794.

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SUPPORTING INFORMATION

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

How to cite this article: S Bond, MJ Kirkby, J Johnston, A Crowle, J Holden. Seasonal vegetation and management influence overland flow velocity and roughness in upland grasslands. *Hydrological Processes*. 2020;34:3777–3791. https://doi.org/10.1002/hyp.13842