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Effects of grazing on soil properties and hydrology of a small Dartmoor catchment, southwest England

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Abstract The impact of overgrazing on the hydrological behaviour of a small Dartmoor catchment was investigated. Soil moisture content was measured grid-wise on 19 occasions within an 18-month period. At 23 sites within this grid, water release characteristics, bulk density and organic matter content of the topsoil were measured. Grazing densities within the catchment were estimated and the patterns observed were related to vegetation type and cover. Results from the soil moisture grid showed that in dry conditions the pattern was heterogeneous in contrast to a more uniform pattern in wet periods. A threshold soil moisture content of about 55–60% divided the two different conditions. An exponential relationship was found between average soil moisture and stream runoff. Analysis of the water release characteristics found that soils associated with areas of intense grazing had a significantly lower porosity, causing a difference in hydraulic conductivity. In consequence the soil moisture threshold value between wet and dry states was reduced in these areas.

Key words grazing; grazing intensity; rainfall–runoff; soil moisture patterns; porosity

INTRODUCTION

There is increasing concern that high sheep grazing intensities on British moorlands may have an impact on the hydrology. There is strong evidence of a change in vegetation due to continuous grazing with a steady decline of heather species (Weaver *et al.*, 1998). Also, there is anecdotal evidence of altered hydrological responses of moorland basins with relatively high grazing intensities, with increased storm discharges and low flows in summer (Sansom, 1999). The aim of this paper is to investigate the indirect effect of vegetation on soils and consequently on the hydrological behaviour of a Dartmoor basin. Firstly, vegetation patterns will be examined as a function of grazing density. Secondly, soil structure under different vegetation types will be characterized and thirdly, the relationship between soil structure and hydrology will be investigated. Finally, possible implications for regional water management will be explored.

Site description

The study catchment, 0.61 km^2 in area, is situated in the southeast of Dartmoor (Fig. 1), draining into a drinking water reservoir. The altitude ranges from 290 to 450 m a.m.s.l. The climate of Dartmoor is temperate with monthly rainfall ranging from 263 mm in December to 114 mm in April, with an average annual total of 2104 mm in Princetown (425 m a.m.s.l.; 9 km west of the study area). The soils in the study area show subtle differences mainly within the subsoil. They consist of permeable gritty loams with black humose or peaty topsoils on the steeper slopes. On the less sloping areas, in places the topsoil has a thin ironpan at 30 cm depth (Hogan, 1988); valley bog is found in parts of the lower catchment.

The vegetation in the study area is typical for grazed areas on Dartmoor and is dominated by grasses such as *Molinia caerulea*, *Agrostis capillaris*, *Agrostis curtisii* and *Festuca ovina*. In places, heather (*Calluna vulgaris*) and gorse (*Ulex* spp.) remain.

On Dartmoor, sheep are free to roam and no records are available on grazing densities. Also, sheep grazing behaviour is very complex and is dependent on many factors, including vegetation, shelter and season (Hester & Baillie, 1998).

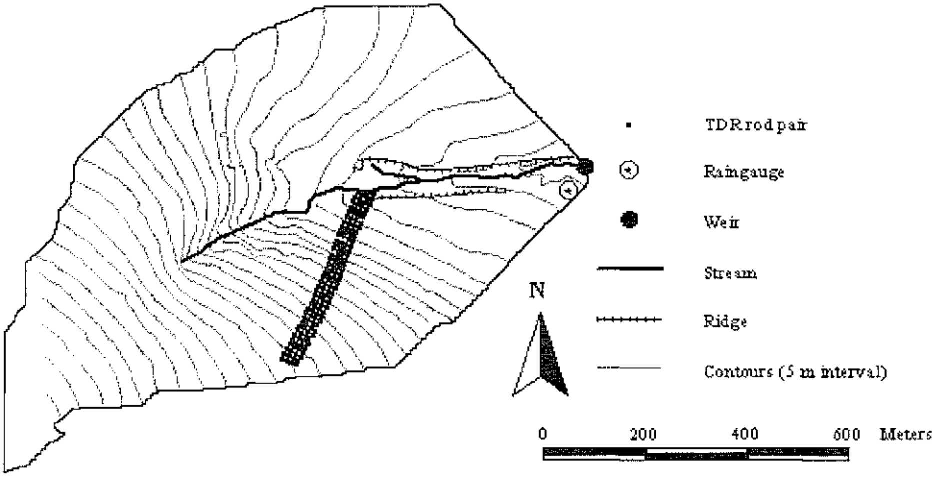

Fig. 1 The study area.

METHODOLOGY

Stream discharge and rainfall were logged at the catchment outlet. On part of the southern hillslope, a permanent soil moisture monitoring grid was established using time domain reflectometry (TDR). This non-destructive method determines the dielectric constant of the soil, a measure of water content, by conducting a small current through two parallel steel probes inserted into the soil (Topp *et al.*, 1980). Stainless steel rod pairs (20 cm long) were installed vertically in the topsoil with a 10 by 10 m spacing. The grid consisted of 151 rod pairs covering the hillslope from top to bottom (Fig. 1). Nineteen measurements were made over a one-year period, each time within a 2–4 h period. The equation of Topp *et al.* (1980) adapted by Roth *et al.*

(1992) for organic soils with high moisture contents was used to derive volumetric soil moisture values. Meyles *et al.* (2001) have shown that throughflow in the topsoil is the main soil water pathway, indicating that the soil moisture content of the top 20 cm gives a good reflection of soil water movement.

A digital aerial photo (scale 1:25 000) split into three bands (red, green and blue) was used to classify vegetation in the basin in a geographical information system (GIS). Four different vegetation classes were distinguished, and could be specified more precisely with field observations: Heather–grass mosaic (heather), with *Calluna vulgaris* and *Festuca ovina* as main species; Gorse (*Ulex* spp.) and long grasses (mainly *Molinia caerulea*); Bracken (*Pteridium aquilinum*) with an underlying layer of short grasses (*Festuca ovina* and *Agrostis capillaris*); and Short grass (short grasses only).

In order to estimate the grazing pressures and patterns, individual animals were indicated on a detailed map during 15 field visits in the summer period. This was assumed to represent the grazing behaviour sufficiently. The maps were combined in a GIS and a chi-squared test was used to test the vegetation effect on grazing patterns.

Water release characteristics of the topsoil were determined at 23 TDR locations within the grid after the TDR measurements were completed. The sites were selected systematically to represent the different slopes, vegetation and soil moisture conditions. At each location, undisturbed samples (3 cm high, 5.4 cm diameter) were taken at four different depths to represent the length of the TDR rods (0–3, 4–7, 12–15 and 16–19 cm). Water retention was determined using a sand table with pressure heads at 0, –30, –50 and –100 cm, which were assumed to reflect the naturally wet conditions in the study area. Bulk densities of the samples were established after oven drying. Organic matter content was also measured with loss on ignition. Differences in water release curves, bulk density and organic matter content under different vegetation was tested with the Kruskal-Wallis test.

RESULTS

The total rainfall for the catchment for 1999 was 2114 mm. During the recording period (December 1998–June 2000) maximum rainfall intensities were around 30 mm h^{-1} and the maximum rainfall volume was 45.6 mm within one single event. Mean daily flow (baseflow) was about 30 l s^{-1} and peak discharge averaged 76 l s^{-1}. Ninety-one single peaks were recorded with peak discharge ranging from 1.2 to more than 1000 l s^{-1}. Stream discharge rose rapidly by an order of magnitude during large storms (Fig. 2). Lag times in the basin (time from peak rainfall to peak discharge) were found to be 2 h on average and recession times were in the order of 7 h. Runoff coefficients (total storm runoff/total rainfall) ranged from 0.003 to 0.64 and increased with increasing antecedent moisture conditions. Soil moisture measurements varied seasonally, with average values ranging from 36% (July) to 66% (November). Generally, soil moisture contents were greatest in the flat area adjacent to the stream (67%) and least (55%) in the area with the steepest slope (17°).

Results of the grazing patterns observations in combination with vegetation (Table 1) revealed that sheep grazed significantly more than expected in the Short grass areas (3.9 sheep ha^{-1}), and that grazing intensities were significantly lower in

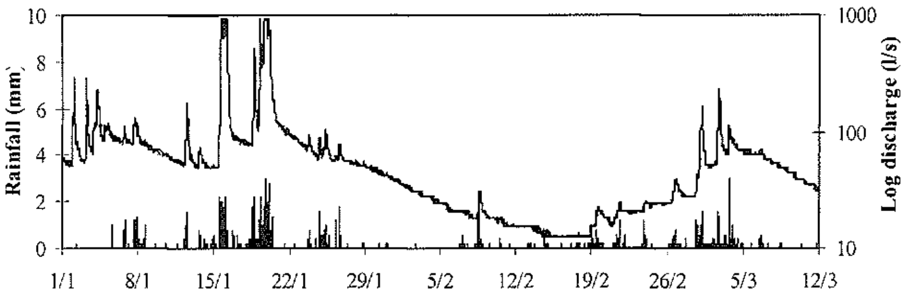

Fig. 2 Rainfall–runoff response.

Gorse and Heather areas (1.3 and 0.8 sheep ha^{-1}, respectively). Figure 3 shows the distributions of sheep for all 15 observations combined, overlaid on the vegetation map.

Bulk density near the soil surface was 0.25 Mg m^{-3} with a minimum of 0.14 Mg m^{-3}, and increased with increasing depth, averaging 0.76 Mg m^{-3} at 16–19 cm depth (Table 2). These very low values reflect the high organic matter content of the soils. Bulk densities were significantly higher under Short grass and Bracken (0.18 Mg m^{-3} near the soil surface) than under Gorse and Heather (0.32 Mg m^{-3}).

The water release curves showed a distinct difference in slope between near-saturation and lower suctions when plotted with hydraulic head on a linear scale

Table 1 Results of the grazing density per vegetation analysis.

Vegetation class	Observed*	Expected	χ^2	p	Density (sheep ha^{-1})
S (Short grass)	1132	560.5	582.7	0.00	3.9
B (Bracken and grass)	502	560.5	6.1	0.11	1.7
G (Gorse and grass)	368	560.5	66.1	0.00	1.3
H (Heather/grass mosaic)	240	560.5	183.3	0.00	0.8
Total	2242		838.2	0.00	

* Observed frequencies have been corrected for the area covered by the vegetation class.

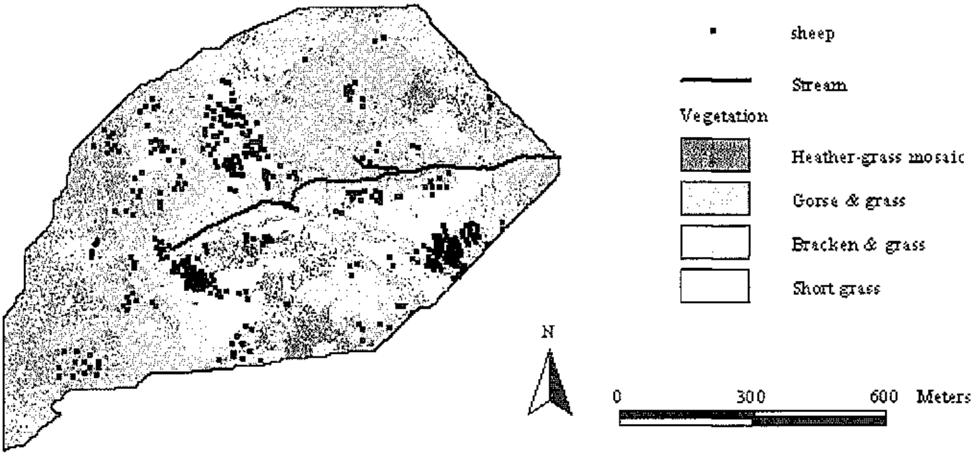

Fig. 3 Vegetation map based on the aerial photo and sheep distributions.

Table 2 Average soil property values per vegetation class and depth and results of the Kruskal-Wallis test.

Vegetation class	N	$\rho_{0\text{-}3}$	$\rho_{4\text{-}7}$	$\rho_{12\text{-}15}$	$\rho_{16\text{-}19}$	$\Phi_{0\text{-}3}$	$\Phi_{4\text{-}7}$	$\Phi_{12\text{-}15}$	$\Phi_{16\text{-}19}$	$om_{0\text{-}3}$	$om_{4\text{-}7}$	$om_{12\text{-}15}$	$om_{16\text{-}19}$
Heather/grass mosaic	7	0.18	0.31	0.58	0.70	91.5	87.5	78.2	73.0	86.3	72.7	55.4	33.8
Gorse and grass	5	0.19	0.26	0.45	0.62	93.1	91.1	82.0	76.1	76.9	67.0	43.7	32.3
Bracken and grass	9	0.30	0.37	0.72	0.82	87.6	84.1	72.8	69.2	77.4	57.4	32.6	18.6
Short grass	2	0.34	0.57	0.76	0.97	88.2	77.1	69.3	62.8	55.1	33.0	16.4	11.9
Test statistic		9.77	5.44	2.53	1.81	7.59	9.47	2.05	1.36	6.16	6.76	3.73	2.69
p		0.02	0.14	0.47	0.61	0.06	0.02	0.56	0.71	0.10	0.08	0.29	0.44

ρ: dry bulk density (Mg m^{-3}), Φ: total porosity(m^3 m^{-3}), om: organic matter content (loss on ignition, g g^{-1}).

(Fig. 4). This suggests a relatively high proportion of transmission pores (determined by the 0–50 cm suction interval; Rowell, 1994). Water release curves associated with their vegetation class showed a significantly different behaviour at 4–7 and 12–15 cm depth (Fig. 4). Although the shape of the water release curves remained constant under different vegetation classes, the intercept value i.e. total porosity was different: Values under Heather and Gorse were significantly higher than under Short grass and Bracken (90 *vs* 80% at 4–7 cm and 80 *vs* 70% at 12–15 cm, respectively, Table 2). Similar high porosity values in organic soils are found by Pepin *et al.* (1991), Roth *et al.* (1992).

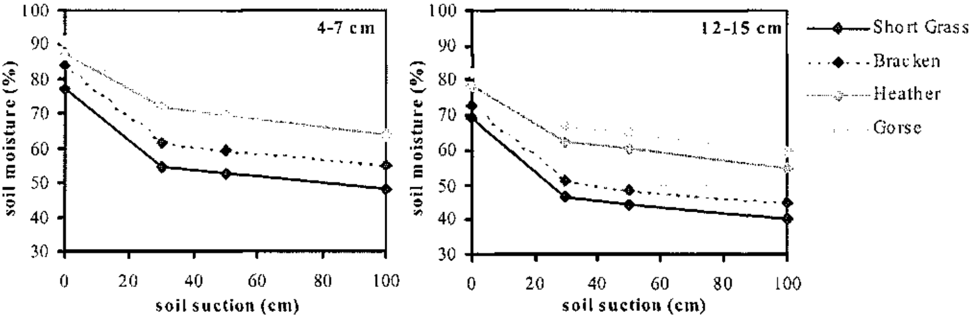

Fig. 4 Water release curves per vegetation type and depth.

DISCUSSION

The grid soil moisture average compared with the stream runoff measured on the same occasion showed an exponential behaviour (Fig. 5(a)). Although the relationship is continuous for simplicity, the graph can be divided into two sections representing dry and wet conditions by a soil moisture content of around 55–60%. The graph shows that in dry antecedent conditions, a given rain event yields little runoff, whereas in wet conditions, the same rain event is associated with large increases in stream discharge.

This distinctively different hydrological behaviour in both sections is primarily influenced by the soil moisture patterns. In conditions with low antecedent moisture, the mosaic of drier and wetter areas is localized and unconnected, but above a soil moisture content of 60%, still well below saturation, the pattern is much more homogeneous (Fig. 6). Grayson *et al.* (1997) found similar soil moisture behaviour in temperate Australia and explained the two different states in terms of local and non-

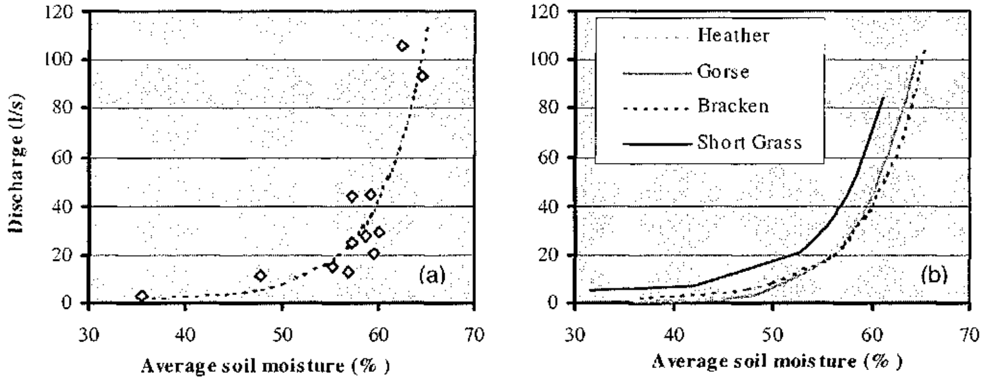

Fig. 5 Average soil moisture–runoff curve (a) and per vegetation type (b).

local controls, which also apply to the study area. In dry conditions, soil moisture is mainly determined by vertical (local) flow, controlled primarily by evapotranspiration from the vegetation and soil. In sufficiently wet conditions, the hydraulic conductivity increases and soil water is enabled to move laterally, determined by topography, forming a much more homogeneous moisture pattern on hillslope scale and is therefore non-local.

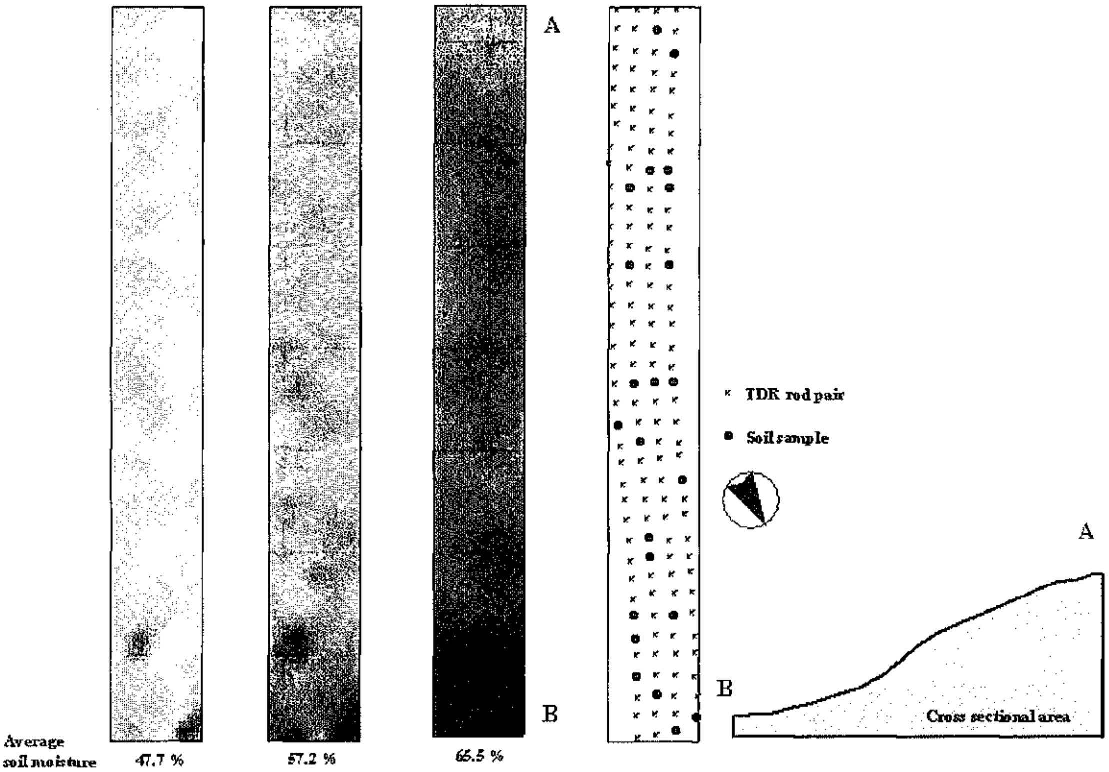

Fig. 6 Soil moisture patterns in dry and wet conditions.

The shape of the water release curve (Fig. 4) can explain the process that determines the change from local to non-local control. The curve suggests that above the soil moisture threshold the transmission pores fill up and therefore the hydraulic conductivity increases rapidly. Hydraulic connections are formed between areas with high moisture levels and, as a result, water can be transported to the stream from larger contributing areas. This process explains the higher discharge levels in the wet limb of the soil moisture–runoff curve and the high runoff coefficients in wet conditions, with up to 64% of the area of the catchment contributing according to the runoff coefficient.

However, spatial variation within soil properties also influences these two soil moisture patterns. Water characteristic curves and total porosity values show that soils under Short grass and Bracken need a smaller input to reach saturation than soils under Heather and Gorse for a given moisture content. This means, that the change from heterogeneous unconnected soil moisture patterns to a homogenous, hydraulically connected appearance occurs at a lower average soil moisture content under Short grass than under Heather. The average soil moisture by vegetation type *vs* stream runoff relationship (Fig. 5(b)) confirms this effect. This shows a threshold for Short grass that is between 50 and 55%, which is 5% lower than the other vegetation curves.

Thus, the change in rainfall–runoff response in the river is dependent on the vegetation pattern. If the Short grass area is increasing at the base of the slope adjacent to the stream, a direct hydraulically active connection to the stream will be established in lower moisture conditions and rainfall–runoff responses will become more extreme. This could cause quicker rainfall–runoff response with higher peak levels, and lower baseflow levels in dry periods. However, if, for example, a Heather area is dividing the Short grass and the stream, this area will act as a sink and water being shed from the Short grass area will be stored in the Heather area. A change in rainfall–runoff response will thus be damped. Hence, the heterogeneity of vegetation patterns within the basin are a crucial factor in holding and shedding water to the catchment outlet.

CONCLUSIONS

Analyses have shown that two types of hydrological behaviour occur in the catchment. In dry antecedent conditions (below a soil moisture threshold of 60%), moisture conditions on the hillslope are heterogeneous and unconnected. Therefore, a certain rain event induces a minimal increase in stream discharge. In wet antecedent conditions however, soil moisture patterns on the hillslope are much more homogenous and hydraulically connected and a similar rain event produces a much higher increase in runoff.

The threshold between states is mainly determined by the water characteristic curve. Under vegetation types with high grazing intensities, the porosity values within the water release curve are 10–15% lower than under vegetation with low grazing intensities. The soil moisture threshold between states decreases with about 5%, inducing quicker rainfall–runoff responses in wet conditions in heavily grazed areas and reduced recharge low flows in dry periods depending on the spatial distribution of vegetation within the basin. Therefore, with a given topography, land use has a critical impact on stream runoff, with high flows in wet conditions (with a possible link to the recent flooding in the area) and low flows during summer. This could have important implications for the regional water supply.

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