Generation of storm runoff and the role of animals in a small upland headwater stream

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Generation of storm runoff and the role of animals in a small upland headwater stream.

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ABSTRACT

This paper illustrates the hillslope storm runoff mechanisms and the effects of livestock in upland areas. The research site was a small upland catchment area on Dartmoor (Southwest England). It was shown that overland flow on the tracks and paths created by animals in the area responded very rapidly to rainfall, in the same order of magnitude as stream runoff. Livestock stocking densities were significantly different in different vegetation compositions. The topsoil bulk density values, moisture content and spatial track densities were significantly higher in areas associated with higher stocking rates. These areas reach a wetness threshold at an earlier state than surrounding, drier areas. When isolated, the wetter areas start discharging water only locally into downslope drier areas, but are not contributing to storm runoff in the stream. In areas with a high density of animal tracks, water is being discharged onto the track directly. The tracks comprised an ephemeral hydrological network contributing storm runoff to the stream quickly after rainfall. They transmit water rapidly downhill, short-circuiting local areas, reducing runoff lag time and increasing storm stream runoff. The runoff producing mechanism, in which soil conditions, vegetation types and path networks are a complex interplay of contributing factors, may be relevant to other uplands, especially when they act as water reservoir or source area for possible flooding events. Therefore, upland management policies need to take into account that the heterogeneity of hillslopes at local scales have implications for storm runoff at the catchment scale.

Keywords (max 8)
Runoff generation, animal tracks, hillslope hydrology, vegetation patterns, Dartmoor

INTRODUCTION

There are a variety of possible hillslope hydrological pathways which can deliver precipitation rapidly to the stream. In upland areas, stormflow through the subsurface is the main route to produce runoff (Tromp-van Meerveld & McDonnell, 2006a). However, the mechanisms that drive hillslope hydrology are still not fully understood (Weiler & McDonnell, 2007) and show a complex interplay of infiltrating rainfall, heterogeneity of hydraulic conductivity, vertical preferential flow paths, the existence of lateral soil pipes etc. (Tromp-van Meerveld & McDonnell, 2006b). Often only a small proportion of the catchment generates a large part of the storm runoff. This is true of many catchments, as is described by Hewlett (1961), Dunne and Black (1970) and many other authors since the 1960s (Srinivasan & McDowell, 2009). To understand the hydrological hillslope mechanisms, it is important to identify the area(s) that actively contribute to the stormflow in a catchment. This is not only important for water quality (Srinivasan & McDowell, 2009), but also from a flooding perspective, given the concern about increased flooding in recent years (Wheater & Evans, 2009; Wheater, 2006; Bronstert *et al.*, 2002).

Livestock management can change runoff patterns indirectly by modifying the vegetation characteristics, particularly in grasslands, as well as by changing the soil characteristics directly by trampling (Evans, 1998; Ferrero, 1991; Wheater & Evans, 2009) so that these areas become wetter and more prone to overland flow than the surrounding ones (Meyles *et al.*, 2006; Marshall *et al.*, 2009). Of crucial importance is how animals create a series of paths as they walk along preferred routes between grazing areas (Hester & Baillie, 1998), which can become efficient conduits of surface flow during wet weather (Bracken & Croke, 2007; Croke *et al.*, 2005). Srinivasan and McDowell (2009) showed that overland flow on semi pervious surfaces such as animal tracks (paths) can bypass relatively dry areas within catchment areas. Ziegler and Giambelluca (1997) have found that during small rainfall events, rural unpaved roads were the only contributors to storm runoff in a catchment in Northern Thailand.

Meyles *et al*. (2003) have demonstrated in a small upland catchment that the proportion of a catchment area adding to storm runoff increases when soil moisture is raised above a certain wetness threshold. We therefore hypothesise that during large storms, water reaches animal tracks and paths and that these tracks function as ephemeral channels connecting to the stream, potentially adding a large source area contributing water to the storm runoff.

This paper aims to illustrate the direct and indirect effects of animal tracks on soil hydrology, ephemeral water pathways and ultimately stream storm runoff in an upland area of Dartmoor, Southwest England. The research is relevant for many uplands in temperate climates as they are often stocked by roaming animals but also act as drinking water reservoirs (Mitchell, 1991; Mitchell and McDonald, 1995) and are source areas for potential flooding events downstream (Hall *et al*., 2014).

The paper builds upon our earlier work in the Holne Moor catchment. Newly established data are added to the existing ones in this paper and are explained in detail here. Where necessary, the paper summarizes the most important results and conclusions of earlier papers. Full information on our earlier research can be found in Meyles, 2002; Williams *et al.*, 2002; Meyles *et al.*, 2003 and Meyles *et al.*, 2006.

HOLNE MOOR EXPERIMENTAL CATCHMENT SITE

The Holne Moor catchment (Figure 1) is located on the eastern flanks of southern Dartmoor in Southwest England. It covers an area of 61 ha and ranges in altitude from 340 m above sea level at the catchment outlet at Venford Reservoir to 480 m at the blanket bog plateau of Ryder's Hill. The Venford Brook itself is a 0.9 km long, first order stream. Typical annual rainfall near Venford Reservoir is 2022 mm increasing to 2452 on the plateau (Environment Agency, 2000, unpublished data). Rainfall occurs all year round but is highest in autumn and winter, with winter half year rainfall sums of 1489 mm at the lowest point within the catchment up to 1739 mm on the plateau. There are around 20 days with snowfall per year, although the figure is higher at the highest elevations within the National Park. The days of snow lying are limited to 10-14 (Metoffice, 2014). In comparison to the 214 rain days per year, we regard the snowfall to be of limited importance to the hydrology. Comprehensive descriptions of the geology, ecology and land management of this catchment can be found in Williams *et al.* (2002), Meyles (2002) and Meyles *et al.* (2006).

The soils of the area were affected by recurrent periglacial processes and episodes of weathering during the Late Pleistocene, which contributed to the formation of the surface sediments. They are down-slope, pseudo-bedded, poorly-sorted, typically sandy materials to about six metres in depth, derived primarily from the weathered granite and loessic sediment (Gerrard, 1989). The uppermost part of the catchment (around 5% of the catchment, situated above 470 m above sealevel) consists of a blanket bog plateau of poorly drained amorphous soil, while the valley sides support well-drained brown podzolic soils. The gentler lower slopes are dominated by ironpan stagnopodzols, and the soils of the valley bottom are highly gleyed (Gerrard, 1990). Locally, these slopes have been cultivated and grazed since the Bronze Age (Caseldine, 1999; Maguire *et al.*, 1983).

Vegetation in the area is typical for the grass moors of Dartmoor, with a mosaic of different grass and heath species. Meyles *et al*. (2006) defined four vegetation types (Figure 2): (1) HG: heather-grass mosaic, with *Calluna* and *Festuca ovina* as the main species; (2) GG: gorse and grass: (*Ulex* spp.) and/or long grass species, mainly *Molinia caerulea*; (3) BG: bracken and grass: predominantly bracken (*Pteridium aquilinum*) with an underlying layer of short mainly grazed grasses (*Festuca ovina* and *Agrostis capillaris*); and (4) SG: short grass – grasses with a very short sward height (mainly *Festuca ovina* and *Agrostis capillaris*).

Stream discharge in the area shows a very rapid response to rainfall, with quick rise and fall in discharge and a short time to peak (Meyles *et al*., 2003). During large rainstorms, a substantial proportion of the catchment (around 40%) was calculated as contributing to storm runoff (Meyles, 2002). This figure of 40% was much higher than the 10% variable source area that was suggested based on field observations (Meyles *et al*,. 2003). In principle, while overland flow is possible, the relatively small amount of sheet flow observed cannot explain the large volume of storm water (Meyles *et al.*, 2001a). This is in line with observations by Freeze (1974) that for many catchments, a large portion of storm flow is generated by less than 10% of the catchment area. Likewise, although the saturated conductivity of the soil is relatively high, the conductivity is not high enough for storm water to be transported to the stream quickly enough to explain the flashy stream flow response (Meyles, 2002; Williams *et al.*, 2002). The surface and shallow subsurface water pathways at Holne Moor show a complex pattern, depending on topographic and wetness conditions as well as vegetation type (Meyles *et al.*, 2003).

METHODOLOGY

The approach adopted in this paper is to describe the primary vegetation and physical characteristics of the soils and consider how these vary locally in different grazing regimes. How animal tracks and other paths receive water, and how storm flow is transported from the adjacent hillslopes into the stream were investigated with hydrological instrumentation. This was then analysed by establishing the successes and limitations of the application of conventional assumptions and standard hydrograph analyses to the hydrological data. The nature of the possible connection between the pattern of flashy discharge and the differential interactions between grazing animals and hydrology was examined through detailed analysis of the hydrographs of storm runoff from three locations. Supplementary data were gathered to be combined with existing datasets of the area as published in earlier papers (*e.g.* Meyles *et al.*, 2003 and Meyles *et al.*, 2006). The locations of the site instrumentation are shown in Figure 1.

The action of the tracks as ephemeral channels was measured on a path situated midway down the slope using a thin-plate weir (path weir in Figure 1). The path was selected as being a typical path in terms of width and orientation within the catchment. Hillslope overland flow was captured in a shallow existing gully parallel to the stream at the base of the southern hillslope. The overland flow, mainly coming off an area with BG and SG vegetation types, was monitored using a thin-plate weir fitted with a gutter (hillslope weir in Figure 1). Stream discharge was monitored at ten-minute intervals using a trapezoidal flume at the catchment exit. Rainfall totals were recorded every minute in the vicinity of the catchment outlet using a tipping bucket. The detailed stream and ephemeral discharge measurements extended from 1 October 2006 to 30 April 2007. As the discharge of the stream is very flashy, the flow quickly returns to approximately typical seasonal non-storm values, especially after larger storms. Storm flow could therefore be separated from the baseflow by a line that connects the start of the storm runoff and the selected end of the storm. The rainfall runoff coefficient was calculated as the volume of storm runoff less baseflow volume, divided by the volume of rainfall. Response lag times were defined and calculated as the time from the centroid (depth weighted centre) of rainfall to peak discharge (Black, 1991).

Soil moisture content was measured using Time Domain Reflectometry (TDR) (Topp *et al.*, 1980; Nielsen *et al.*, 1995) adapted by Roth *et al.* (1992) for organic soils in the monitoring period from 1 October 1998 to 30 September 1999. Two grids were established as shown in Figure 1 – one was situated in an area with observed low grazing intensity (hillslope TDR grid; about 1 sheep per ha or less) and the other was in an area of high grazing intensity (grazing TDR grid; about 5 sheep per ha on average) (Meyles, 2002). TDR rods were installed at four points at each of the two main paths on the hillslope (Figure 1), thus creating a total of eight measuring locations. Each location was accompanied by two soil moisture measuring points: one upslope and one downslope of each path location, at a maximum of five metres from the track. As the distance between these points was short, it is assumed that soil properties other than those related to path usage does not differ between the measuring points. The non-parametric Kruskal Wallis test was used to determine statistically significant differences in average soil moisture content.

On the southern hillslope, the properties of the topsoil were measured at 23 locations within the TDR grid in varying topographic conditions and vegetation compositions. The measured variables comprised bulk density, porosity distribution and organic matter content at depths of 0-3, 4-7, 12-15 and 16-19 cm, see Meyles *et al.* (2001b) and Meyles *et al.* (2006) for full descriptions.

As the study area is common land, grazing animals (sheep, ponies and cattle) are allowed to roam freely. Livestock distributions in the study area were recorded on fifteen different occasions during 1999, when the locations of all individual animals were recorded and subsequently digitised in a GIS (Meyles, 2002). As grazing and trampling pressures vary between different livestock types, species were converted into livestock units (LU) according to the Dartmoor ESA standards (DEFRA, 2012), in which sheep represent 0.15 LU, cattle 0.9 and ponies 1.0. The Dartmoor ESA standards have been implemented in the mid-1990s after concerns of overgrazing and have not been changed since. We therefore assume that the 1999 data is representative for the 2006-2007 period. All fifteen instances were combined to create a livestock density map, generated by using a spatial Kernel density function (ArcGIS). A 25 m search radius was applied to compensate for observation location errors.

Paths and animal tracks were digitised from aerial photos. The distance to the nearest path was calculated on a cell-by-cell basis (original cell size based on remote sensing imagery of 1.7 m). Statistical differences of median distances to the nearest path between different vegetation types (Figure 2; Meyles *et al.*, 2001b) were tested using a Kruskal Wallis test because the data were not normally distributed.

RESULTS

Hydrologic characteristics of the Holne Moor Catchment

The hydrological response of Venford Brook to rainfall can be characterised as extremely flashy. During the study period from 1 October 2006 to 30 April 2007, the total rainfall was around 1700 mm. Because of a small amount of missing data in rainfall measurement (see Figure 3), we know that this is a slight underestimation. As winter seasonal rainfall averages at around 1600 mm, we regarded the sample winter season as only slightly wetter than average. Though the baseflow in the study period was generally around 50 l s^{-1}, there were ten storms in which discharge was greater than 500 l s^{-1} and five greater than 1000 l s^{-1} (Figure 3). From fifteen rain event, twelve storms (with a peak discharge of more than 250 l s^{-1} were selected for further analysis (Table 1). The lag time during this period was shown to be very short and averaged 3:10h, ranging from 2:00h (Q_{max} 1,080 l s^{-1}) to 6:30 h (Q_{max} 910 l s^{-1}). These values are comparable to the data from the nineteen-month 1998-2000 recording period in the same area described in Meyles *et al.* (2003). To obtain an order of magnitude impression of the contribution of paths and hillslopes to the total stream runoff per storm in the catchment, storm discharge totals from the path and hillslope weirs were added to the table. The mean rainfall-runoff coefficients for the twelve largest storms were calculated to have been 44% (Table 1) and the maximum noted during the monitoring period was 55%.

The path weir responded rapidly to rainfall (Figure 4). It was characterised by a very flashy response with a rapid rise (lag time average 2:30 h) and rapid decay, indeed the rapid recession almost mirrored the rise in flow (Table 2a). The weir at the base of slope also responded rapidly to rainfall. Unlike the path weir, the lag was from 5:00 to 8:10 h and at peak discharge there was a small second peak and then a slow decay. The lag time of all but one storms followed the order: path weir - stream - hillslope weir. The difference between flow lag times was significantly different (Table 2b). A possible explanation of the difference in lag times might be that the paths have a lower infiltration capacity than the hillslope, possibly due to trampling of the topsoil of the paths, therefore generating overland flow at an early stage of the rainstorm.

Stocking densities

The 1999 stock census found that livestock were not evenly distributed across the catchment area (Figure 5; Meyles *et al.*, 2006). When the presence of livestock was compared between vegetation types, it was found that stocking densities were significantly higher in the short grass (SG) area and to a lesser extent in adjacent areas dominated by grass with bracken (BG) (Meyles *et al.*, 2001) decreasing to the lowest intensities in gorse and grass and heather grass mosaics. This could be fully attributed to sheep densities; pony and cattle distribution were shown not to differ significantly according to a Chi-square analysis (Table 3). Because of their free movement, at some locations, the concentration of sheep led to overstocking according to the Dartmoor ESA regulations (Table 4; DEFRA, 2002). Stocking densities were close to average in the BG vegetation class, and stocking rates were lower in the gorse-grass (GG) and heather-grass mosaics (HG). The distribution pattern was also reflected in the vegetation species. Vegetation cover samples showed that grass species such as *Agrostis capillaris* and *Agrostis curtisii* are abundant and *Calluna* species virtually absent in BG and SG classes (Meyles, 2002). These grass species have been shown to increase only when *Calluna* species decrease, indicating higher grazing pressures (Hester & Baillie, 1998; Weaver *et al.*, 1998). The data showed therefore that different stocking densities were reflected in the vegetation types and patterns.

Spatial path distribution

A Kruskal Wallis analysis (Table 5) showed that median distances to paths were significantly different between the vegetation types. In the SG vegetation type, the median distance to the closest path was only 7 m, and distances in other classes corresponding to lower stocking densities were higher. The median distance to paths in the HG vegetation class was 16 m. As median distances are a measure of path densities (expressed in path length distance unit per surface unit) it was shown that with typical values of nearly 400 m ha^{-1} in the SG type, down to around 180 m ha^{-1} in the HG mosaic, path densities were significantly higher in vegetation types that are associated with higher stocking densities.

Soil properties in relation to vegetation

Based on 23 different soil sampling sites (see methodology section), Meyles *et al.* (2001b, 2006) have shown that the soil properties of the uppermost topsoil showed significant differences between vegetation classes (Table 6). As the number of observations was limited (n-23), we accepted a slightly lower significance level ($p<0.10$, indicated in the table, Meyles *et al.*, 2006). Near-surface total soil porosity (0-3 and 4-7 cm depth) was the lowest in the SG and BG types. Consequently bulk density was significantly higher in these vegetation types, But only in the top samples (0-3 cm depth). The organic matter content of the short grass was significantly lower than in other vegetation classes, by more than 20 g 100 g^{-1} at 0-7 cm depth. Deeper in the soil profile, bulk density, porosity and organic matter content decreased to statistically insignificant differences. Saturated hydraulic conductivities were not statistically different (Meyles, 2002). Meyles *et al.* (2006) therefore concluded that topsoils under vegetation types associated with increased stocking densities were more compact, with lower porosities, lower organic matter content and higher bulk densities than soils associated with lower stocking densities. It has to be stressed however, that we have not fully established a causal relation. We have only shown statistically that soil properties of the top soil under different vegetation types differ significantly, which may be due to direct or indirect grazing pressures. One way to establish such a causal relation is to carry out long term exclosure experiments such as by Kuijper and Bakker, 2003 and Schrama, 2012, by excluding roaming animals from specific sites. Comparable ecological experiments on Dartmoor were abandoned in the mid-1990s without taking into account soil properties, unfortunately.

But although we cannot fully establish the causal relation, the data show that the topsoil in areas associated with high stocking densities have less capacity to store water and this will impact on the hydrology on the hillslope.

Soil moisture in relation to vegetation and topography

The relative importance of topography and vegetation to hillslope soil moisture was studied using multiple linear stepwise regression (Table 7; Meyles *et al.*, 2003). In relatively dry conditions (average hillslope soil moisture content lower than 0.60 cm^3 cm^{-3} as defined by Meyles, 2002), the topographic index (Quinn *et al.*, 1995) and slope apparently play an important role in the redistribution of soil water, and therefore explain a significant part of the regression. The three vegetation types included are significantly negatively correlated to soil moisture, meaning that sites with the species *Agrostis capillaris*, *Calluna vulgaris* and *Vaccinium myrtillus* are related to drier soils. The standardised β (Table 7) reflects the relative importance of the different independent variables. In relatively dry conditions, the absolute sum of the standardised β is 0.44 for the topographic variables, whereas this is 1.20 for the vegetation. This means that the contribution of the vegetation composition to the explained variability of soil moisture content is much more important than the local topography. Hence, vegetation in relatively dry conditions appears to be a more important factor in determining soil moisture content. Possibly, evapo-transpiration differences between vegetation compositions may explain this, but different dry-end soil water retention characteristics might also play a role here.

In wet conditions, variation in soil moisture is explained by the topographic variables, slope and altitude, following the concept of two preferred wetness states as proposed by Grayson *et al.* (1997) and Western *et al.* (1999). Potentially locally wet areas are hydrologically connected, so soil moisture differences due to upslope contributing areas are overridden. In other words the area becomes part of the same upslope contributing area. Therefore, the topographic index does not contribute significantly to soil moisture. The relative contribution of the topographic and vegetation variables is similar (standardised β of 0.7 and 0.8, respectively), showing that topography becomes much more important in wet conditions than in dry conditions. This is similar to work by Western *et al.* (2004) who have shown that for several small (sub)humid catchments, in wetter conditions, the variability in soil moisture patterns decrease. In addition, they also concluded that the spatial scale of soil moisture variability in wet conditions is comparable to the topography scale.

Soil moisture in relation to stocking densities

The grazing grid was situated on the part of the hillslope that showed relatively high stocking densities and covered only three of the four vegetation types (Figures 2 and 5). It was considered topographically uniform in terms of slope and topographic index. Since we consider the vegetation as a representation of stocking densities, the assumption is that variations in soil moisture within this grid would be due to vegetation/stocking densities. A one-way ANOVA analysis showed that soil moisture contents were significantly higher in more heavily stocked areas in all four measured instances (Table 8).

Soil moisture in relation to paths

Table 9 shows the difference in average soil moisture content in the topsoil of paths and their immediate surroundings. Because the data were not normally distributed, the non-parametric Kruskal Wallis test was used here. The average hillslope soil moisture content (N=150) is used as a measure of wetness conditions. Generally, in relatively dry conditions, there is no significant difference in soil moisture content between paths and their surroundings, although incomplete data for drier conditions prevent a complete analysis. In wetter conditions, typically above a soil moisture content of around 0.58 cm^3 cm^{-3}, the moisture content of the paths tends to be higher than their surroundings. This is similar to the hillslope average threshold value of 0.60 cm^3 cm^{-3} (Meyles, 2003). However, when closely examining the table, the significance is closely related to the number of observations. On four occasions (all during relatively dry conditions), the difference was not significant, probably because $n<8$. Therefore, this would mean that paths are *always* wetter than their surroundings. This suggests that paths would generate overland flow at an earlier stage after the onset of rainfall than surrounding areas.

DISCUSSION AND CONCLUSIONS

Evidence at Holne Moor has been presented to show that areas associated with different stocking intensities respond differently to rainfall. In addition, a network of tracks has been observed serving as ephemeral channels feeding storm water into the upland stream.

Livestock were found to be more densely stocked on grassland than heath. Such grassland areas were significantly wetter, had lower soil porosities and higher bulk densities than elsewhere. During rainfall, such areas could reach a wet state more quickly and could therefore generate storm runoff as overland flow or shallow subsurface flow sooner than surrounding other vegetation types. In principle, the wetter areas can feed into drier areas down the slope, but as they are not hydrologically connected to the stream, water from these areas is expected to contribute to baseflow, but not to stream storm runoff directly.

Water was observed flowing along the animal tracks during rainstorms. The soils of the path were also significantly wetter than their surroundings and therefore start conducting water at an early stage of a rainstorm, shown by the path weir, characterised by a flashy response to rainfall. Hydrologically, the animal tracks behaved similarly to the path weir. The livestock-induced paths could therefore be regarded as an ephemeral flow network and the frequent intersections and organised patterns of the paths ensured that the lag time was short. Tracks tend to be orientated largely upslope and downslope and in many cases were connected to the variable source areas or directly to the stream. The ephemeral networks produced by the animals were particularly associated with grassland areas because these are preferred areas where the animals congregate.

A key point is therefore, that these ‘wet’ paths comprised an ephemeral network capable of responding quickly to rainfall (similar to the findings by Srinivasan & McDowell, 2009) and transmitting water rapidly downslope, short-circuiting local discharge areas to the stream downslope, reducing runoff lag time and increasing storm runoff in Venford Brook. We conclude that during rainstorms, when areas on the hillslope reach their wetness threshold (Meyles *et al.*, 2006) relatively wet areas become hydrologically connected. This is in line with the extensive research on lateral preferential flow networks by Tromp-van Meerveld & McDonnell (2006a,b) and Weiler & McDonnell (2007), in which the importance of wetness thresholds in stormflow generation on hillslopes was described. Soon after the onset of a storm, tracks and paths start contributing to the stream runoff, along with the variable source area surrounding the stream. Stream discharge rises quickly, with a consequent short lag time. During the course of the rainstorm, the more heavily stocked areas also start contributing water to the ephemeral path network, as shown by the hillslope weir. The potential for increasing runoff in this manner should be viewed as episodic, not continuous, and only occurs in wet conditions. That is, the addition of new runoff areas will significantly affect runoff when they occur, but they can be expected to occur at unknown increases in stocking.

The contribution of water from these more heavily stocked areas start at a slightly later stage than the paths themselves. This means that the lag time of this water is slightly longer and we therefore assume that the contribution of the relatively wet areas to the storm runoff in the stream is mainly in the recession limb of the hydrograph. The stream hydrograph is a sum of many hydrological pathways in the catchment. This means that the individual responses of different relativity wet areas are smoothed out and are therefore not visible as a secondary peak in the hydrograph.

The extensive experiments in the catchment area offer us insight into the interplay of the various water routes in generating storm runoff. However, further experiments are required to assess the relative importance of the different routes, both in wet and dry conditions. Installation of tracer experiments to distinguish between 'old' and 'new' water is planned for future research. Although from literature, the relationship between stocking densities and compacted soils is well established (Kuijper & Bakker, 2003; Marshall et al, 2009; Bragg & Hallis, 2001), more research on the specific interrelation between stocking densities, roaming behaviour, vegetation composition and soil properties is required for the Dartmoor environment. In recent years the grazing pressure on vegetation on Holne Moor has been reduced in response to European farming policies. Farmers receive environmental payments to improve sensitive upland areas such as those found on Dartmoor. If the relationship between stocking densities and soil properties is indeed causal, than in the short term, the influence of reduced stock on the hydrology is likely to be minimal: while the vegetation composition is expected to change, the soil characteristics will take much longer to respond. Gradual improvement of soil conditions will eventually result in reduced runoff, but this could take a long time. For this reason, the conservative approach from a hydrological perspective it is preferable to err on the side of under-stocking.

We have shown, that animal tracks play an important role in hydrologically connecting wet areas to the stream that are otherwise isolated. Although generally speaking, stocking densities are within prescribed Dartmoor ESA standards, the spatially heterogeneous behaviour of the roaming animals cause local areas to be overstocked. This means, that local areas associated with higher stocking densities not only show a different vegetation type, higher average soil moisture contents and lower soil porosity values but also have a higher number of paths, making the hydrological connection to the stream possible. This mechanism, in which soil conditions, vegetation types and path networks are a complex interplay of contributing factors, may also be relevant to other uplands and their areas downstream, especially when the uplands act as water reservoir or source area for possible flooding events. Therefore, upland management policies need to take into account that the heterogeneity of hillslopes generating runoff at local scales have implications for storm runoff at the catchment scale.

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Tables

Table 1. Flow characteristics from individual storms

storm		rainfall	discharge				rainfall-runoff	lag time			lag time ord
nr	date	sum mm	max stream l/s	total stream mm	total path 10^{-4} mm	total hillslope 10^{-4} mm	coefficient (%)	stream (hrs)	path (hrs)	hillslope (hrs)	
1	22/11/2006	32.5	265.5	6.2	7.2	12.1	19.0	3:40	2:10	4:30	path<stream
2	24/11/2006	39.2	606.9	15.4	3.4	32.2	39.3	3:20	1:50	5:40	path<stream
3	27/11/2006	30.7	322.9	4.9	11.3	24.8	15.9	3:30	3:10	4:10	path<stream
4	27/11/2006	36.6	390.6	11.2	6.3	32.9	30.6	4:30	5:00	6:00	stream<path
5	03/12/2006	36.8	389.1	8.1	2.3	17.1	21.9	2:50	1:00	3:50	path<stream
6	06/12/2006	54.5	1148.4	22.7	3.0	26.4	41.7	2:20	1:10	5:20	path<stream
7	11/12/2006	79.2	920.1	22.1	1.9	17.7	27.9	6:30	5:20	8:10	path<stream
8	29/12/2006	178.0	1284.7	84.5	4.1	18.7	47.5	3:30	2:30	7:50	path<stream
9	07/01/2007	52.3	927.9	22.3	5.6	25.2	42.6	3:10	1:30	5:10	path<stream
10	09/01/2007	41.0	1083.2	21.5	5.6	34.0	52.4	2:10	1:00	5:00	path<stream
11[1]	13/02/2007	40.0	856.8	16.9	0.1	27.5	42.3	2:40	10:00	5:10	stream<hills
12	19/02/2007	49.9	482.4	13.9	3.5	14.0	27.8	4:50	2:30	6:00	path<stream
13	22/02/2007	62.6	893.5	25.5	4.4	24.4	40.8	3:30	2:00	6:00	path<stream
14[2]	04/03/2007	79.6	1096.9	40.0		29.8	50.2	2:30		5:10	stream<hills
15[3]	05/03/2007	69.7	1153.1	38.4		36.4	55.0	2:40		5:00	stream<hills

[1] Outlier

[2] Double peak, so not from base flow. Left out of analysis

[3] Long period gentle rain before large storm, so not from base flow. Left out of analysis

Table 2a: Flow characteristics for all storms at Holne Moor with a clearly identifiable single peak (n=12; 1 October 2006 to 30 April 2007).

	flow characteristics	mean	st. dev.	max	min
Q_{max} ($l\ s^{-1}$)	Stream (flume)	997	195	1285	607
	Path (weir)	0.71	0.56	1.50	0.00
	Hillslope (weir)	2.90	0.91	4.38	1.75
Lag time (h:mm)	Stream (flume)	03:40	01:11	06:30	02:10
	Path (weir)	02:30	01:26	05:20	01:00
	Hillslope (weir)	05:40	01:18	08:10	03:50
Catchment	Rainfall runoff co-efficient (-)	34.0	11.7	52.4	15.9
	Quickflow proportion (%)	59.9	9.9	80.9	45.7
	Quickflow active area (%)	26.8	7.8	38.4	12.8
	Quickflow active area (ha)	17.4	5.1	25.0	8.3

Table 2ba Statistical differences between flow lag times (Kruskal Wallis). Figures in italics denote statistical significant difference ($p<0.05$).

Lag time	**n**	**Mean rank**	**Mean rank**	**Mean rank**	**Mean rank**
Stream	12	17.17	15.92		7.75
Path	12	9.92	9.08	7.33	
Hillslope	12	28.42		17.67	17.25
	test statistic	18.791	5.606	12.819	10.830
	df	2	1	1	1
	sign.	*.000*	*.018*	*.000*	*.001*

Table 3: Mean livestock densities are different between vegetation types and can be fully attributed to sheep distribution (Meyles, 2002).

			Livestock densities					
Vegetation class			**Sheep (N*)**	**Sheep (ha^{-1})**	**Cattle (N*)**	**Cattle (ha^{-1})**	**Ponies (N*)**	**Ponies (ha^{-1})**
SG	Short grass	Observed	75.51	1.24	8.05	0.13	1.01	0.02
		Expected	37.41		8.49		1.87	
		χ^2	38.81		0.02		0.40	
BG	Bracken and grass	Observed	33.51	0.55	7.84	0.13	1.89	0.03
		Expected	37.41		8.49		1.87	
		χ^2	0.41		0.05		0.00	
GG	Gorse and grass	Observed	24.58	0.40	8.06	0.13	1.79	0.03
		Expected	37.41		8.49		1.87	
		χ^2	4.40		0.02		0.00	
HG	Heather/grass mosaic	Observed	16.04	0.26	10.02	0.16	2.81	0.05
		Expected	37.41		8.49		1.87	
		χ^2	12.21		0.28		0.46	
Weighted mean			**28.73**		**8.33**		**1.93**	
χ^2			**55.83**		**0.37**		**0.87**	

O_i = observed, E_i = expected, χ^2_i= Chi square test statistic, p = 0.01 significance level: χ^2= 11.34.
**Averaged total over 15 occasions*

Table 4: Maximum stocking densities according to the Dartmoor ESA scheme (DEFRA 2002; Tier 1E – moorland).

Period		Moorland type	Stocking density	
			cattle/sheep; LU ha^{-1}	ponies; LU ha^{-1}
Winter	1 November-15 April	Dry grass moorland	0.235	0.04
		Other moorland	0.17	0.04
Summer	16 April-31 October	Dry grass moorland	0.36	0.04
		Other moorland	0.225	0.04

Table 5: Distance to path & path densities in different vegetation types, based on a cell-by-cell grid analysis.

	Area	Path		Distance to path					Kruskal Wallis
Vegetation class	(ha)	Length (m)	Density (m ha^{-1})	N (raster cells)	Min (m)	Max (m)	Median (m)	St. dev. (m)	Mean rank
SG	4.0	1537	380.25	14882	0	98	7	12	77571.66
BG	15.1	4439	294.74	51104	0	99	10	14	90026.46
GG	31.8	9148	287.75	90701	0	112	11	17	97466.22
HG	10.1	1811	178.43	37643	0	111	16	21	113879.19
Test statistics		Chi-square	5994.242						
		df	3						
		sig.	0.000						

Table 6: Physical soil characteristics for the vegetation classes. Values that are significantly different (Kruskal-Wallis) are indicated. Adapted after Meyles et al. (2006)

	HG	GG	BG	SG	Mean	St. Dev.	Test statistic	*p*
Sheep density	0.26	0.40	0.55	1.24	0.47			
N (23)	7	5	9	2				
Φ_{0-3}	0.915	0.931	0.876	0.882	0.900	0.041	7.59	0.06*
$\Phi_{4–7}$	0.875	0.911	0.841	0.771	0.860	0.056	9.47	0.02**
$\Phi_{12–15}$	0.782	0.820	0.728	0.693	0.765	0.121	2.05	0.56
$\Phi_{16–19}$	0.730	0.761	0.692	0.628	0.712	0.145	1.36	0.71
ρ_{0-3}	0.18	0.19	0.30	0.34	0.25	0.10	9.77	0.02**
$\rho_{4–7}$	0.31	0.26	0.37	0.57	0.35	0.13	5.44	0.14
$\rho_{12–15}$	0.58	0.45	0.72	0.76	0.61	0.31	2.53	0.47
$\rho_{16–19}$	0.70	0.62	0.82	0.97	0.76	0.39	1.81	0.61
om_{0-3}	86.3	76.9	77.4	55.1	78.1	14.4	6.16	0.10*
$\text{om}_{4–7}$	72.7	67.0	57.4	33.0	62.0	18.4	6.76	0.08*
$\text{om}_{12–15}$	55.4	43.7	32.6	16.4	40.9	27.3	3.73	0.29
$\text{om}_{16–19}$	33.8	32.3	18.6	11.9	25.9	24.4	2.69	0.44

Sheep density (LU ha^{-1}); Φ: porosity (cm^3 cm^{-3}), ρ: dry bulk density (g cm^{-3}); om: organic matter content (LOI; g 100 g^{-1}).

** significant for p<0.05

* significant for p<0.10

Table 7: Multiple linear regression analysis (stepwise) on the influence of topography and vegetation on soil moisture status. Adapted after Meyles et al. (2003).

	Wet conditions			Dry conditions		
	β (unstandardised)	β (standardised)	p	β (unstandardised)	β (standardised)	p
(Constant)	88.98		0.000	66.57		0.000
altitude	-0.11	-0.263	0.026			
slope	-1.04	-0.469	0.000	-0.42	-0.183	0.065
topographic index				1.20	0.253	0.023
$\sum\|\beta_{standardised}\|$		0.732			0.436	
Agrostis capillaris	-4.50	-0.238	0.021	-5.26	-0.270	0.038
Calluna vulgaris				-7.69	-0.396	0.007
Vaccinium myrtillus	-11.95	-0.559	0.000	-11.67	-0.532	0.000
$\sum\|\beta_{standardised}\|$		0.797			1.198	
R^2	0.853			0.880		
R^2_{adj}	0.820			0.845		

Topographic variables entered: Altitude (m amsl), slope (°), topographic index (ln a/tan β).

Vegetation variables entered (dummy: presence=1/absence=0): *Molinia caerulea, Agrostis capillaris, Agrostis curtisii, Festuca ovina, Carex spp., Galium saxatile, Potentilla erecta, Calluna vulgaris, Erica tetralix, Vaccinium myrtillus, Sphagnum spp., Pteridium aquilinum.*

Table 8: Soil moisture content under different vegetation types under similar topographic conditions.

	BG		SG		HG		GG		All		One-way ANOVA	
Date	$\theta_{average}$	N	$\theta_{average}$	N	$\theta_{average}$	N	$\theta_{average}$	N	$\theta_{average}$	N	F	p
15-11-1999	0.559	48	0.612	5	n/a	0	0.560	10	0.563	63	4.490	0.015**
02-12-1999	0.572	50	0.623	5	0.511	1	0.578	10	0.576	66	6.151	0.004***
25-10-1999	0.584	50	0.624	5	0.534	1	0.587	10	0.587	66	2.682	0.076*
26-11-1999	0.585	49	0.638	5	0.534	1	0.589	10	0.589	65	5.227	0.008***

Note: Vegetation code HG only occurred once in the grazing grid and was therefore left out of the analysis.

θ: Soil moisture content ($cm^3\ cm^{-3}$).
*** significant for $p<0.01$
** significant for $p<0.05$
* significant for $p<0.10$

Table 9: Soil moisture content of two tracks and surrounding areas. Hillslope soil moisture is added as a reference but is not included in the statistical analysis.

	Hillslope		Path		Path surroundings		Kruskal Wallis test	
Date	$\theta_{average}$	N	$\theta_{average}$	n	$\theta_{average}$	n	H	p
28-07-1999	0.355	123	0.366	2	0.356	14	0.025	0.874
22-06-1999	0.477	121	0.501	3	0.477	12	0.021	0.885
18-03-1999	0.553	151	0.593	6	0.563	16	1.230	0.267
17-02-1999	0.569	151	0.613	8	0.584	16	1.743	0.187
04-02-1999	0.572	140	0.608	8	0.577	16	3.507	0.061*
25-10-1999	0.572	71	0.674	1	0.567	8	2.420	0.120
30-11-1998	0.586	150	0.649	8	0.596	16	5.913	0.015**
17-12-1998	0.591	150	0.631	8	0.588	16	4.757	0.029**
23-11-1998	0.594	150	0.656	8	0.603	16	8.158	0.004***
12-04-1999	0.601	149	0.638	6	0.610	16	2.805	0.094*
21-01-1999	0.624	151	0.649	8	0.618	16	3.525	0.060*
09-11-1998	0.639	150	0.688	8	0.640	16	5.772	0.016**
26-10-1998	0.641	150	0.680	8	0.638	16	5.749	0.017*
05-01-1999	0.645	150	0.683	8	0.643	16	7.304	0.007***
02-11-1998	0.655	149	0.707	8	0.666	16	3.742	0.053*

θ: Soil moisture content (cm^3 cm^{-3}).
*** significant for $p<0.01$
** significant for $p<0.05$
* significant for $p<0.10$

Figures

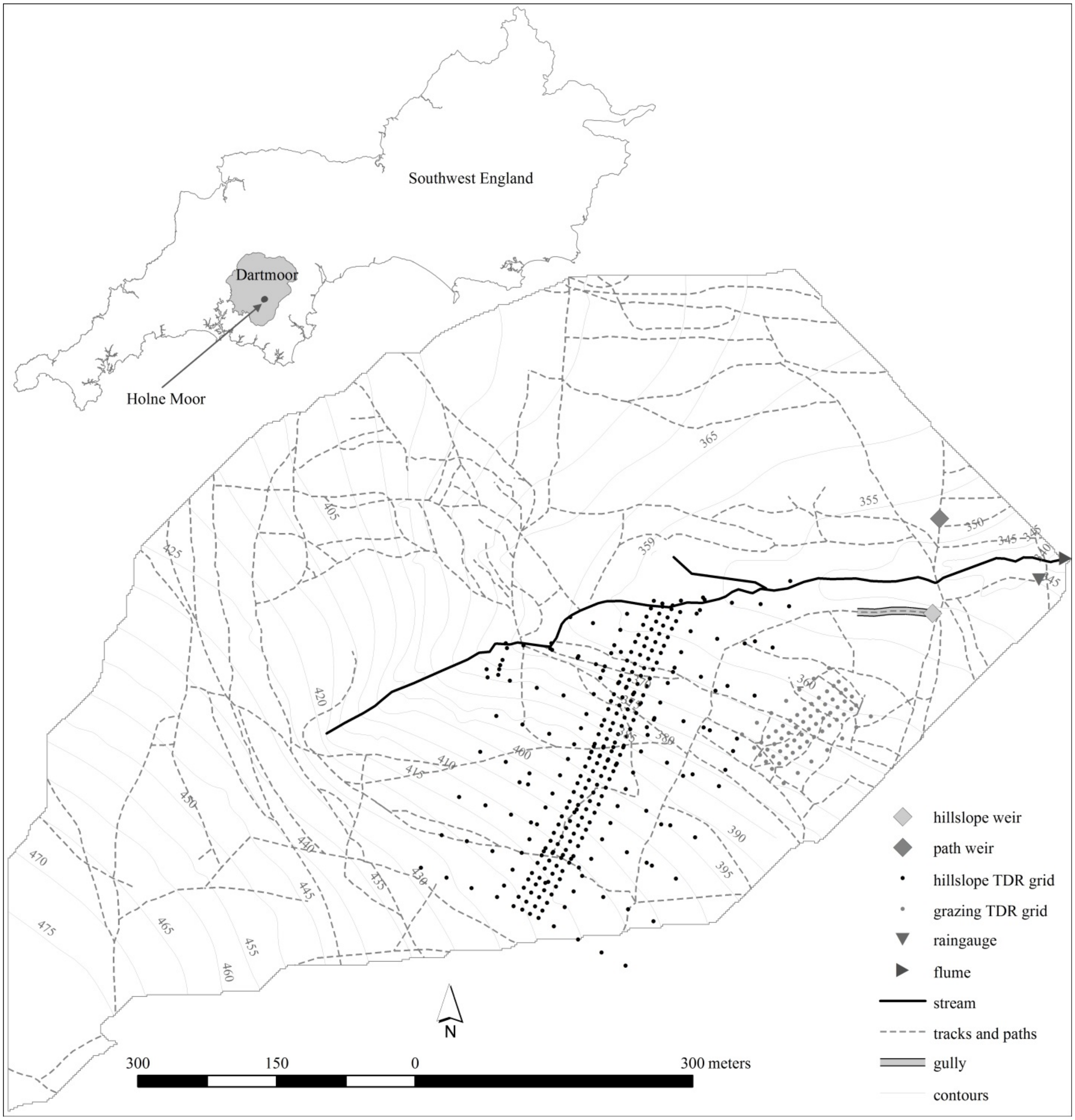

Figure 1: Catchment topography and instrumentation.

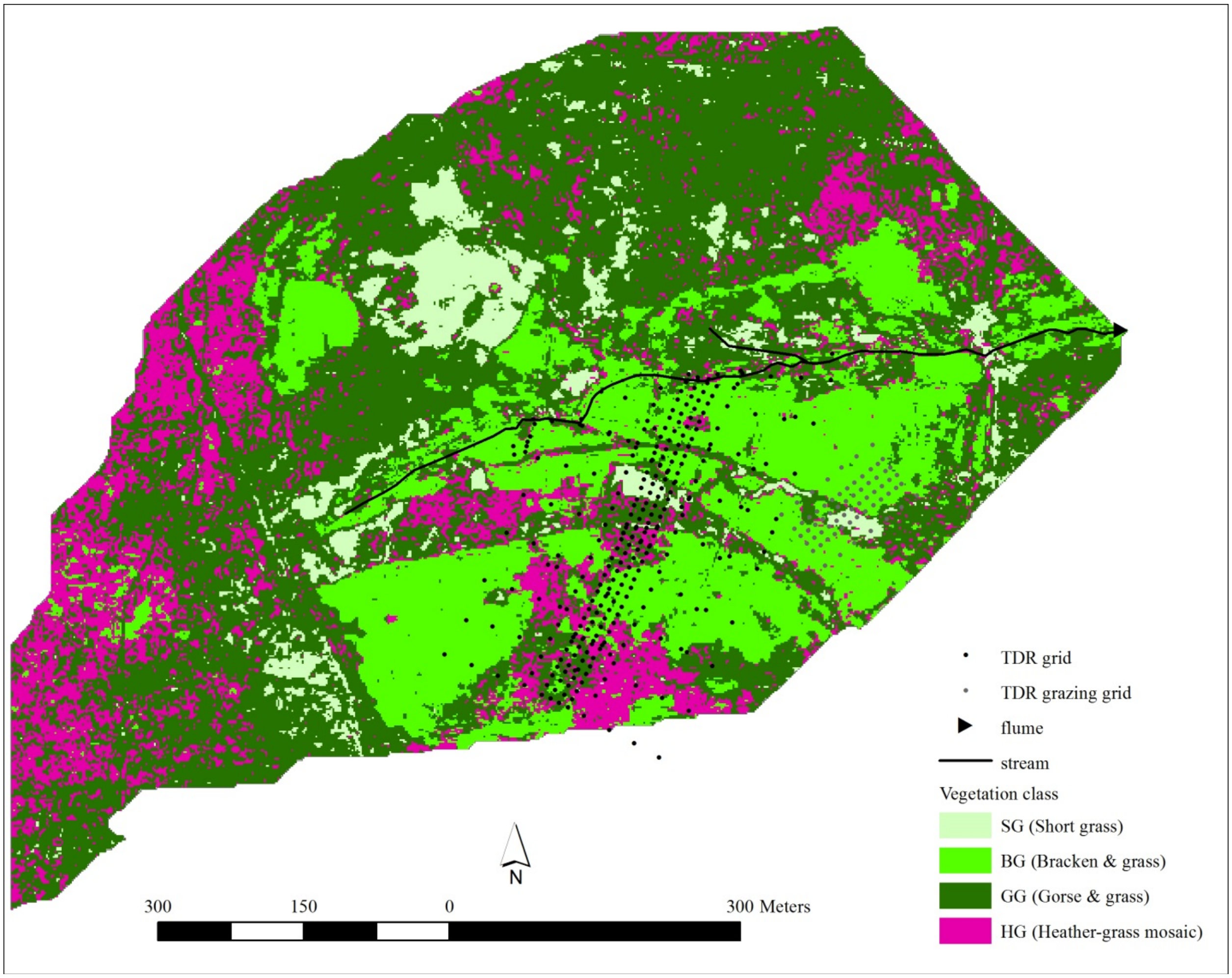

Figure 2: Vegetation types in the study area based on RS images and field observations.

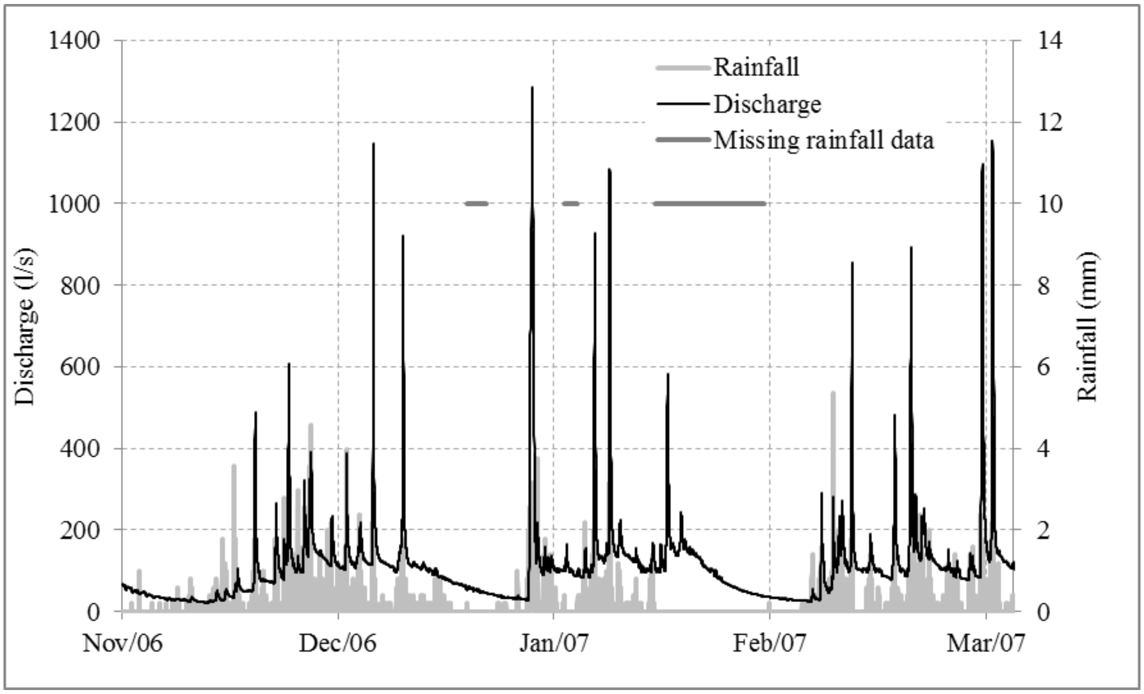

Figure 3: Discharge and ten-minute rainfall totals for Holne Moor.

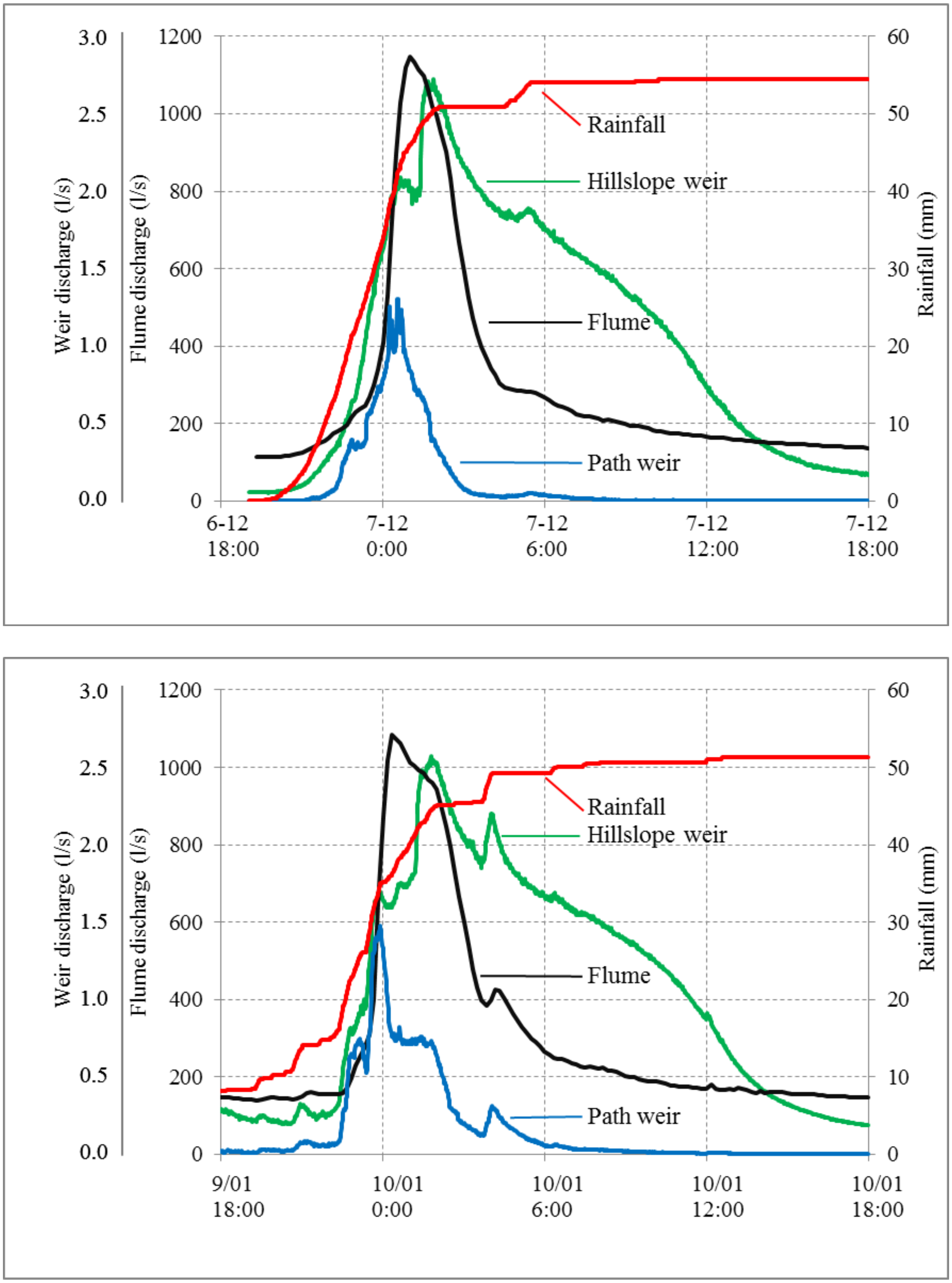

Figure 4: Cumulative rainfall and discharge of path weir, hillslope weir and flume for storm 6 (top) and 10 (bottom).

Figure 5: Stocking densities (in livestock units per hectare; LU ha^{-1}*) based on 15 different observation occasions. Class division is based on Dartmoor ESA regulations (Table 4).*