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RESEARCH ARTICLE

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The influence of land management and seasonal changes in surface vegetation on flood mitigation in two UK upland catchments

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Abstract

As the frequency and magnitude of storm events increase with climate change, understanding how season and management influence flood peaks is essential. The influence of season and management of grasslands on flood peak timing and magnitude was modelled for Swindale and Calderdale, two catchments in northern England. Spatially-Distributed TOPMODEL was used to investigate two scenarios across four storm events using empirically-based soil and vegetation data. The first scenario applied seasonal changes in vegetative roughness, quantifying the effect on flood peaks at catchment scale. The second scenario modelled the influence of grassland management from historical high-intensity grazing to a series of natural succession stages between grassland and woodland, and a conservation-based management. Model outputs were analysed by flow type, measuring total, overland and base flow peaks at the catchment outlet. Seasonal changes to vegetation were found to increase overland flow peaks by up to +2.2% in winter and reduce them by −5.5% in summer compared to the annual average. Percentage changes in flood peak due to hillslope grassland management scenarios were more substantial; overland flow peaks were reduced by up to 41% in Calderdale where extensive woodland development was the most effective mitigation strategy, and up to 35% in Swindale, where a rank grassland dominated catchment was the most effective. Conservation-based farming practices were also useful, reducing overland flow peak by up to 42% compared to the high intensity grazing scenario. Neither management nor seasonality changed the timing of runoff peaks by >45 min. Where overland flow dominates, especially in catchments with shallow soils, surface roughness was found to be more influential than soil permeability for flood mitigation. We recommend that seasonal changes to roughness are considered alongside the spatial distribution of Natural Flood Management in mosaiced upland catchments.

KEYWORDS
grassland, hydrological modelling, land cover, natural flood management, overland flow, SD-TOPMODEL, season

1 | INTRODUCTION

Flooding is a key concern as extreme weather events increase globally (Carrick et al., 2019; Chan et al., 2018; Priestley, 2017). Natural flood management (NFM), as a form of nature-based flood risk solutions, has been adopted in the European Union (WG POM, 2014) and UK (Defra & Coffey, 2017; National Audit Office, 2020), and is recommended as both a sustainable and affordable approach that can be used alongside traditional flood management methods. In the UK, NFM is most often applied in uplands which are generally located in a wet, temperate climate (Köppen classification Cfb with small areas of Cfc, Kottek et al. (2006)) and are likely to experience greater increases in precipitation compared to lowland sites (Burt & Holden, 2010). Many UK headwaters are covered by blanket peat (Holden, Chapman, et al., 2007; Xu et al., 2018), for which saturation-excess overland flow dominates (Holden & Burt, 2003). This hydrological feature is likely shared by organo-mineral (OM) soil grasslands, typically found in the uplands downslope of peat headwaters. OM soils, also known as shallow peaty soils, are defined as having a surface horizon ≤40 cm deep with >20% organic content (Holden, Chapman, et al., 2007; Joint Nature Conservation Committee, 2011; Smith et al., 2007). Although OM soils underlie large swathes of land, including approximately 31% of Europe, 11% of England and Wales (of which 59% are in uplands), and 50% of Scotland and Ireland (Bol et al., 2011), very little is known about their hydrological function (Bond et al., 2021). However, the hydrology of these soils, and influence of grassland management upon them, may be important factors to consider in flood mitigation efforts.

Grasslands account for 69% of global agricultural land, including 60% of the UK (Defra, 2016; Wood et al., 2000). In upland England, OM soils underlie 29% of all rough grassland, 35% of all bracken and 33% of all acid grasslands, and are typically used for livestock grazing (Bol et al., 2011). Although further research is needed to fully assess the influence of grazing on hydrological processes in Europe, current evidence suggests that grazing, especially 'overgrazing', likely increases catchment runoff via influence on soils and vegetation (Minea et al., 2022). Field studies have shown that hydraulic conductivity and infiltration rates are lower in areas subject to grazing due to the influence of compaction (Holden, Shotbolt, et al., 2007; Zhao, 2008). Where soils are significantly compacted there is a reduction in macropore formation and root growth (Greenwood & McKenzie, 2001) from which infiltration-excess overland flow may be induced. Grazing has also been shown to reduce wetness thresholds in soils so that field capacity is reached more rapidly in storm events, contributing to rapid runoff pathways and increased stream discharge (Meyles et al., 2006). Selective grazing by animals changes the structure and volume of vegetation present, which may alter surface roughness. Surface roughness is an important modifier of overland flow with research showing that vegetation has the capacity to significantly reduce overland flow velocity with varying effectiveness depending on season and management (Bond et al., 2020; Holden et al., 2008; Monger, Bond, et al., 2022). Vegetation roughness retains water so that duration of overland flow during storm events can be longer in rougher vegetation (Bond et al., 2021), potentially delaying flood peaks. Change in management can alter hydrological function, although existing estimates of time taken for grassland soil hydrological function to 'recover' vary significantly between 5 and 62 years (Gifford & Hawkins, 1978, Holden et al., 2007).

Upland UK grasslands have great capacity to be managed for NFM as they are typically 'mosaiced' landscapes for which there are multiple uses such as livestock grazing, hay meadows for production and leisure activities. In 2021, the UK Government announced plans for a new approach to land management under Future Farming Schemes (Defra, 2021b, 2022a, 2022b). The basis of this proposal is a move away from paying farming subsidies based upon area to one that rewards the provision of public goods. With incentives to introduce nature-based methods, it is essential that the implications are understood on a catchment scale. Considerations also need to be made regarding land-use configuration for which 'sensitive' catchment areas, such as the riparian or hilltoe zones, could have three times more influence on flow peaks than the same management applied to steeper hillslope locations (Gao et al., 2016).

A modelling approach allows land management scenarios to be tested at the catchment scale before implementation, informing intervention effectiveness and accounting for seasonal and spatial influences. Spatially Distributed TOPMODEL (SD-TOPMODEL), developed by Gao et al. (2015) and used in our research, is a fully distributed model, which functions well in temperate humid upland systems, allowing parameters to be applied to individual land covers. Therefore, the mosaicked nature of catchments can be represented, mirroring real-world differences in soil and land cover types which can be directly derived from empirical sources.

Previous empirical work on upland grasslands has shown that season and management are important controls of vegetative surface roughness, which strongly modifies overland flow velocity. At the hillslope scale, Bond et al. (2020) found winter velocities to be significantly higher than in summer for four common grassland land covers; seasonal management practices, including grazing and hay meadow cutting, also strongly influenced overland flow velocity. Following this work, we directly apply the observed field data to SD-TOPMODEL to test the impact of upscaling these findings to a landscape scale, for which there is currently limited information (Burgess-Gamble et al., 2017; Dadson et al., 2017; Ellis et al., 2021; Rogger et al., 2017). The influence of season on surface vegetation roughness at the catchment scale may be especially important for NFM as most large storm events occur in winter in the UK when vegetation is the least rough; the occurrence of large winter storms is also expected to increase with climate change (Lowe et al., 2018).

The aim of this paper is to understand the impact of season, specifically changes in vegetative roughness driven by annual growth and decay, and land management practices on catchment runoff. Two UK upland catchments are modelled, allowing the relative differences in soil properties and surface roughness between land covers to be investigated and the influence of these factors over runoff peaks and timing to be determined. Two scenario sets are investigated. The first scenario set models, for the first time, the influence of season on vegetative surface roughness and how this impacts runoff peaks. Current land cover will be modelled, applying changes to vegetative surface roughness only. The second scenario set investigates grassland management change from intensive grazing to natural succession of grassland into woodland, and conservation management. Excluding the high-intensity grazing management for which the extent of grazing is expanded, all other management scenarios retain the same spatial configuration within the catchment, changing only the type of land cover within each segment (i.e within each field). In both scenarios, land management change will be applied only to the parts of the system which are currently OM soil grasslands, so that their influence on river flow peaks in response to major rainfall events can be assessed.

2 | METHODS

2.1 | Study sites

Two catchments were chosen for the study: Swindale (Figure 1, Table 1) and Upper Calderdale (Figure 2, Table 2), both with peatland headwaters and predominantly grassland-covered OM soil on their mid- and lower-catchment regions. Both catchments have experienced recent flood events and were chosen for their similar land covers, within which there is opportunity to implement NFM. However, the two catchments have very different topographies.

Swindale is a 15.3 km^2 catchment in the Lake District, UK of which approximately 2.89 km^2 is currently used as commons grazing for sheep, 1.84 km^2 is ungrazed commons land, 8.48 km^2 is ungrazed hill land (locally called Mosedale) and 2.66 km^2 is an upland farm situated within a U-shaped valley. Swindale Farm is managed as part of a higher-level stewardship scheme, which pays land managers to use environmentally conscious practices (Natural England, 2012).

Upper Calderdale, specifically the River Calder from source to Walsden Water at Todmorden and henceforth referred to as Calderdale, is a 21 km^2 basin-shaped catchment which has a relatively flat catchment top and bottom with steep slopes and has been heavily modified (Defra, 2021a). It is managed by multiple authorities, including Calderdale Council and private landowners.

Hereafter, parcels of land are referred to as land 'covers', encompassing both the physical surface of that land parcel, its land use (i.e., the economic purpose of that land) and any specific management

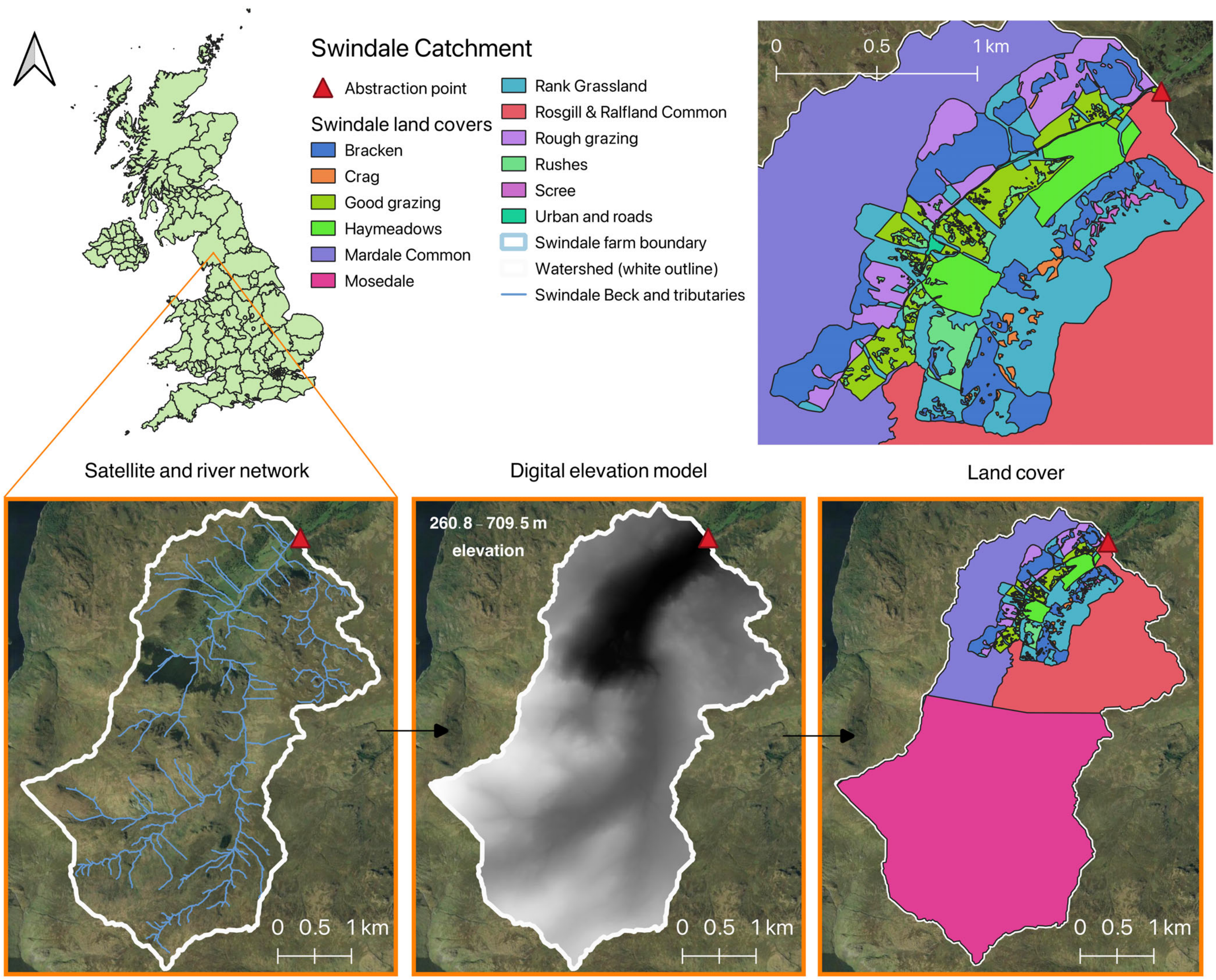

FIGURE 1 Swindale catchment and current land cover. Land cover maps provided by RSPB Haweswater.

TABLE 1 Swindale location, area, mean slope, elevation, climate and current catchment land covers, including their CEH (2017) designated land cover, area, grazing status and primary underlying soil type

		Swindale				
54°30′23″ N, 002°45′47″ W				Area: 15.3 km^2		
Mean Slope: 6.9 ± 5.3°				Elevation: 260 m – 709 m		
RSPB land cover (abbreviation)		**CEH land cover designation**	**Area (km^2)**	**Grazing status**	**Primary underlying soil type**	**Climate**
Mosedale	(MD)	Acid grassland/Peat bog	8.48	Deer	Blanket bog peat: Winter Hill 1011b	1991–2020 Shap – 5 km from Swindale Mean annual precipitation: 1863 mm Mean daily temperature: Max = 11.8°C Min = 4.3°C
Rosgill & Ralfland Common	(RRC)		2.89	Sheep and deer		
Mardale Common	(MC)		1.84	Deer		
Rank Grassland	(RG)	Improved/Acid grassland	0.71	Ungrazed	Organo-mineral: Malvern 611a and Bangor 311 e	
Bracken	(B)		0.51	Largely ungrazed, depends on location		
Rough grazing	(RoG)	Improved grassland	0.25	Sheep		
Good grazing	(GG)		0.24	Sheep		
Hay Meadows	(HM)		0.20	Sheep		
Rushes	(R)	Improved/Acid grassland	0.12	Largely ungrazed, depends on location		
Crag	(C)	Acid grassland	0.03	Ungrazed		
Scree	(S)		0.02	Ungrazed		
Urban & Roads	(UR)		0.02	Ungrazed		

Note: Climate data derived from Met Office (2022a). Primary underlying soil type derived from Cranfield University (2022). Swindale land cover was established using data provided by RSPB Haweswater - for a description of Swindale land covers, including dominant vegetation species present, see supporting information 1. CEH land cover designation was established from CEH land cover 2015 data – For a description of land covers, see Morton et al. (2011). For 'equivalent' land covers between Swindale and Calderdale, where model parameters used to represent land covers are the same, see supporting information 1.

applied. Since land cover, use and management are all known to influence hydrological function, they have been considered together. A breakdown of land covers is given in Table 1 for Swindale and Table 2 for Calderdale.

2.2 | SD-TOPMODEL

To investigate the influence of seasonal changes in surface roughness and land cover on downstream flow peaks, SD-TOPMODEL (Gao et al., 2015) was used. SD-TOPMODEL uses the original runoff equations from TOPMODEL (Beven & Kirkby, 1979), solving these for each user defined regular grid cell in a fully distributed grid. This approach is preferred to the original semi-distributed TOPMODEL because it allows infiltrated water to reach the saturated zone at different times, according to local wetness, and, more importantly in the present context, by generating overland flow in each grid cell, and routing it according to local conditions. Critically, SD-TOPMODEL allows the user to vary surface landscape properties that influence overland flow velocity, and subsurface properties that influence infiltration and soil water storage. Therefore, it is ideal for assessing the influence of season and land cover on modelled flood risk. SD-TOPMODEL outputs three predicted catchment outlet flow rates per timestep: overland flow; shallow subsurface flow; and total flow, the sum of overland and subsurface flow values. The model is well suited to catchments with shallow soils and moderate topography (Beven et al., 2021; Gao et al., 2015), therefore is ideal for Swindale and Calderdale.

2.2.1 | DEM, land cover and rainfall

In Swindale catchment, a 5 m digital elevation model (DEM) was used, and in Calderdale a 20 m DEM was used, both derived from photogrammetry and LiDAR data sources (Ordnance Survey, June 2018). Land cover data of the same resolution as the DEM were used in the model to describe spatial distributions of land and vegetation types. The resolution used was the highest possible as determined by data availability and limitations to model run time (maximum 48 h). For Calderdale, the 2017 CEH land cover data were used to represent key land cover types (CEH, 2017). For Swindale, land cover data were provided by RSPB Haweswater. Different land cover sources were used so that field data could be directly applied to corresponding baseline land covers.

Using FEH/ReFH (Kjeldsen et al., 2005), four storm events were produced for each catchment with durations of 6 and 24 h, and frequencies of 1 in 10-year and 1 in 50-year events (Table 2). Each ReFH storm had a timestep of 15 min between rainfall and runoff observations. These synthetic storm events were used so that specific return-period events could be represented, allowing like-for-like recurrence interval comparison between catchment response. Within each storm

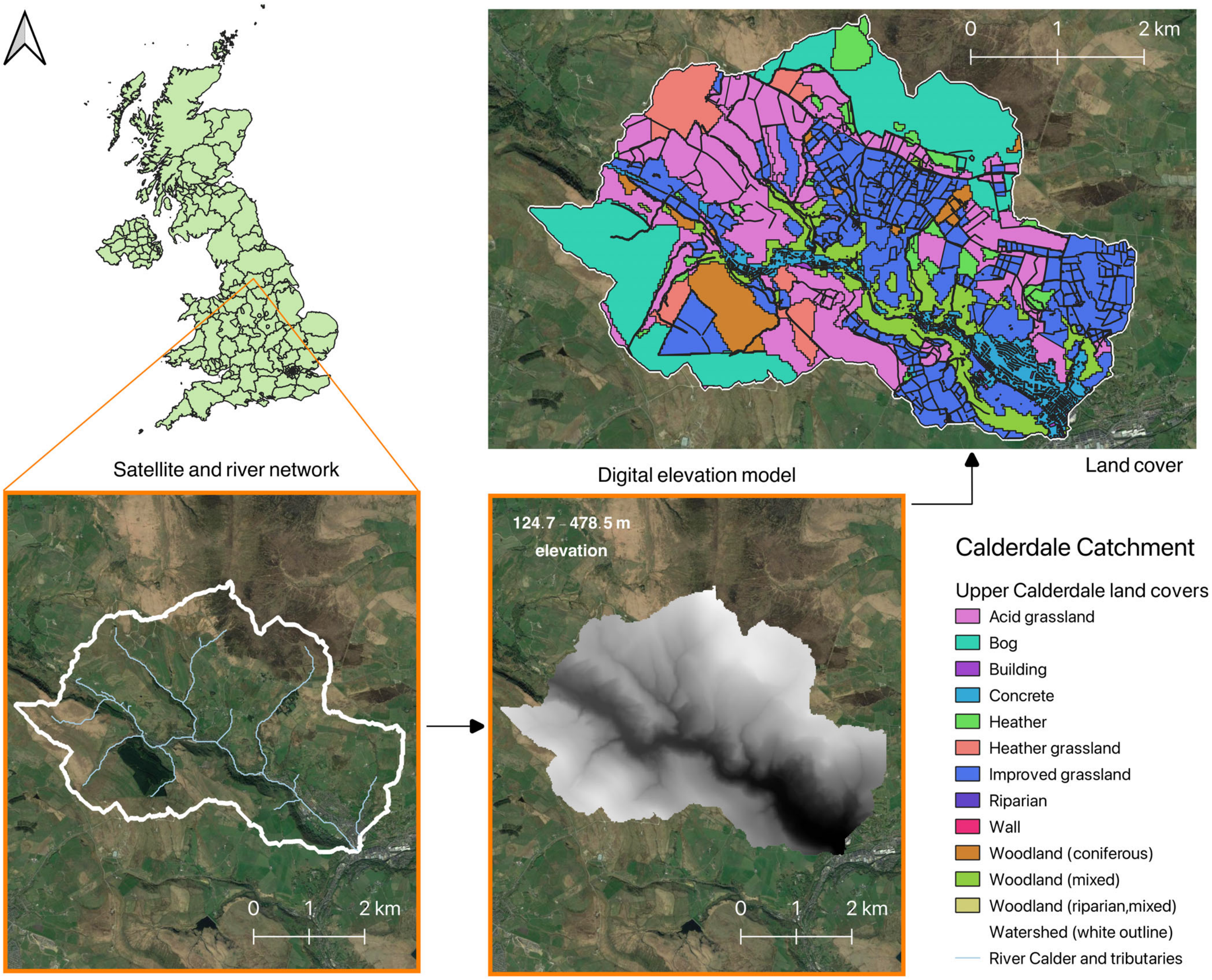

FIGURE 2 Upper Calderdale catchment and current land cover. Land cover established from CEH land cover 2015 data

event, rainfall was distributed in a Gaussian fashion, using the winter storm profile where rain falls continuously for the duration of the event with the highest intensity in the middle of the storm.

Regardless of season, evapotranspiration during individual storm events (mean of 1–2 mm per day; Blyth et al., 2019) is very small compared to storm size (36–148 mm), therefore we chose not to include its within-storm effects in either scenario (Haan et al., 1994). This also ensured that changes in runoff response were driven by the interventions alone. By excluding evapotranspiration from the seasonality scenarios, model results could also be considered conservative, where the addition of further water loss would only produce more extreme differences in seasonal runoff (Table 3).

2.2.2 | Parameter sources

In SD-TOPMODEL, three key parameters are employed to account for catchment properties: *K*, the notional hydraulic conductivity of the soil; *m*, a scaling parameter describing the active water storage of the soil; and *Kv*, an overland flow velocity parameter representing surface roughness (Gao et al., 2015). A fourth parameter, interception, I_n, is an additional feature to SD-TOPMODEL, created by Boisgontier (2018) which allows interception to be spatially distributed. Parameters are input into SD-TOPMODEL in two formats: (1) a map format to spatially distribute parameters based on land cover; and (2) a parameter file which provides the base number from which final land cover values are calculated.

To spatially distribute the model, parameters are represented in map format with one map for each parameter. With each map, a value is applied per grid cell based on measured or estimated field data from literature sources (Table 4). All spatially distributed map values are relative to the land cover with the greatest area, maintaining the difference between land covers without using absolute field-based data. Since *m* is calculated on a catchment scale, *m* was input to SD-TOPMODEL as a single lumped value ($m = 1$ for each grid cell). One map per parameter is produced for each model scenario, including the

TABLE 2 Calderdale location, area, mean slope, elevation, climate and current catchment land covers, including area, grazing status and primary underlying soil type

Calderdale					
53°43′45″ N, 002°07′41″ W			Area: 21 km^2		
Mean Slope: 10.2 ± 7.8°			Elevation: 124–478 m		
CEH land cover (abbreviation)		**Area (km^2)**	**Grazing status**	**Primary underlying soil type**	**Climate**
Peat Bog	(PB)	3.80	Ungrazed	Blanket bog peat: Winter Hill 1011b	1991–2020
Acid Grassland	(AG)	5.20	Predominantly sheep with some cattle		Bingley SAMOS – 18.5 km from Calderdale
Buildings	(Bd)	0.22	Ungrazed	Organo-mineral: Belmont 0651a and Wilcocks 0721c	Mean annual precipitation: 1057 mm
Concrete (Urban & Roads)	(Co)	1.37	Ungrazed		Mean daily temperature: Max = 12.1°C
Drystone Wall	(DW)	0.46	Ungrazed		Min = 5.5°C
Heather	(H)	0.72	Ungrazed		
Heather Grassland	(HG)	1.01	Largely ungrazed, depends on location		
Improved Grassland	(IG)	5.57	Predominantly sheep with some cattle and horses		
Riparian Grassland	(RiG)		Ungrazed		
Woodland, Coniferous	(WC)	0.78	Ungrazed		
Woodland, Mixed	(WM)	1.65	Ungrazed		
Woodland, Riparian (mixed)	(WR)	0.03	Ungrazed		

Note: Climate data derived from Met Office (2022b). Primary underlying soil type derived from Cranfield University (2022). Calderdale land cover was established using CEH land cover 2015 data – For a description of land covers, see Morton et al. (2011). Grazing density information was unavailable for the majority of land covers. For 'equivalent' land covers between Swindale and Calderdale, where model parameters used to represent land covers are the same, see supporting information 2.

TABLE 3 Modelled storm events and their rainfall intensity

Catchment	Storm duration (h)	Storm recurrence interval	Total rainfall (mm)	Rainfall intensity (mm/h)	Maximum rainfall intensity (mm/h)
Swindale	6	1 in 10 years	67.45	11.24	28.22
Swindale	6	1 in 50 years	85.36	14.23	35.71
Swindale	24	1 in 10 years	121.63	5.07	13.23
Swindale	24	1 in 50 years	148.06	6.17	16.10
Calderdale	6	1 in 10 years	36.11	6.02	15.11
Calderdale	6	1 in 50 years	50.38	8.40	21.08
Calderdale	24	1 in 10 years	61.24	2.55	6.64
Calderdale	24	1 in 50 years	81.73	3.41	8.87

baseline scenario. It is the baseline scenario map which is used for calibration. A complete overview of the map values for each scenario modelled is given in Supporting Information 1 for Swindale and Supporting Information 2 for Calderdale.

The parameters file is a scaling file, which contains one value for each of the first three key parameters. I_n is added in map format only and not included in the parameters file. As scaling factors, the values in the parameters file do not directly reflect observed field data, however units are maintained as if the values were 'measured' (see derivation in Supporting Information 3). During model processing, for each parameter, the relative map value per grid cell is multiplied by the associated parameter file value to create the final land cover value per parameter. Since units are maintained in the parameter file, this final value has an associated unit, and it is that value which influences modelled runoff. The parameter file values are calculated during calibration (see section 2.2.3) using the baseline land cover maps. Once chosen, the parameter file values remain the same for all model runs.

2.2.3 | Calibration and validation

SD-TOPMODEL was calibrated for each catchment using the four ReFH events, in place of observed data, to find the best combined model fit (i.e., the parameter values which best represented all four storm events for the baseline model). Based on the range and incremental steps for each of the parameters in Table 5, all combinations of parameter values were modelled, with the calibrated parameter set being determined by evaluating the model output using the Nash-Sutcliffe Efficiency and comparative shapes of the observed and modelled hydrographs, and then selecting the best performing model from this range. This process set the baseline values, from which the scaling factors in the spatially distributed file process were applied to. The

TABLE 4 Parameter sources and application to the baseline model

Parameter	Field measurement	Source	Source field location	Baseline land covers data was used to represent in SD-TOPMODEL: Swindale	Calderdale
m	*m* (*catchment scale*)			Input as a lumped valued, not spatially distributed	
K	K_S	Bond et al. (2021)	Swindale	B, GG, HM, RG, RoG	IG, RiG
		Kingsbury-Smith (2019)	Calderdale		H, WC, WM, WR
		Branham and Strack (2014) – median value	Various – broad literature review	MD, RRC, MC	AG, PB
		Estimates		R = mean (GG, HM & RG); UR, C & S = as low as SD-TOPMODEL inputs allowed (impermeable surfaces)	HG = mean (RG & WM); Bd, Co, DW = as low as SD-TOPMODEL inputs allowed (impermeable surfaces)
Kv	Velocity, m s^{-1}	Bond et al. (2020)	Swindale	GG, HM, RG, R	AG, IG, HG, RiG
		Holden et al. (2008) – *Eriophorum-Sphagnum* mix	Upper Wharfe, North Yorkshire, UK	MD, MC, RRC	PB
		Holden et al. (2008) – Bare peat		UR, C & S	Bd, C & DW
		Monger, Bond, et al. (2022)	Naddle valley, Cumbria, UK (neighbours Swindale)	B	H, WC, WM & WR
		Estimates		RoG = mean of GG and RG	HG = mean of RG & WM
I_n	Interception, %	Herbst et al. (2006)	Swindon, Wiltshire, UK		H, HG
		Herbst et al. (2008)	Newbury, Berkshire, UK		WM, WR
		Gash et al. (1980)	Various – UK coniferous forest		WC

Note: Scenarios use the same sources; further details can be found in supporting information 1 for Swindale and supporting information 2 for Calderdale.

TABLE 5 Calibration ranges, chosen calibrated values and Nash-Sutcliffe ranges for Swindale and Calderdale

Parameter	Calibration range (incremental step)	Swindale calibrated value	Calderdale calibrated value
m	0.006–0.02 (0.02)	0.008	0.008
Kv	5–30 (5)	9	12
Ln(*K*)	*K* = 50–600 (50)	6.214608	6.109248
Calibrated model Nash-Sutcliffe Efficiency range for all ReFH storms:		0.9411–0.9657	0.8134–0.8947

Note: Derivation of each parameter and associated units is given in supporting information 3.

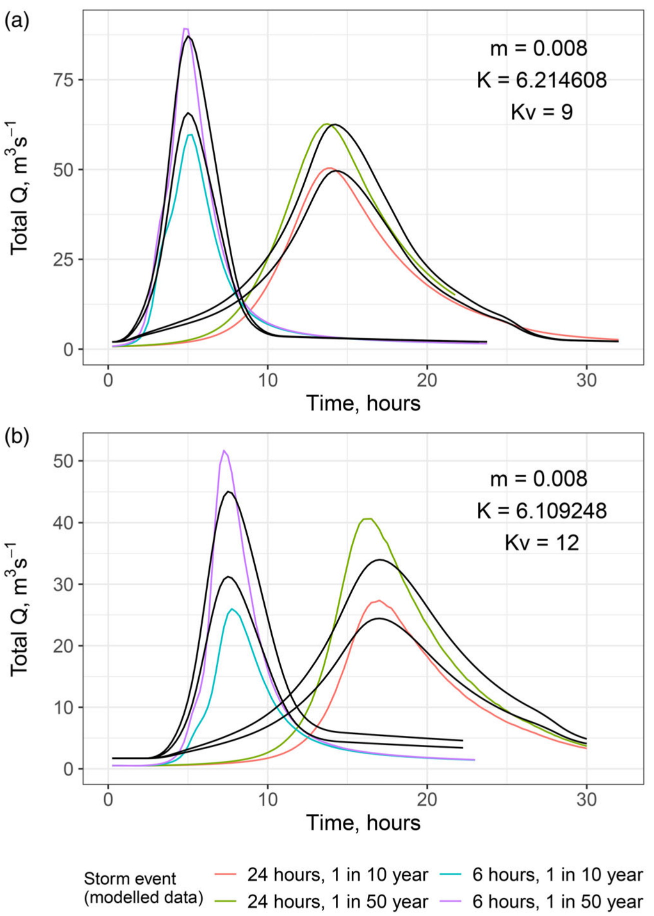

FIGURE 3 Final calibration model runs for Swindale (a) and Calderdale (b). The black line represents the ReFH data (in place of observed data) per storm event.

four calibrated storm events for each catchment are shown in Figure 3.

Following calibration using the ReFH storm events, validation was conducted using observed rainfall and runoff data from local gauges. This ensured that the model was representative of real storm events in addition to being calibrated to 'designed' ReFH storms. In Swindale, 15-minute precipitation data were obtained from Mickleden station, approximately 24 km SWW of Swindale (Middle Fell Farm telemetry, Station number 586820, NY 28 06). 15-minute flow gauge data from Swindale Beck was recorded by the Environment Agency gauge near the catchment outlet (Environment Agency, 2021). These data were used to isolate Storm Ciara, a 1 in 2 year rainfall event. For Swindale the NSE was 0.71. Calderdale was validated using a storm event from December 2015, which produced a NSE of 0.72 (Willis & Klaar, 2021).

2.3 | Scenarios tested

A variety of scenarios were tested (Table 5). Scenarios were designed to be compared with the baseline scenario, representing each catchment in its current land cover configuration where parameters were based on the annual average value. For the management scenarios, interception values, including for the baseline model, were for 'winter interception'; this was to provide a conservative estimate of I_n, since data sources were not directly from the catchments modelled.

2.3.1 | Scenario 1: Seasonality

To test the influence of seasonal change in roughness, driven by vegetation growth, decay and management, on flood peak and duration, five scenarios were produced. All scenarios used the current land cover configuration and the same *m* and *K* values as the catchment baseline model. *m* and *K* were not changed seasonally. To represent season, *Kv* and I_n parameters were employed. Seasonal scenarios were compared to the baseline map, for which *Kv* and I_n parameters were the annual average value.

Through flume investigations at the hillslope scale, Bond et al. (2020) found significant seasonal differences in overland flow velocity as the result of seasonal growth, decay and management within different grassland types. Scaling up to the catchment scale, *Kv* was applied based on the relative difference in measured overland flow velocity as recorded in Swindale in April, June, July, September, and November by Bond et al. (2020) (Table 5; Supporting Information 1 & 2).

Within the months represented, April and November were chosen to represent 'winter', and June, July and September to represent 'summer'. This designation was based on Bond et al. (2020) who applied the same winter and summer comparisons. Since true winter (December to February) values could not be obtained, seasonal designation was based on the 2019 growing season for which April and November were relatively cold and therefore the vegetation reflected winter dormancy. Using this, summer and winter I_n was applied based on values obtained by Herbst et al. (2006), Herbst et al. (2008) and Gash et al. (1980).

2.3.2 | Scenario 2: Influence of grassland management

To test the potential role of upland management on flood peaks and timing, the catchment configuration and associated land cover parameters were altered based on seven management possibilities (Table 6). These included a historical land cover (1980s–1990s) and future possibilities between 2 and 50 years from the present day. Management scenarios were informed by discussions with practitioners about what potential changes would be most feasible and would be supported by ongoing policy development. To specifically model grassland management, changes were applied to grassland designated areas of the baseline land cover only.

Kv, *K* and I_n parameters were employed, where literature suggests all change in response to management over the proposed time frames. Where scrub and woodland were introduced, it was assumed to be established scrub or broadleaf woodland with comparatively high *K* and I_n, and low *Kv*, to all grassland.

Land cover maps for each management scenario and the relative parameter differences are shown in Supporting Information 1 for Swindale and Supporting Information 2 for Calderdale.

TABLE 6 Seasonality and management scenarios tested

Scenario	Scenario name	Scenario description	Baseline components maintained per scenario	Baseline components changed per scenario
Baseline	Baseline	Baseline map: annual average data, current catchment land cover		
Seasonality	1_1	April	• Land cover configuration • *m* • *K*	• *Kv* • I_n (Winter = April & November, Summer = June – September)
	1_2	June		
	1_3	July		
	1_4	September		
	1_5	November		
Management	2_1	Revert to high-intensity grazing based on historical land cover.	• *m*	• Land cover configuration • *Kv* • *K* • I_n (winter values only)
	2_1a	(Calderdale only) High-intensity grazing based on Swindale 2_1, allowing for a direct comparison between catchments.		
	2_2	Passive management: catchment in 2 years' time if all active management were removed. Grazing fields and hay meadows are replaced by rank grassland.		
	2_3	Passive management: catchment in 5–10 years if all management were removed. Following scenario 3, scrub develops across 10% of the catchment.		
	2_4	Passive management: catchment in 10–50 years if all active management were removed. Following scenario 4, scrub and woodland develops across 20% of the catchment.		
	2_5	Passive management: extreme scenario. Catchment in 50+ years if all active management were removed and woodland spread to cover 80% of the catchment.		
	2_6	Active management: conservation management. Haymeadows are maintained for biodiversity, rank grassland and bracken are converted to woodland and scrub, low-density cattle grazing is introduced.		

Note: Historical land cover, based on high-intensity farming in the 1980s and 1990s, was determined through conversations with current land managers. For scenario maps, see supporting information 1 for Swindale and supporting information 2 for Calderdale.

2.4 | Analysis methods

Model outputs were analysed for each catchment, comparing each scenario to the baseline scenario. Due to catchment topography and its influence on subsurface flow calculations, Calderdale was overly sensitive to changes in permeability (*K*) as the catchment outlet is predominantly urban which is represented as low permeability region in the model; therefore, Calderdale management scenarios were analysed for overland flow only. In Swindale, subsurface flow, and therefore total flow, could be modelled for all scenarios. The model limitations were not considered problematic because in upland catchments with shallow soils, particularly the OM grasslands on which NFM interventions were placed within this research, overland flow is the primary driver of flooding (Bond et al., 2021; Gao et al., 2016). Therefore, overland flow was chosen as the focus of analysis. In both catchments, changes in peak runoff were compared between scenarios and the baseline condition and the time to peak from rainfall start was measured. The shape of each model hydrograph was visually compared.

3 | RESULTS

In the following section, model runs are coded by month of the year (seasonality scenarios) or model number from Table 6 (management scenarios). Changes to peak runoff from the baseline scenario are given as percentages with the absolute difference in peak runoff volume from the baseline scenario for that storm event in parentheses.

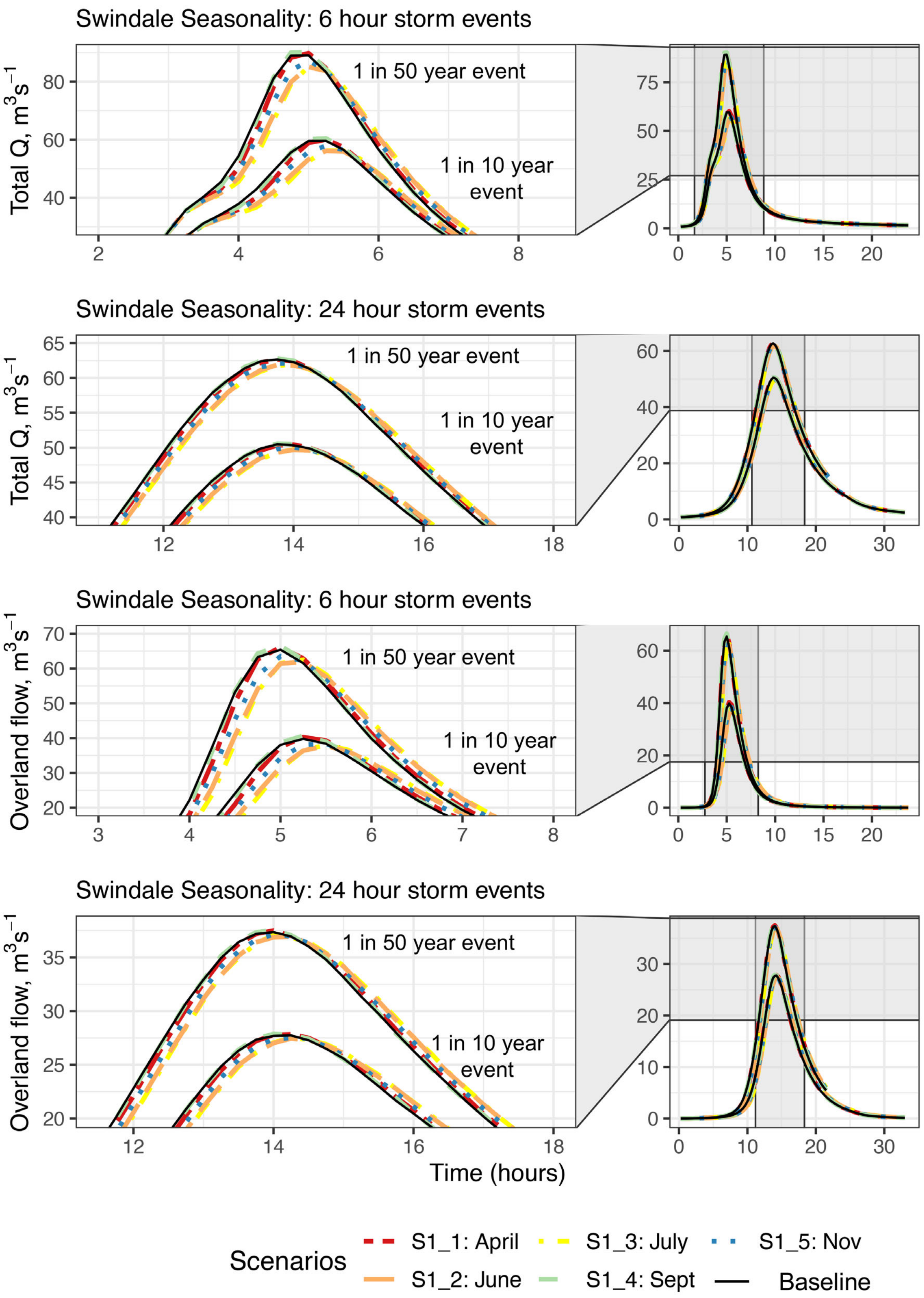

FIGURE 4 The influence of seasonality on total runoff and overland flow peak and timing for ReFH storm events in Swindale. The black line represents the baseline model (annual average).

A table containing results in full is provided in Supporting Information 4.

3.1 | Scenario set 1: Seasonality

3.1.1 | Swindale

Seasonal vegetative roughness influenced flood peak and timing for both total flow and overland flow, with the most substantial changes predicted in the 6-h events (Figure 4; Figure 6). For all scenarios the highest flow peaks were predicted in November with up to 2.1% (0.85 $m^3 s^{-1}$) increase in overland flow peak and 1.4% (0.84 $m^3 s^{-1}$) increase in total runoff peak (both from the 6-h, 1 in 10-year event) from the baseline scenario. The lowest runoff peaks occurred in July with decreases in overland flow of up to 5.4% (3.51 $m^3 s^{-1}$; 6-h 1 in 50-year) and decreases in total runoff of up to 5.7% (3.39 $m^3 s^{-1}$; 6-h 1 in 10-year). Subsurface flow was the least influenced by changes in seasonal vegetative roughness with all changes to peak runoff <0.03% different from the baseline model.

There were no delays to total runoff peak timing in the 6-h storms, however a 15-min peak delay was predicted for the April, June, July and September 24-h 1 in 10-year storms and the 24-h 1 in 50-year June event.

3.1.2 | Calderdale

Calderdale models produced a similar response to those for Swindale, also reacting to seasonality with the most pronounced changes in the 6-h storm events. In Calderdale, the highest flow peaks occurred in April with up to 2.2% (0.87 $m^3 s^{-1}$) increase in overland flow and 1.9% (0.92 $m^3 s^{-1}$) increase in total runoff (both from the 6-h, 1 in 50-year event) from the baseline scenario (Figure 5; Figure 6). The lowest runoff peaks were found in September, from the 6-h, 1 in 10-year event, with decreases in overland flow of up to 5.5% (0.96 $m^3 s^{-1}$) and decreases in total runoff of up to 5.1% (1.21 $m^3 s^{-1}$) from the baseline scenario. Subsurface flow was more influenced by seasonality than in Swindale, changing by ±0.85% from the baseline model (July compared to November, both 24-h, 1 in 10-year).

In Calderdale, for the 6-h events, only the April, 1 in 10-year event, produced a peak time difference (15 min earlier) compared to the baseline model. In the 24-h events, the 1 in 10-year storm produced peaks flow 15 min after the baseline model peak in June, July and September, and 15 min before the baseline model in November. For the 24-h, 1 in 50-year model, peak total runoff was 15 min delayed in all months compared to the baseline model.

3.2 | Scenario set 2: Land management

Management also influenced flood peak and timing, with the greatest changes observed for the 6-h storm events. The following results describe the modelled outcome for each scenario in Swindale (Figure 7), Calderdale (Figure 8) and the two catchments combined (Figure 9).

3.2.1 | Swindale

Scenario S2_1 increased overland flow peak (by between 13.1% (8.59 $m^3 s^{-1}$; 6-h, 1 in 50-year) and 25.2% (7.00 $m^3 s^{-1}$; 24-h, 1 in 10-year)) and total runoff peak (by between 1.0% (0.57 $m^3 s^{-1}$; 6-h, 1 in 10-year) and 2.0% (1.81 $m^3 s^{-1}$; 6-h, 1 in 50-year)) for all storm events. All other scenarios decreased overland flow and total runoff peaks compared to the baseline land cover (Figure 7; Table S1_1). Scenario S2_2 was the most effective at reducing flow peaks with overland flow reduced by 13.5% (5.03 $m^3 s^{-1}$; 24-h, 1 in 50-year), 15.7% (4.33 $m^3 s^{-1}$; 24-h, 1 in 50-year), 21.5% (14.04 $m^3 s^{-1}$; 6-h, 1 in 50-year) and 24.2% (9.62 $m^3 s^{-1}$; 6-h, 1 in 10-year) (Figure 7). Total runoff peak was reduced by more in the 6-h events than in the 24-h events: 20.5% (12.20 $m^3 s^{-1}$; 6-h, 1 in 10-year) and 17.1% (15.26 $m^3 s^{-1}$; 6-h, 1 in 50-year) compared to 6.1% (3.06 $m^3 s^{-1}$; 1 in 10-year) and 4.8% (3.03 $m^3 s^{-1}$; 1 in 50-year). The next most effective management for reducing overland flow peak was S2_5, 80% woodland, and this scenario was also more effective at reducing overland flow peak than S2_2 for the 24-h storms.

Scenarios S2_3, S2_4 and S2_6 were similarly effective at reducing overland flow peaks, with reductions between 6.0% (S2_3: 6-h, 1 in 10-year, 2.25 $m^3 s^{-1}$) and 10.9% (S2_6: 6-h, 1 in 10-year, 3.02 $m^3 s^{-1}$). For these scenarios, storm duration did not influence percentage change from the baseline scenario, however management scenarios were more effective at flood peak reduction for the 1 in 10-year events (median overland flow peak reduction from baseline = 8.7%) than the 1 in 50-year events (median overland flow peak reduction from baseline = 7.1%). Scenario S2_2 delayed the total flow peak by 30 min in the 6-h storms and 45 min in the 24-h storms. In the 6-h storms, no other scenario caused a delay in total runoff peak timing. In the 24-h, 1 in 10-year storms, total peak was delayed by 15 min in scenarios S2_3, S2_4, S2_5 and S2_6. In the 24-h, 1 in 50-year models, total runoff peak was delayed by 15 min in scenarios S2_3 and S2_4.

Modelled subsurface flow peaks varied more than for the Seasonality scenarios. Subsurface peaks decreased for all storm events in Scenario S2_1 (by between 28.8% (17.35 $m^3 s^{-1}$; 24-h, 1 in 10-year) and 33.4% (23.24 $m^3 s^{-1}$; 6-h, 1 in 50-year)), and increased for all other S2 scenarios. The greatest increases in subsurface flow peak were for scenario S2_5 (maximum 20.7%; 42.10 $m^3 s^{-1}$; 6-h, 1 in 50-year) and scenario S2_2 (maximum 16.1%; 40.5 $m^3 s^{-1}$; 6-h, 1 in 50-year). Scenarios S2_3, S2_4 and S2_6 responded similarly, increasing subsurface flow peaks by between 6.6% (S2_3: 24-h, 1 in 10-year, 26.00 $m^3 s^{-1}$) and 12.7% (S2_6: 6-h, 1 in 50-year, 39.40 $m^3 s^{-1}$).

For overland flow peak, delays of 15 min were modelled in the 6-h, 1 in 10-year and 24-h, 1 in 50-year events for S2_3, S2_4 and

S2-6. In the 6-h, 1 in 50-year event, 15-min delays were modelled for S2_3 and S2_4. With the exception of the 6-h, 1 in 10-year event, overland flow peak runoff was 15 min earlier for scenario S2_1.

3.2.2 | Calderdale

Only overland flow was modelled in Calderdale for the management scenarios (Figure 8). Response was similar to Swindale in that scenarios

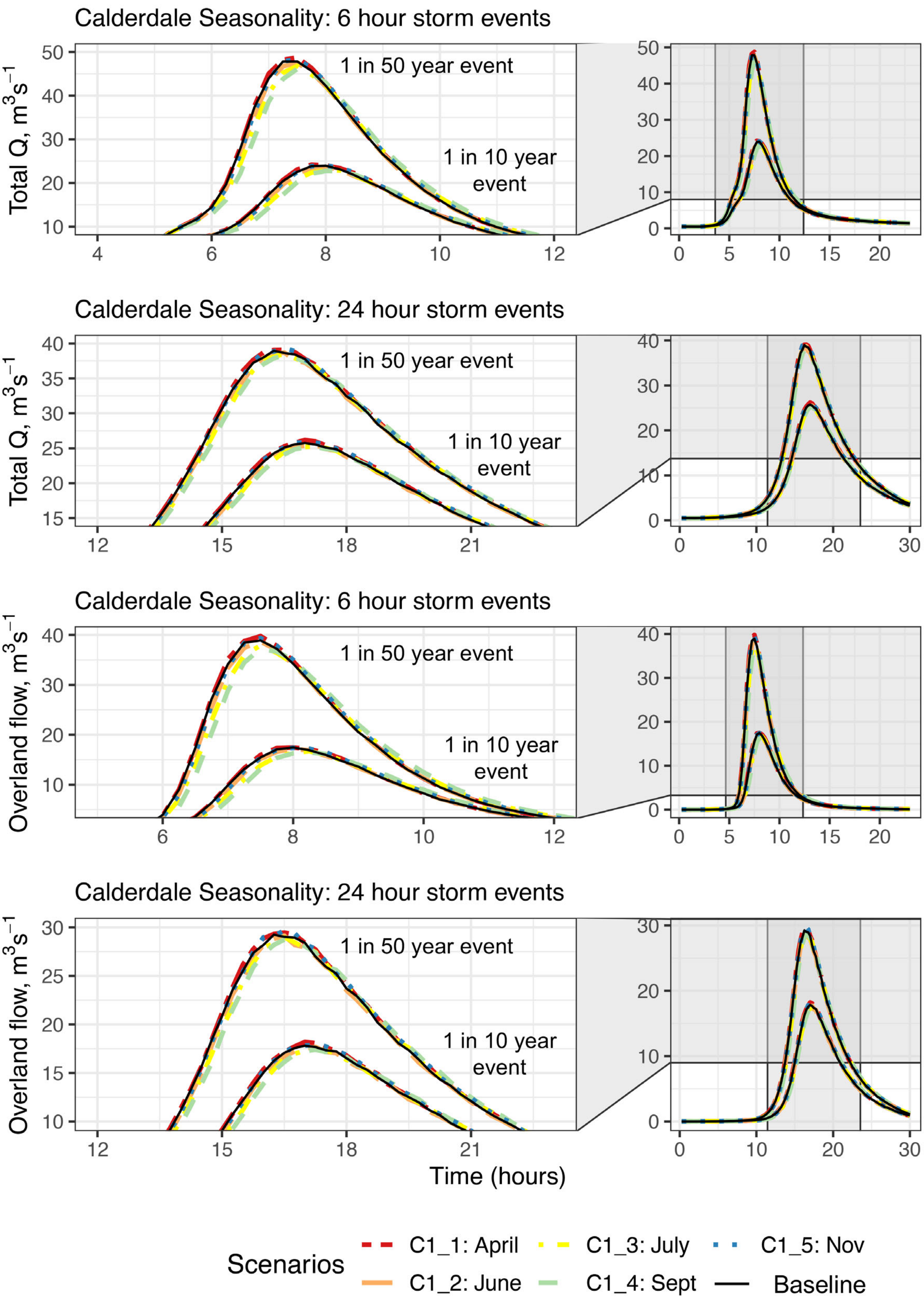

FIGURE 5 The influence of seasonality on total runoff and overland flow peak and timing for ReFH storm events in Calderdale. The black line represents the baseline model (annual average).

C2_1 and 1a increased overland flow peaks for all storm events and all other scenarios decreased peak runoff. However, land management changes in Calderdale produced higher differences from the baseline model (Figure 9) when compared to Swindale. From the baseline model, overland flow peak in Calderdale increased by between 0.3% (0.09 m^3 s^{-1}; 24-h, 1 in 50-year) and 5.9% (1.03 m^3 s^{-1}; 6-h, 1 in 10-year) for C2_1 and by between 15.3% (6.01 m^3 s^{-1}; 6-h, 1 in 50-year) and 24.7% (4.49 m^3 s^{-1}; 24-h, 1 in 10-year) for scenario C2_1a.

Scenario C2_5 was the most effective for all storm events; overland flow peak was reduced by 33.1% (13.03 m^3 s^{-1}; 6-h, 1 in 50-year), 37.3% (6.53 m^3 s^{-1}; 6-h, 1 in 10-year), 37.8% (11.24 m^3 s^{-1}; 24-h, 1 in 50-year) and 41.0% (7.45 m^3 s^{-1}; 24-h, 1 in 10-year). The next largest reductions in peak overland flow were for scenario C2_2 followed by scenarios C2_3 and C2_4, and then scenario C2_6 which still produced substantial overland flow peak reductions by between 18.4% (7.24 m^3 s^{-1}; 6-h, 1 in 50-year) and 27.7% (5.03 m^3 s^{-1}; 24-h, 1 in 10-year).

Peak timing was affected by management being up to 30-min earlier and later than for the baseline model. Scenarios C2_1 and C2_1a brought forward the overland flow peak in all storm events except scenario C2_1 for the 24-h, 1 in 10-year event, for which overland flow peaked at the same time as the baseline. In the 6-h storm events (both C2_1 and 1a), the 24-h, 1 in 10-year event (C2_1a) and the 24-h, 1 in 50-year event (C2_1), the overland flow peak was 15 min earlier than the baseline. Scenario C2_1a peaked 30 min earlier than the baseline in the 24-h, 1 in 50-year storm event. Delays of 15 min occurred for scenarios C2_2 and C2_4 in the 6-h, 1 in 10-year event. Scenarios C2_3, C2_4, C2_5 and C2_6 resulted in flow peaks that were delayed by 15 min, and, for C2_2, by 30 min for the 24-h, 1 in 10-year storm event. In the 24-h, 1 in 50-year event, peak delays of 15 min were predicted for scenarios C2_2 and C2_5. There were no overland flow peak delays predicted for the 6-h, 1 in 50-year storm event.

4 | DISCUSSION

4.1 | Surface roughness

Overall, seasonal changes in surface vegetation roughness and land cover distributions were shown to influence total and overland flow peaks in response to storm events in two upland grassland-dominated

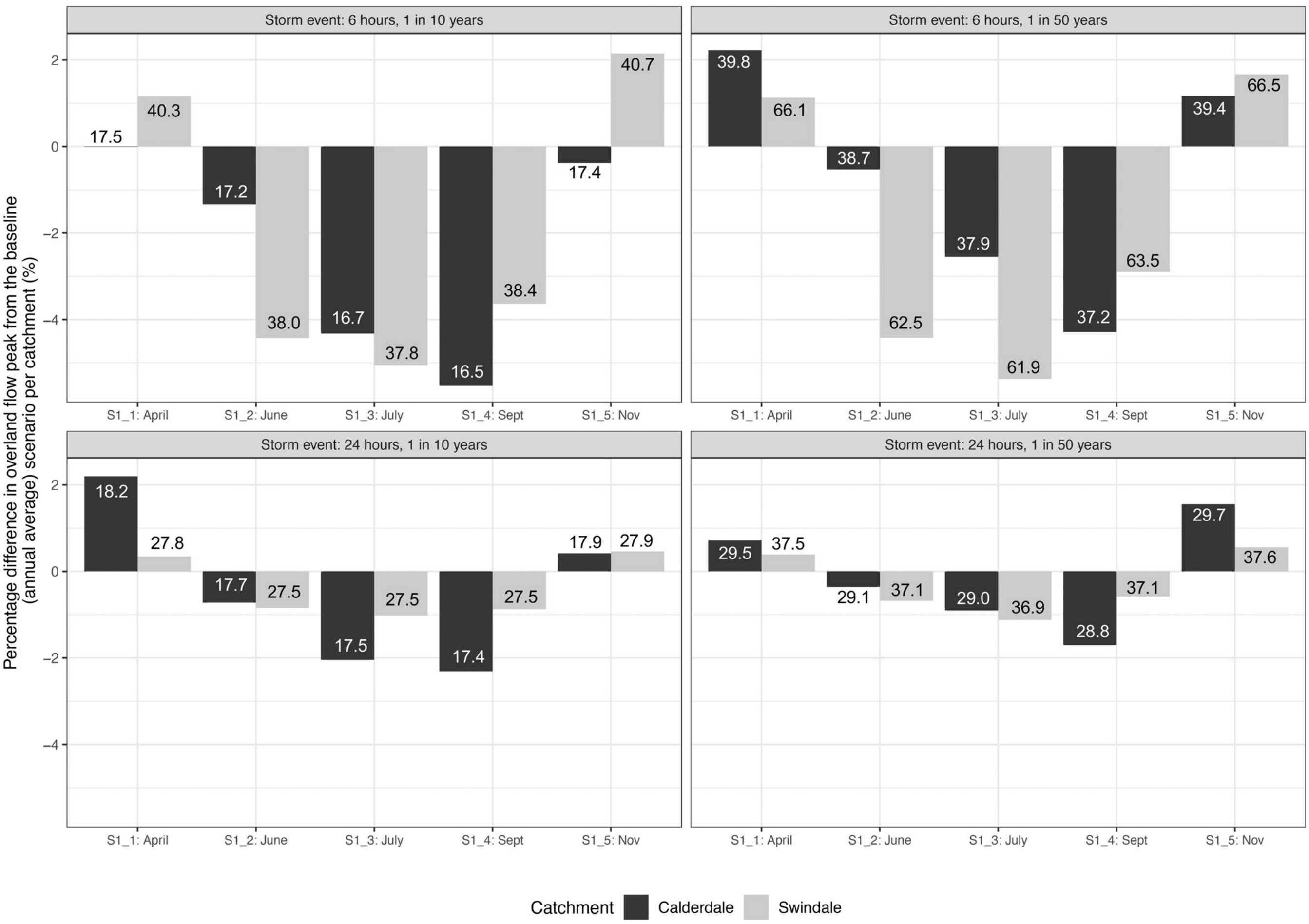

FIGURE 6 A comparison of the percentage difference in overland flow peak from the baseline (annual average) seasonality scenario for Swindale and Calderdale, with numbers inside each bar showing absolute peak overland flow, m^3 s^{-1}. Baseline absolute peak overland flows for Swindale were 39.8 m^3 s^{-1} (6-h, 1 in 10-year), 65.4 m^3 s^{-1} (6-h, 1 in 50-year), 27.7 m^3 s^{-1} (24-h, 1 in 10-year), 37.4 m^3 s^{-1} (24-h, 1 in 50-year). Baseline absolute peak overland flows for Calderdale (seasonal scenario only) were 17.5 m^3 s^{-1} (6-h, 1 in 10-year), 38.9 m^3 s^{-1} (6-h, 1 in 50-year), 17.8 m^3 s^{-1} (24-h, 1 in 10-year), 29.3 m^3 s^{-1} (24-h, 1 in 50-year).

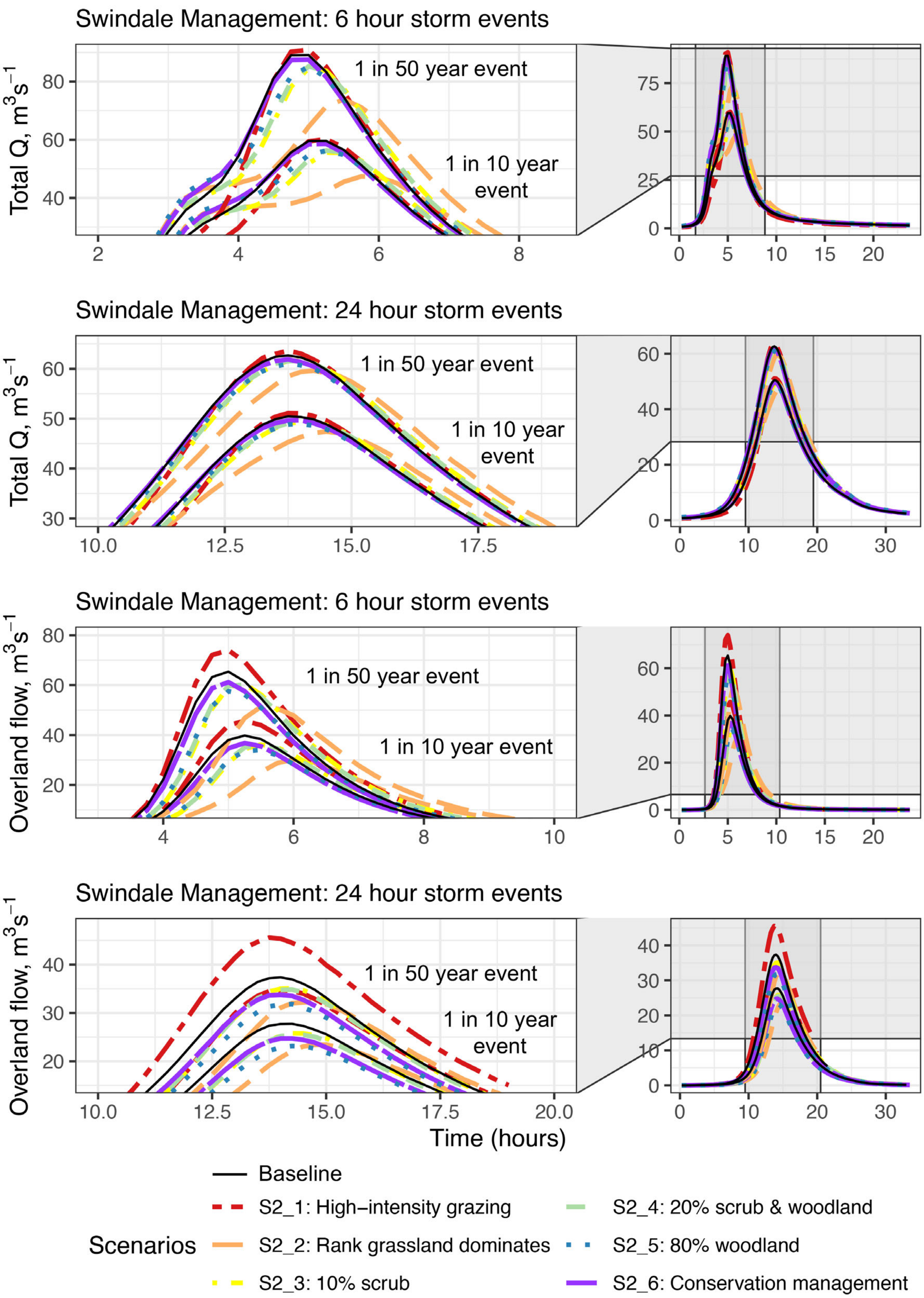

FIGURE 7 The influence of management on total runoff and overland flow peak and timing for ReFH storm events in Swindale. The black line represents the baseline model (current land cover).

systems. The variation in discharge peak and timing based on seasonal changes to vegetation growth, decay and management alone shows variation in catchment response which has not been modelled before. Both catchments responded similarly, with winter roughness producing the highest total and overland flow peaks, and summer roughness producing the lowest peaks. The extent of variation in peak discharge

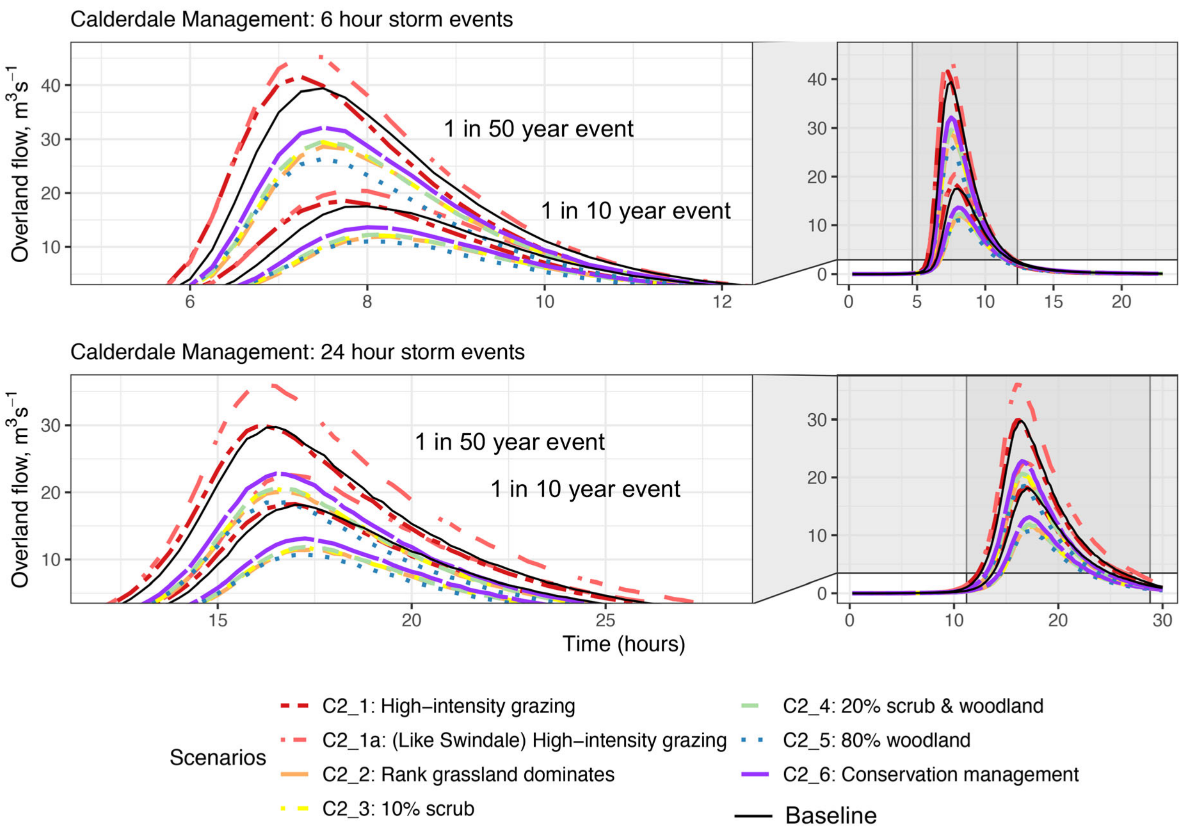

FIGURE 8 The influence of management on overland flow peak and timing for ReFH storm events in Calderdale. The black line represents the baseline model (current land cover).

as the result of seasonal surface roughness is comparable to previous modelling of a large runoff attenuation feature in Swindale (Hankin et al., 2019), and of multiple, combined NFM features in Calderdale, including woodland planting and soil improvements (Willis & Klaar, 2021). Hankin et al. (2019) modelled peak reductions of 4% ± 2%, and Willis and Klaar (2021) modelled a 6.1% peak reduction. This suggests that seasonal change alone can be as influential as NFM features, although variation in peak change will also depend on the size, position and types of NFM applied, as well as the model used, its resolution and parameter sources. Only very small percentage changes were recorded in the seasonality scenario for subsurface flow, demonstrating that modelled response to season was overland flow driven.

Roughness is dependent on natural seasonal processes as well as seasonal management activities such as hay meadow cutting and livestock grazing density changes (Bond et al., 2020). Therefore, the influence of management and any changes to the vegetation species present should be considered in their seasonal context, especially with the increasing prevalence of winter flood events (Smith & Redding, 2012; Vormoor et al., 2015). In winter, interception and evapotranspiration are reduced in comparison to summer; therefore, saturation conditions are more likely to occur, inducing surface flows (Ledingham et al., 2019; Wallace & Chappell, 2020). Although model results showed overland flow peaks to be up to 2.2% higher than the annual average in winter and winter roughness is generally lower than in summer, careful management might be used to minimize change in flood peaks. For example, understories of dense mosses, considered to be one of the most effective vegetation types for reducing flow velocity (Bond et al., 2020; Holden et al., 2008; Shuttleworth et al., 2019), might be encouraged to grow in source-areas of overland flow. Where overland flow is expected to be deeper (due to location or storm magnitude), taller, tussocky vegetation such as the Rank Grassland (for which immovable stems act as a barrier even in winter (Prosser et al., 1995)) might be used to intercept flow. Consideration should be given to all land cover types that may have appropriate structural characteristics. With the introduction of Future Farming Schemes, an opportunity is created to apply management, such as buffer strips, that considers location and seasonality. Future hydrological modelling should account for the (often opposing) influence of seasonal storms and roughness, especially when forecasting NFM impacts. If possible, models should also incorporate varying antecedent conditions to simulate seasonal change in soil moisture, which influences available water storage and associated probability of overland flow occurrence.

The influence of vegetative roughness was also shown in the management scenario simulation, alongside permeability and interception. Woodland has been found to have lower surface roughness (the ground level understory of woodlands can be shaded out and is not dense) and higher permeability than grassland (Bond et al., 2020; Bond et al., 2021; Monger, Bond, et al., 2022). In Swindale, scenario

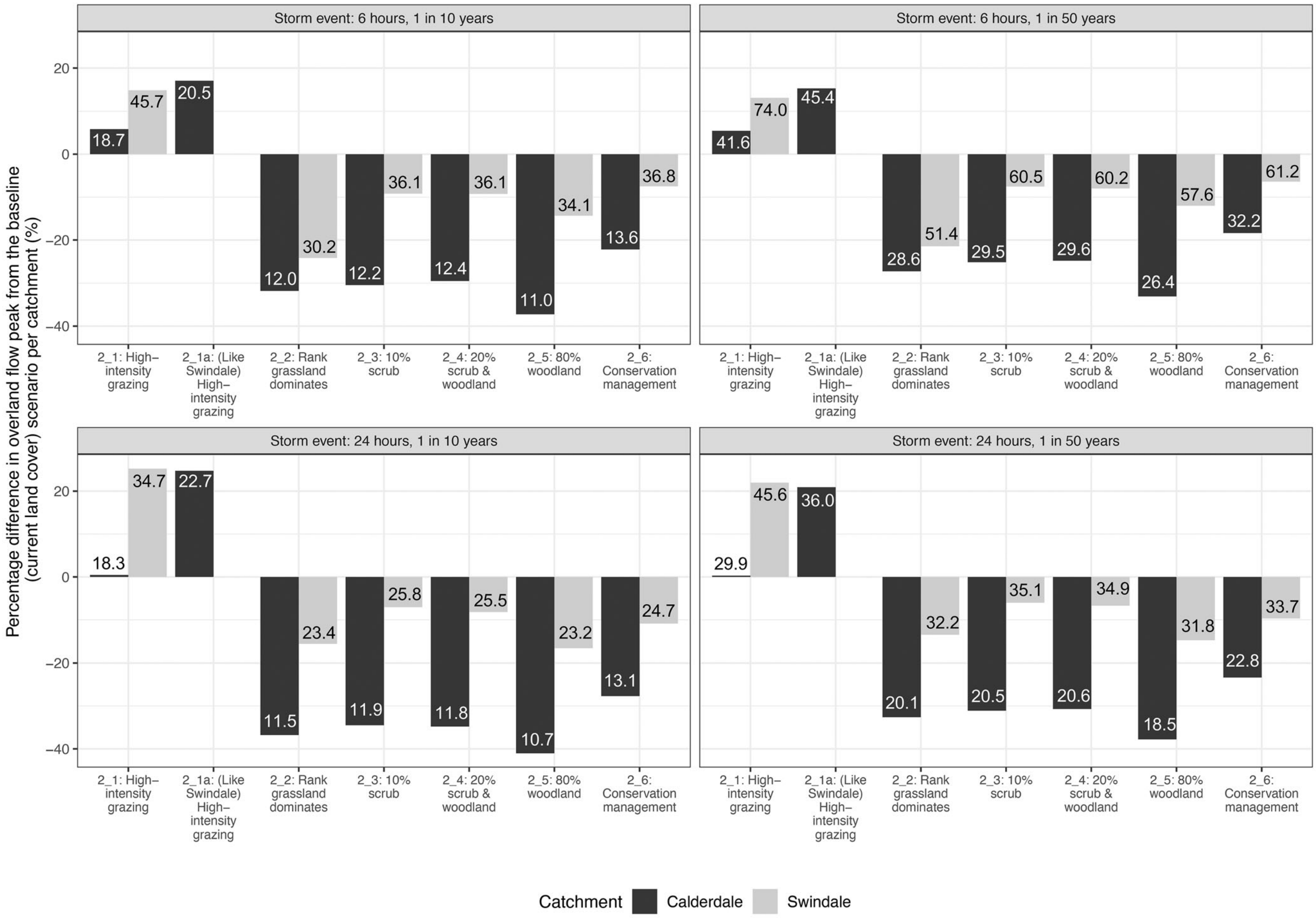

FIGURE 9 A comparison of the percentage difference in overland flow peak from the baseline (current land cover) management scenario for Swindale and Calderdale, with numbers inside each bar showing absolute peak overland flow, $m^3\ s^{-1}$. Baseline absolute peak overland flows for Swindale were 39.8 $m^3\ s^{-1}$ (6-h, 1 in 10-year), 65.4 $m^3\ s^{-1}$ (6-h, 1 in 50-year), 27.7 $m^3\ s^{-1}$ (24-h, 1 in 10-year), 37.4 $m^3\ s^{-1}$ (24-h, 1 in 50-year). Baseline absolute peak overland flows for Calderdale (management scenario only) were 17.5 $m^3\ s^{-1}$ (6-h, 1 in 10-year), 39.4 $m^3\ s^{-1}$ (6-h, 1 in 50-year), 18.2 $m^3\ s^{-1}$ (24-h, 1 in 10-year), 29.8 $m^3\ s^{-1}$ (24-h, 1 in 50-year).

2_2 reduced overland flow and total flow peaks by up to 24.2% and 20.5% respectively, and increased subsurface peaks by up to 16.1%. As scrub and woodland were added in other scenarios, total and overland flow peaks increased (and subsurface peaks decreased) despite greater permeability and interception. This suggests that the added water infiltration and canopy storage benefits were not enough to outweigh the decrease in vegetative roughness. This matches the hypothesis presented by Bond et al. (2020) who suggested that the density of vegetation at ground level was the most important factor in influencing upland hillslope runoff, especially where shallow soils dominate as they do in both Swindale and Calderdale. Where overland flow dominates (Bond et al. (2021) showed that overland flow can occur up to 60% of the time in Swindale, roughness becomes the primary control of hillslope runoff contribution to the hydrograph. Therefore, in catchments such as Swindale, management which works towards soil aeration for increased storage may be less important for flood mitigation than management which aims to control hillslope runoff through increased surface friction.

Conversely, when modelling overland flow only in Calderdale and in the 24-h Swindale models, scenario 2_5 with 80% woodland cover produced the most effective flood mitigation. Given this, the increased permeability and interception are likely to be more influential factors for overland flow management in Calderdale and the 24-h Swindale storms. However, there may be a threshold at which the extent of influence occurs (Smith & Redding, 2012). For example, within each catchment and per storm event, scenarios 2_3 and 2_4 produced very similar responses to each other despite the 10% increase in scrub and woodland cover. In addition, only scenario 2_5 was more effective than scenario 2_2 suggesting that for most practical changes in management, ground-level roughness may be the most important factor. However, seasonality may also influence the extent to which roughness; permeability and interception affect flow peaks where annual average *Kv* and winter I_n parameters were used within the management scenarios. In summer, any existing threshold may be different to in winter, potentially affecting flow peaks and timing; future research should investigate this. Unfortunately, our research cannot differentiate between the influence of permeability and interception as both change proportionally with the addition of woodland and scrub. However, the overall influence of roughness compared to permeability alongside interception may occur for a variety of reasons, as discussed below.

4.2 | Topography

The difference in topography between catchments may influence the extent to which *K* and *Kv* parameters are influential and explain why April produced the highest overland flow peak in Swindale compared to November in Calderdale. On steeper slopes, roughness is less able to reduce downslope overland flow velocity (Maske & Jain, 2014); with increased permeability, water may infiltrate soils but also be subject to increased sub-surface lateral flows (Dunne, 1978). Topography may also explain why the 24-h models in Swindale produced lower overland flow peaks for scenario 2_5 than 2_2; with lower rainfall intensity and longer duration, infiltration-excess overland flow was less likely to occur, thus permeability outweighed the influence of roughness.

4.3 | Data resolution

Due to land cover data availability and catchment size (which limits model processing power), land cover resolution in Swindale (5 m cells) was much greater than that of Calderdale (20 m cells). This may influence runoff pathways and the relative contributions of land cover types. For example, road cover is relatively sparse in the catchments modelled, however asphalt surfaces are known to act as conduits of water in storm events (Hollis, 1988); due to the relatively small size of surfaces such as this, their impact may not have been accounted for properly in the lower resolution Calderdale model. The difference in data resolution may limit comparison between catchments.

4.4 | Availability of soil hydrology data

SD-TOPMODEL parameters for Calderdale were predominately based on fieldwork from Swindale and its neighbouring catchment, the Naddle valley. Ideally, catchment parameters would always be specific to the location modelled, especially where the intensity of management differs. At the very least, a collated database of soil and vegetation hydrological properties is needed to provide options from which hydrologists can make informed parameter decisions. This is especially true for woodland data, where our fieldwork and subsequent modelling has shown rank grassland can be more effective than woodland for reducing overland flow; especially where roughness data traditionally used for modelling, such as that by Chow (1959), show woodland as the rougher land cover. Further fieldwork is required to determine whether this is Swindale-specific (since most *Kv* data were from Swindale and its neighbouring catchment), or a common error that propagates from the assumptions through into model outputs, especially since 'woodland' is a wide category for which there may be much variation in understorey vegetative roughness. In addition, the influence of roughness, permeability and interception change with scrub and woodland growth over time was not modelled due to a lack of available empirical data; future research into the effect of land cover change on hydrological properties over time is required. Finally, further work is also required to understand how surface roughness and slope combine to influence overland flow to ensure that numerical schemes of models are based on empirical data, rather than previous assumptions.

4.5 | Implications for NFM planning

While changes to total flow were more moderate across all storm events and scenarios (where total flow = overland flow + subsurface flow), the proportion of runoff in a catchment which is overland flow versus subsurface flow is vital in flood management. Several UK upland studies have reported overland flow dominance on hillslopes during high river flow events, particularly related to readily saturated thin organo-mineral soils and thicker peat deposits (e.g., Holden and Burt, 2003; Burt, 1996). Many land-cover based NFM initiatives use management to influence the volume of runoff infiltrating the subsurface in addition to the roughness of the ground surface itself. For example, high intensity grazing is frequently associated with increased overland flow production and higher flood peaks caused by soil compaction (reduced surface permeability) and low roughness as the result of overgrazing (Alaoui et al., 2018; Ochoa-Tocachi et al., 2016). Scenario S2_1 demonstrated this effect, predicting a mean 31% decrease in subsurface flow and 18.8% increase in overland flow across all storm events. Conversely, nature friendly farming and conservation management often involves reducing grazing intensity so that soil structure and vegetation are better maintained, increasing infiltration and roughness to 'slow the flow' (English Nature, 2005). An example of this is scenario S2_6, where overland flow peaks were reduced by up to 10.8%, and subsurface flow increased by up to 12.7%. However, when S2_1 and S2_6 are compared using total flow, peak changes are a maximum 2% different to the baseline. This demonstrates the complexity of the interaction between overland flow and subsurface flow, which may vary greatly whilst the total volume moving through a catchment remains at a similar level during storm events. Generally, the greatest reductions in Swindale total flow were associated with increased surface roughness (e.g., summer or higher proportion rank grassland), although only scenario S2_2 produced a percentage reduction in total flow greater than 7%. This likely reflects 'slowing the flow' for which surface roughness reduces overland flow velocity, lowering the volume of surface water reaching the catchment outlet at any one time.

The results of our modelling are also reflected in other land-cover based NFM studies for which increased surface roughness and permeability were the primary objectives. Examples from UK uplands include an average 7.2% modelled peak reduction through use of 10 m riparian buffer strips (Mason-Mclean, 2020); modelled peak reductions of 12.1% and 10.8% under conservation management (revegetation, no grazing or burning) compared to baseline (Gao et al., 2017); and measured specific peak discharge reductions of 23%–60% in broadleaf woodlands compared to grazed pasture (Monger, Spracklen, et al., 2022). This supports evidence (Burgess-Gamble et al., 2017; Nature Friendly Farming Network, 2021) that NFM methods adopted in conjunction with sustainable, nature-based farming, such as those proposed in the new UK Future Farming Schemes (Defra, 2021b, 2022b), can work to reduce flood risk.

In both catchments, interventions were applied to grazed grasslands only. Grassland excludes the commons grazing in Swindale, except for changes made as part of scenario 2_1 and 2_1a. In terms of catchment area, interventions applied in Swindale covered 9.2% (1.41 km^2) of the catchment (for scenario 2_1 interventions covered 6.64 km^2 (43.4%) of the catchment) and interventions in Calderdale covered 27.5% (5.75 km^2) of the catchment (for scenario 2_1a interventions covered 15.10 km^2 (70.3%) of the catchment). Whether policy-makers and land managers can apply interventions over such large proportions of upland catchments remains to be seen, but considering the area to which interventions were applied, and that interventions were applied to grasslands only, the reductions in overland flow peak are important and add to the much needed evidence base on NFM (Burgess-Gamble et al., 2017; Dadson et al., 2017).

The placement of NFM appears to be important. In Swindale, interventions were applied in the riparian and near-stream hillslope zones close to the catchment outlet, whereas in Calderdale, interventions were mainly hillslope based in the mid-catchment. Despite Swindale interventions covering 18.3% less catchment area than Calderdale, percentage change in overland flow peak was on average just 16.0% less. For historical grazing, this difference was even greater, where a catchment area difference of 26.9% produced just a 2.2% difference in overland flow peak. The differences between catchment area and response, and the likely influence of NFM placement, supports research by Gao et al. (2016) who showed that modelled landcover changes in the riparian zone could have three times more influence on flow peaks than changes made in upper hillslope locations.

5 | CONCLUSION

Seasonal change in ground vegetation roughness and management changes to upland catchments can have substantial influence on runoff, especially overland flow. We showed that seasonal changes in vegetation roughness alone can reduce overland flow peaks by up to 5.5% at the catchment scale, demonstrating the importance of considering the nature of surface vegetation cover at different times of the year. In addition to vegetation and soil roughness, flow can also be initially slowed via infiltration before saturation conditions, where subsurface flow velocity is generally lower than for surface runoff. When considering NFM effectiveness, seasonal surface roughness should be considered, and this could be particularly important during winter months when roughness, interception and evapotranspiration are reduced.

Land cover management is also important for controlling runoff through its influence to infiltration rates and surface roughness, with overland flow peaks reduced by up to 41.0% from the baseline scenario. Our research showed the greatest reduction in discharge peaks was associated with two management scenarios: 80% woodland cover, and conversion of grazed grasslands to rank grassland. Surface roughness and permeability are both important factors to consider when implementing NFM. However, factors such as topography and NFM placement can also affect runoff control; these physical characteristics were hypothesised to be the primary cause of difference between catchments, influencing the extent of control provided by roughness and permeability. Where overland flow dominates, surface roughness is likely to be more influential on runoff control than permeability, especially for shallow soils. On a practical basis, most catchments cannot be converted to 80% woodland cover and therefore ground-level roughness should be strongly considered. Conservation practices which combine NFM with nature friendly farming might therefore be deemed very effective, providing a potential practical compromise between economic output, conservation and NFM.

ACKNOWLEDGEMENTS

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article

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SUPPORTING INFORMATION

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

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