
Article:

Holden, J. and Burt, T.P. (2002) Laboratory experiments on drought and runoff in blanket peat. European Journal of Soil Science, 53 (4). pp. 675-689. ISSN 1351-0754

https://doi.org/10.1046/j.1365-2389.2002.00486.x

European Journal of Soil Science, December 2002, **53**, 675–689

Laboratory experiments on drought and runoff in blanket peat

J. HOLDEN[a] & T. P. BURT[b]
[a]*School of Geography, University of Leeds, Leeds LS2 9JT, and* [b]*Department of Geography, University of Durham, Science Laboratories, South Road, Durham DH1 3LE, UK*

Summary

Global warming might change the hydrology of upland blanket peats in Britain. We have therefore studied in laboratory experiments the impact of drought on peat from the North Pennines of the UK. Runoff was dominated by surface and near-surface flow; flow decreased rapidly with depth and differed from one type of cover to another. Infiltration depended on the intensity of rain, and runoff responded rapidly to rain, with around 50% of rainwater emerging as overland flow. Drought changed the structure of the peat and the subsequent behaviour of the peat in response to rain. Surface runoff was reduced, infiltration increased and flow increased within the deeper peat layers. Old and new water produced from the peat during simulated storms was identified by bromide tracing; the amount of old mobile water flushed out of the top few centimetres was small and there was less from deeper peat layers. No significant difference in the old and new water mixing processes could be identified between the control plots and the drought treatment plots. Lissamine staining showed preferential bypass flow through macropores in the peat, though only in the top 5 cm. Following drought, however, macroporosity increased within the upper peat layers, and preferential flow extended deeper than in controls. Peat structure recovered somewhat after drought, but the effects of the drought were long-lasting. If these effects extend to the field during drier summers then we can expect changes to the hydrology and associated chemistry of blanket peat catchments in the British uplands.

Introduction

Blanket peat covers much of upland Britain and sheds a large proportion of the rain that falls on it. Runoff from catchments dominated by blanket peat responds rapidly to storms, with minimal baseflow (Burt *et al.*, 1990; Evans *et al.*, 1999). Matrix throughflow in the lower layers of blanket peat is restricted such that runoff is dominated by saturation-excess overland flow (Holden & Burt, 2002). Therefore if rainfall supply is limited, even for short periods, the effects on streamflow are dramatic. During August 1995, for example, discharge from the 11.4-km^2 Trout Beck blanket peat catchment on the Moor House National Nature Reserve in the North Pennines of the UK was about 0.01 m^3 s^{-1} (equivalent to 0.003 mm hour^{-1}). Despite a near-record wet winter preceding the drought (Burt *et al.*, 1998) and the fact that the water table never fell below 42 cm from the surface, baseflow was virtually non-existent in the Trout Beck system. However, there is increasing concern that climate change may have severe impacts on the hydrology of these upland peatlands. If climate change leads to increased seasonality then the impact on the ecology of upland streams and on downstream water supply may be severe, even though mean precipitation changes little. The summer drought of 1995 in the UK was an extreme event. Comparing July and August 1995 with the predicted climate for 2021 to 2050, Hulme (1998) suggests that summers as warm as 1995 will become 1 in 10 year events rather than 1 in 300 as at present. As temperatures rise and rainfall becomes more variable, drought and flood might recur more frequently in the future. For these reasons it is important to establish the possible effects of drought on the hydrology of blanket peat.

Changes in water storage in mires are reflected in changes in the position of the water table throughout the year. Ingram (1983, 1991) and Hammond *et al.* (1990) have shown that the water table controls the vegetation of the mire; both height and fluctuations are important. In undrained peat the water table is close to the surface most of the time. Evans *et al.* (1999) showed that for a gently sloping peat surface in the North Pennines water tables were within 5 cm of the surface for 83% of the time. Their data spanned the drought summer of 1995 when the water table reached its lowest recorded level at the site, since data logging records began in 1991, at 42 cm, and remained deeper than 20 cm for 35 days. Although this might not seem extreme, it is likely to be important given that

Correspondence: J. Holden. E-mail: j.holden@geog.leeds.ac.uk
Received 12 June 2001; revised version accepted 31 May 2002

the peat below 20 cm depth is usually saturated. Aeration of peat that is normally saturated may result in significant changes to soil structure and to hydrochemical and biological processes. When peat is dried sufficiently it cannot regain its original moisture status because of structural and chemical changes within it (Egglesmann *et al.*, 1993). Cracking associated with surface drying and shrinkage may result in more rapid infiltration down the cracks and changes in the processes that generate runoff. Holden *et al.* (2001) showed that macropores are important hydrological pathways in blanket peat. Locally these macropore networks bypass the peat matrix and penetrate deep into the peat, although more often they contribute to runoff generation at or close to the surface of the peat. Holden (1998) found that artificially drying milled peat for fuel could result in enhanced macropore flow when the peat was eventually rewetted. However, the effects of *drought* on preferential flow in peats have never been investigated. In addition, the crusting that occurs on bare, dried peat surfaces might slow infiltration and encourage overland flow and erosion. Tallis (1997), for example, produced evidence that previous phases of peat erosion in the British Pennines might have begun during, or at the end of, dry periods during the Holocene. No one to our knowledge has attempted to measure the effects of drought on infiltration and flow in near-surface blanket peats and thereby substantiate these suggestions.

We have identified three possible mechanisms that could lead to change in runoff following drought in blanket peat: changes in the wetting behaviour of peat, changes in peat morphology (e.g. cracking), and surface crusting. The hydrological effects of these are conflicting. Crusting, for example, would be expected to increase overland flow, but increases in macroporosity could lead to enhanced infiltration and a reduction in surface flow. We have examined the cumulative effect of these processes following drought in blanket peat in laboratory experiments. Our aims were:

- to assess the infiltration and runoff rates in blanket peat subjected to drought;
- to distinguish fluxes of old water and new water (wetting and water mixing characteristics) in blanket peat subjected to drought, and
- to determine macropore flow and percolation depth in blanket peat subjected to drought.

We describe our results below.

Materials and methods

We examined the effects of drought on processes generating near-surface runoff in blanket peat in laboratory experiments. Twenty-four intact peat blocks were removed with a knife from the field at the Moor House National Nature Reserve in the North Pennines of the UK (54°41′N, 2°23′W). Each block was 0.32 m × 0.42 m and 0.35 m deep, with the top being the natural surface. They were taken to the laboratory in rigid PVC containers, the faces of which were smeared with petroleum gelatine prior to use. Four types of surface cover were chosen as being typical of the blanket peat in the Reserve: bare peat, and *Eriophorum*-, *Sphagnum*- and *Calluna*-covered. Each block had at least 90% of the specified vegetation cover. Six blocks of each type were taken.

Three aluminium troughs were inserted 5 cm into each peat block, which was slightly inclined to ensure flow into the collecting vessel. The troughs were inserted at 1 cm, 5 cm and 10 cm below the peat surface to collect flow from the layer directly above the trough. The troughs had to be positioned with great care to ensure that no water emerging from upper layers could leak down the block face to lower troughs and to minimize disturbance of the peat. The upper trough was inserted 1 cm below the surface because it was difficult to create suitable contact to collect surface runoff above this. Hence infiltration rates indicate infiltration to depths over 1 cm and any lateral flow within 1 cm of the surface contributes to 'surface runoff'. Runoff was measured manually every 5 minutes from each trough in measuring cylinders. Steady-state (final) runoff and infiltration rates were calculated using the mean value of the last five readings taken when runoff was considered to be approximately constant. We did not collect runoff produced below 10 cm depth, but we could calculate it at steady state by subtracting the runoff rate above 10 cm from the rainfall rate. The bottom of the peat block at 35 cm depth was bounded by the PVC container, but runoff from 10 to 35 cm depth was allowed to flow out of the open end of the PVC container into which the runoff troughs were inserted. The other three sides of the peat block were closed.

A drip-type rain simulator as described by Bowyer-Bower & Burt (1989) and Holden & Burt (2002) was used to provide the rain. A manometer controlled the intensity, which could be reproduced to as little as 3 mm hour^{-1}. Rainfall intensity rarely exceeds 12 mm hour^{-1} in the uplands of the UK, and so there is little point in experimenting with more intense rain. Rain was simulated at four intensities (3, 6, 9 and 12 mm hour^{-1}), with the order of the runs varied so as to randomize the effect of antecedent conditions which might otherwise bias results. We allowed the rain to continue until the runoff became constant. Often this took 2–3 hours, particularly at the smaller intensities. The rain was then stopped, and the block was allowed to drain. The block was left for several hours before the next run began. Each block was subject to four separate rain events. The water supplied by the simulator was made up in solution to replicate the mean characteristics of the precipitation at Moor House as determined by bi-weekly sampling from 1991 to 1998.

The design of the experiment is technically a split-plot design in which the six replicates of four vegetation cover types constitute 24 main plots (blocks of peat) on each of which there were three depths in factorial combination with four intensities of rain. Table 2 lists the main effects and their combinations and the way in which the degrees of freedom are partitioned. Figure 1 is a scheme of the experiments on the peat blocks that followed the initial simulations. In subsequent experiments

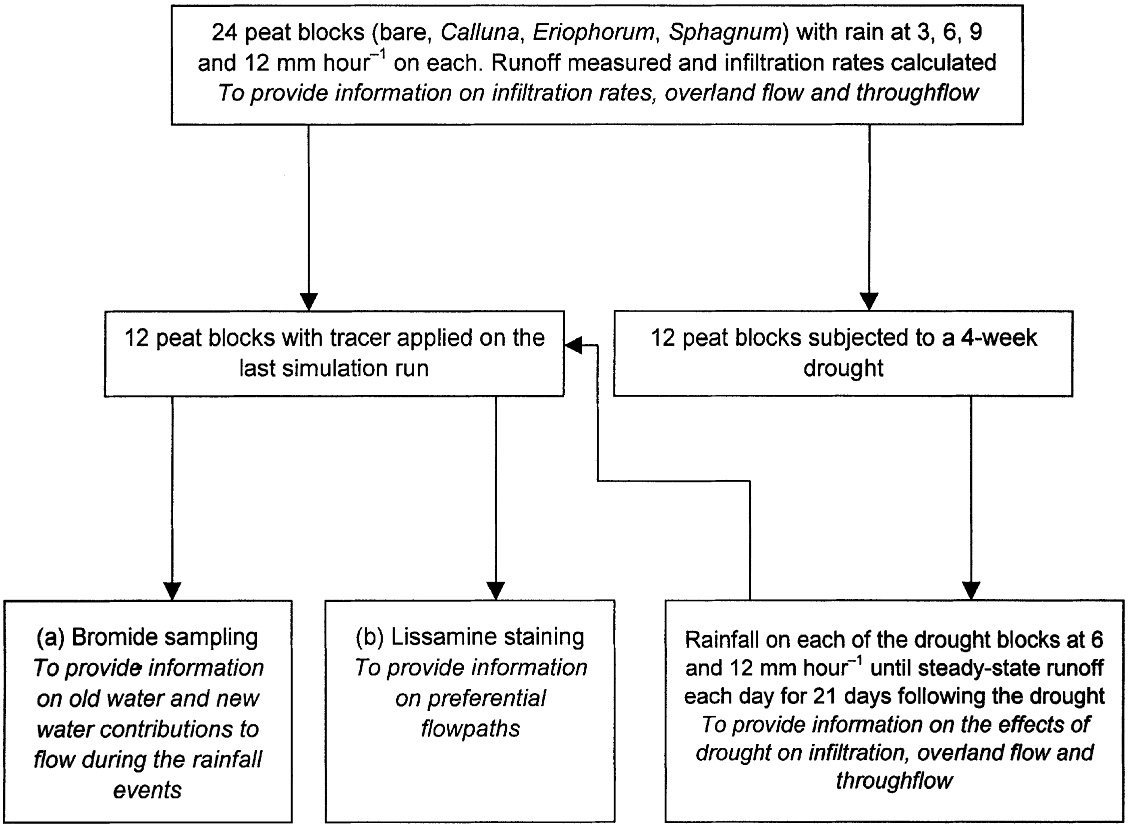

Figure 1 Flowchart showing the outline experimental procedure adopted.

three peat blocks of each vegetation cover type were not subject to drought. Two tracers, Lissamine FF and potassium bromide, were added to the rainwater supply at small concentrations ($0.2\,\mathrm{mg\,l^{-1}}$) during the last simulation on each block. Two separate tracers were used to provide information on two processes. Bromide (as a conservative tracer) was used as an indicator of travel times through the peat by sampling the runoff water. This allowed us to estimate the fluxes of both old and new water through the blocks. Thus some of the characteristics of wetting and throughflow mixing within the peat blocks could be established. Bromide concentrations in runoff samples were determined using a Dionex$^{\mathrm{TM}}$ ion chromatograph. Lissamine FF was used to stain the runoff pathways through the peat so that preferential flow and percolation depths could be identified. This fluorescent dye is particularly suited because it survives in acid peaty soils. The Lissamine FF in the soil samples was determined on a Perkin-Elmer LS-3B fluorescence spectrometer with excitation and emission maxima set as specified by Smart & Laidlaw (1977). We found an almost perfect linear relation between concentration and fluorescence.

Once the tracer runs had been completed the blocks were divided into five horizontal sections, 5 cm apart, to test for preferential flowpaths in the peat. Nine microsamples (5 g) and one bulk sample (500 g) were systematically taken from the lower face of each section. To measure the concentration of Lissamine, samples were extracted with saturated calcium sulphate solution (Omoti & Wild, 1979; Smettem & Trudgill, 1983) at 1:3 soil:solution ratio. Blanks containing soil and deionized water, and dye solutions without soil, were also tested to correct for background fluorescence and dye loss on to the polypropylene containers. Dye adsorption on to the containers was negligible, and so no correction was necessary. A maximum background concentration equivalent to $3\,\mu\mathrm{g\,l^{-1}}$ was recorded and subtracted from the experimental data. Microsamples were classified (before they were removed – otherwise disturbance would have made classification impossible) into two classes on the basis of structural features following the technique adopted by Smettem & Trudgill (1983):
1 those containing fissures, ‘macropores’ and roots with a diameter >1 mm in which bypass flow was likely, and
2 those with voids <1 mm, generally of a uniform and smooth nature, classified as ‘matrix’ and assumed to possess no bypass capability.

The other three blocks from each surface cover class (12 blocks in total), which were neither injected with tracer nor dissected, were left for 4 weeks in the laboratory without rainfall in a regime of temperature fluctuations in both magnitude and duration similar to those at Moor House during the drought summer of 1995. These were from 25°C at 14.00 hours to 10°C at 01.00 hours in a diurnal cycle. Other conditions were not identical to those in the field because humidity, albedo, direct sunlight and wind were not simulated. Nevertheless, this simulation allows us to investigate the effects of a prescribed drought under laboratory conditions.

After 4 weeks of drought the blocks were subject to separate rainfall events of 6 and 12 mm hour^{-1} until flow was steady. Two separate applications of rain were repeated on each block each day for 20 more days after initial rewetting to see whether overland flow, infiltration and near-surface runoff recovered after the drought. On the last application of rain (on post-drought day 21) bromide and Lissamine FF were applied. Runoff was sampled for bromide concentration, and we sampled the peat blocks for preferential flow by extracting classified samples and measuring Lissamine concentration. This allowed us to compare between the wetting and mixing characteristics (old water and new water contributions to flow), depth of percolation, and preferential flow in the control and treated blocks.

Results and discussion

Infiltration and runoff production in blocks before drought simulation

Table 1 presents mean results from the rain simulation tests on all 24 peat blocks before drought. The mean final infiltration rates were small, and overland flow could be produced on both bare and vegetated surfaces at intensities as little as 3 mm hour^{-1}. Saturation-excess overland flow can occur at much smaller rainfall intensities than required for infiltration-excess overland flow (Burt, 1996). Thus, if the peat becomes saturated to the surface, even under gentle rain, then overland flow is likely to be produced, no matter how intense the rain, as long as there is enough water to keep the peat saturated. The water table in six of the plots was measured using a small PVC dipwell. In each case overland flow did not begin until the water table had reached the surface and the peat was saturated. This corroborates work by Evans *et al.* (1999) who showed that peatlands exhibited rapid water table response to rain that resulted in flashy streamflow. Large streamflows occurred only when the water table was at or within 1 cm of the peat surface. Thus, infiltration-excess overland flow is not a dominant process within blanket peat catchments; saturation-excess processes dominate.

Table 1 Mean infiltration rate and standard deviations for 24 peat blocks

	Rainfall intensity /mm hour^{-1}			
	3	6	9	12
Infiltration rate at steady state /mm hour^{-1}	1.71	2.91	4.18	6.01
(Standard deviation)	(0.85)	(1.86)	(2.88)	(3.78)

Steady-state infiltration appears to increase with intensity of rain (Table 1). We tested this relation for significance by analysis of variance. The infiltration rate was found to increase significantly with rainfall intensity ($P < 0.001$), and shows the importance of more than one rainfall intensity in such experiments. We suggest three potential mechanisms for this:

1 ponded water increases with increases in rainfall intensity so that surface water pressure increases (Schiff, 1953);

2 more fine sediment is kept in suspension instead of blocking pores (Bowyer-Bower, 1993), and

3 the lack of uniformity may result in some parts of the plot having more rapid infiltration than others; hence the mean infiltration rate will increase with increasing intensity of rain simply because there is a greater flux of water through the parts of the plot surface that have the larger infiltration capacities (Hawkins, 1982).

Table 2 summarizes the analysis of variance of runoff. Mauchly's test of sphericity showed no significant correlation between repeated measurements on the same blocks ($P > 0.05$), and so we could test for significance in a straightforward way. Calculated significance levels are less than 0.001 for all effects on runoff. The mean square was much larger for the depth effect than for the others.

Table 3 allows the depth and cover type controls to be examined. Runoff declines with depth, and less runoff is collected from the *Sphagnum* blocks than for other surface cover types. This indicates that a greater proportion of rainwater at steady state is percolating to depths greater than the 10 cm collecting trough below *Sphagnum*. This water was produced between 10 and 35 cm depth and drained from the blocks at the bases of the PVC containers. This result accords with the larger near-surface hydraulic conductivities measured under *Sphagnum* than under other kinds of cover (Holden *et al.*, 2001). Thus surface cover type (coupled to soil properties) can partly control runoff in blanket peat. No runoff was produced from the lowest layer of any of the *Calluna* blocks, and almost 100% of the rain emerged at steady state from the upper two layers.

The effects of drought on infiltration and runoff production

Figure 2 shows mean steady-state runoff rates from the drought blocks and for four of the peat blocks subject to drought as examples of the typical response. Pre-drought values are indicated on the figure for comparison. Runoff from the initial rewetting on the first day after drought and values from the 7th and 21st tests afterwards are also shown. On day 1 after the drought the four blocks produced much less surface runoff than prior to the drought; the same is true even after 7 and 21 days. However, most of the blocks produced more surface runoff after 7 and 21 days than they did on the first day. Nevertheless, only under *Calluna* did the surface runoff 21 days after the drought reach the initial value. Thus, the effect of drought on peat appears to be to increase infiltration rates, an effect which persisted for at least

Table 2 Analysis of variance of steady-state runoff

Source of variation	Degrees of freedom	Mean square	*F* ratio	Probability
Main plots (peat blocks)				
Vegetation	3	34.346	6.14	< 0.001
Residual	20	5.591		
Subplots				
Intensity	3	64.793	51.6	< 0.001
Depth	2	305.626	243.2	< 0.001
Intensity × Vegetation	9	4.545	3.62	< 0.001
Intensity × Depth	6	25.479	20.3	< 0.001
Vegetation × Depth	6	31.323	24.9	< 0.001
Intensity × Vegetation × Depth	18	5.499	4.38	< 0.001
Residual	220	1.256		
Total	287			

Table 3 Means and standard errors of runoff rates at steady state

		Rainfall intensity /mm hour^{-1}				
Vegetation	Depth /cm	3	6	9	12	Marginal mean
Bare	1	0.81	2.09	5.29	4.81	3.25
	5	0.39	3.46	1.46	1.66	1.74
	10	0.16	0.18	0.11	0.21	0.16
Marginal mean		0.45	1.91	2.33	2.23	1.72
Calluna	1	2.24	4.54	6.87	7.90	5.38
	5	0.71	1.01	2.31	3.14	1.80
	10	0.00	0.00	0.00	0.00	0.00
Marginal mean		0.98	1.85	3.38	3.88	2.45
Eriophorum	1	1.15	3.74	6.05	9.23	5.04
	5	0.45	0.87	0.83	1.53	0.92
	10	0.11	0.28	0.22	0.42	0.26
Marginal mean		0.57	1.63	3.07	3.73	2.07
Sphagnum	1	0.70	1.54	1.55	1.90	1.42
	5	0.06	0.12	0.23	0.35	0.19
	10	0.38	0.14	0.96	2.04	0.88
Marginal mean		0.38	0.60	0.63	1.43	0.83
All vegetation covers	1	1.29	3.09	4.82	5.99	3.29
	5	0.40	1.36	1.21	1.67	1.16
	10	0.16	0.15	0.32	0.67	0.36
Marginal mean		0.60	1.50	2.16	2.82	
Grand mean						1.77
Standard errors:						
Vegetation			0.28			
Intensity			0.13			
Depth			0.11			
Intensity × Vegetation (meaned over depth)			0.26			
Intensity × Depth (meaned over vegetation)			0.23			
Vegetation × Depth (meaned over intensity)			0.23			
Vegetation × Intensity × Depth			0.46			

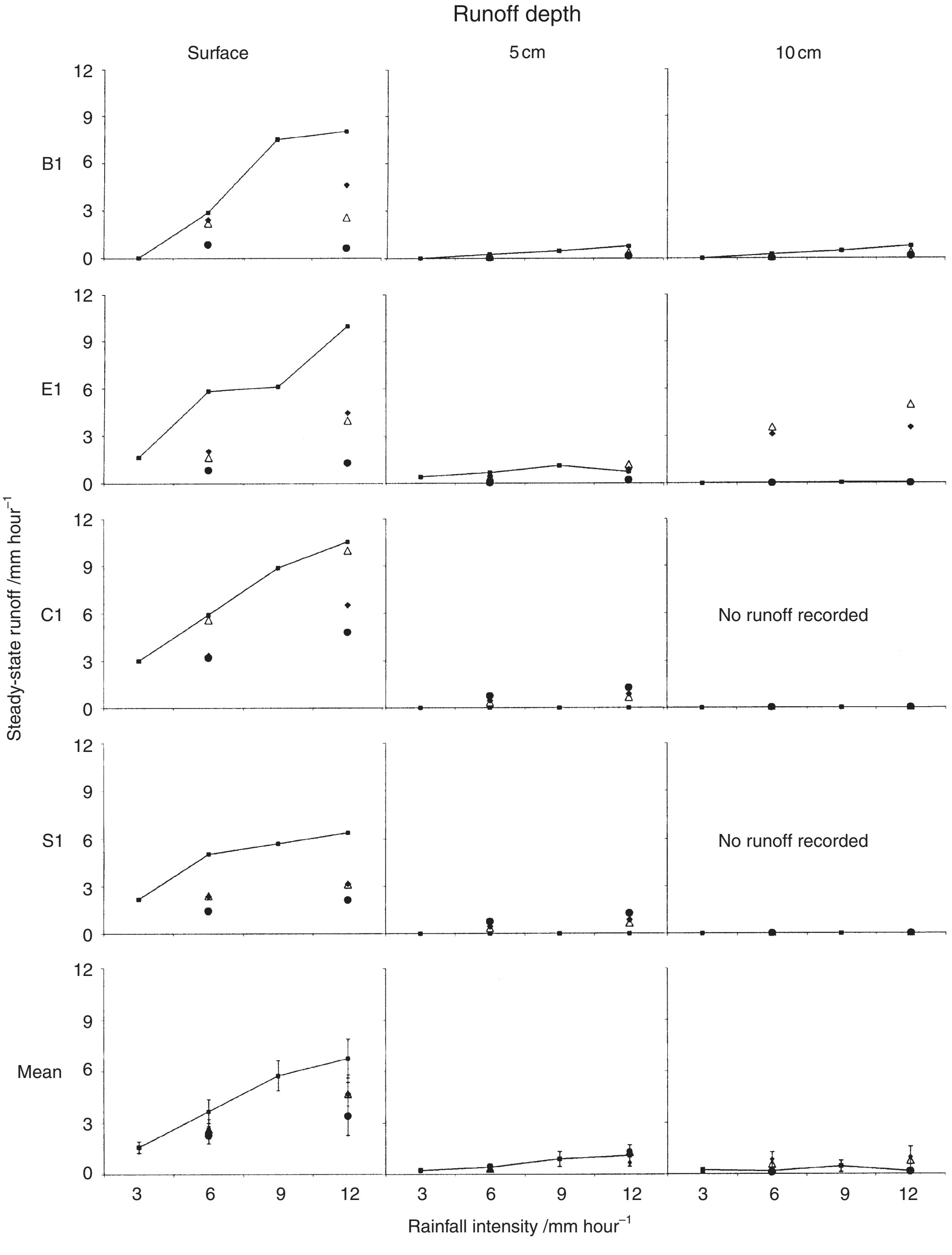

Figure 2 Mean steady-state runoff and runoff from four peat blocks for pre- and post-drought rainfall simulation by rainfall intensity and peat depth; bare (B1), *Eriophorum* (E1), *Calluna* (C1) and *Sphagnum* (S1) examples. ■, pre-drought runoff; ●, post-drought day 1; △, post-drought day 7; ◆, post-drought day 21.

3 weeks after the drought, despite daily rain. Therefore one would also expect runoff from the lower peat layers to increase. This can be seen at 10 cm depth on *Eriophorum* 1, for example, and at 5 cm for *Calluna* (Figure 2). For the unvegetated block (B1), subsurface flow after the drought had to be produced deeper than before because runoff was less in the 5 cm and 10 cm troughs than before the drought. Rain was allowed to fall on the blocks until steady state was reached, and so increased infiltration rates are not simply a result of dry antecedent conditions. Thus immediately following a drought, infiltration was enhanced and more subsurface flow resulted. After drought the surface peat layers produce less runoff than before the drought.

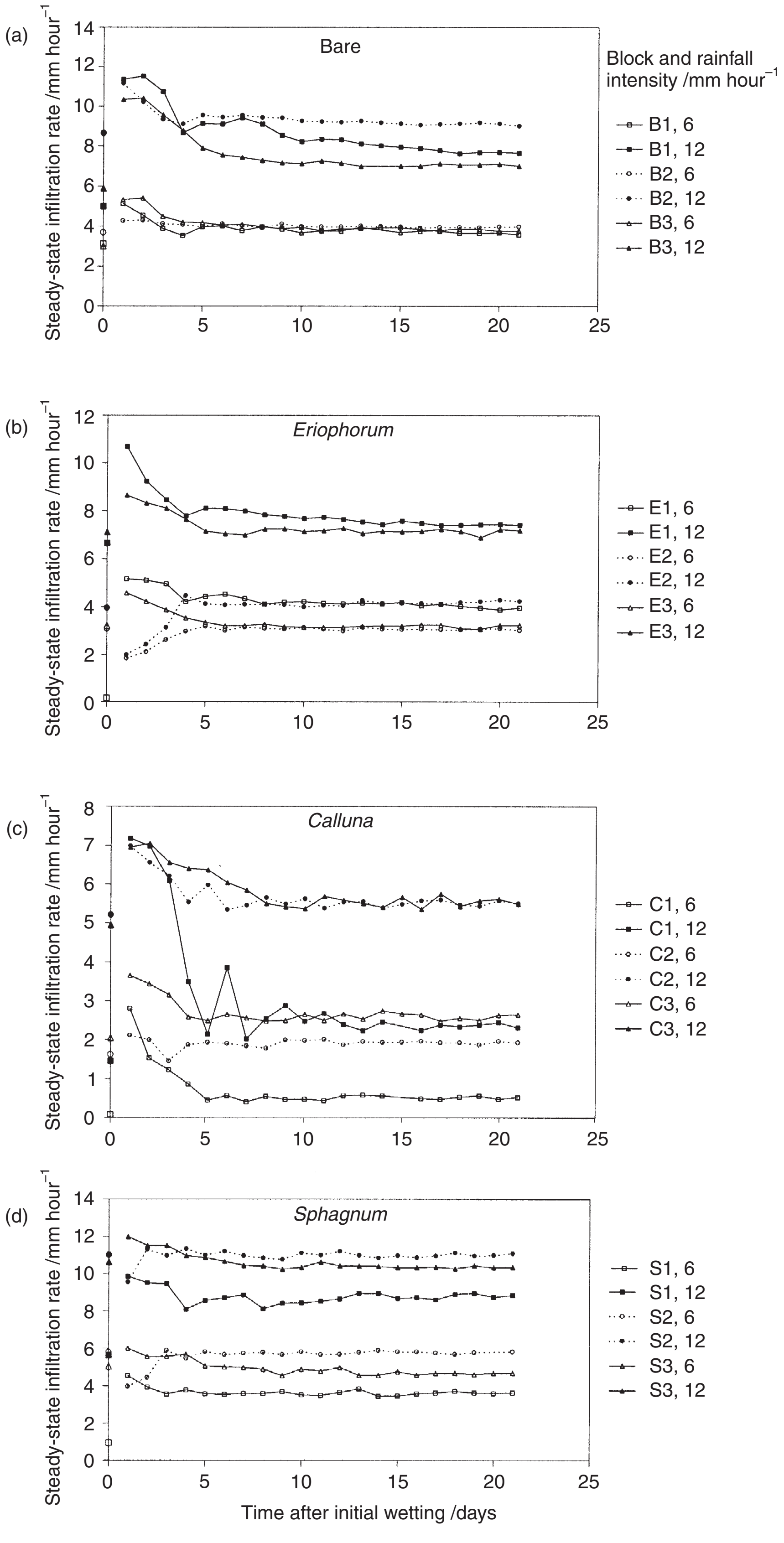

Figure 3 Steady-state infiltration rates over 21 days for all peat blocks tested at 6-mm-hour^{-1} and 12-mm-hour^{-1} runs. Earliest data point in each series is the pre-drought value.

Even after 3 weeks of repeated rain more water percolated deeper into the peat at steady state than before the drought. It is difficult to say whether this would be a permanent change, but the trend in runoff (Figure 3) suggests so. Figure 3 shows the steady-state infiltration rate for each peat block at 6- and 12-mm-hour^{-1} intensities before drought and for the 21 days following drought. In many cases, recovery was more pronounced during the first 3–7 days, after which rates stabilized. The first rain after the drought resulted in a 67% increase in mean steady-state infiltration rates; by day 7 the mean increase was 22%. Three weeks after the drought ended mean infiltration rates were still 19% greater than before the drought. Infiltration rates decreased following the drought on two of the blocks (*Sphagnum* 2 and *Eriophorum* 2). This was a result of crusting on the peat surface being more dominant than increased percolation flow down cracks and through the matrix in these cases. Three of the 12 blocks fully recovered from the drought in terms of attaining pre-drought infiltration rates; these all had a vegetated cover. Evidently, however, droughts such as that experienced in the UK during summer 1995 could have long-lasting effects.

Old and new water production

Specific conductivity. Figure 4(a) shows a typical runoff response from rain on an untreated *Eriophorum* block. The response from the three layers is quick, with a sharp increase in surface runoff only 15 minutes after the onset of rain. Steady-state runoff was achieved after 75–90 minutes for all three layers. The hydrographs are fairly symmetrical, with a rapid recession once the rain ceased. The graphs of specific conductivity (S.C.) in Figure 4(a) indicate that some chemical separation of runoff is possible, with surface flow having a much smaller conductivity than that deeper in the peat. Mean specific conductivities of the runoff produced from each layer from 24 peat blocks are listed in Table 4. For the 10 cm layer,

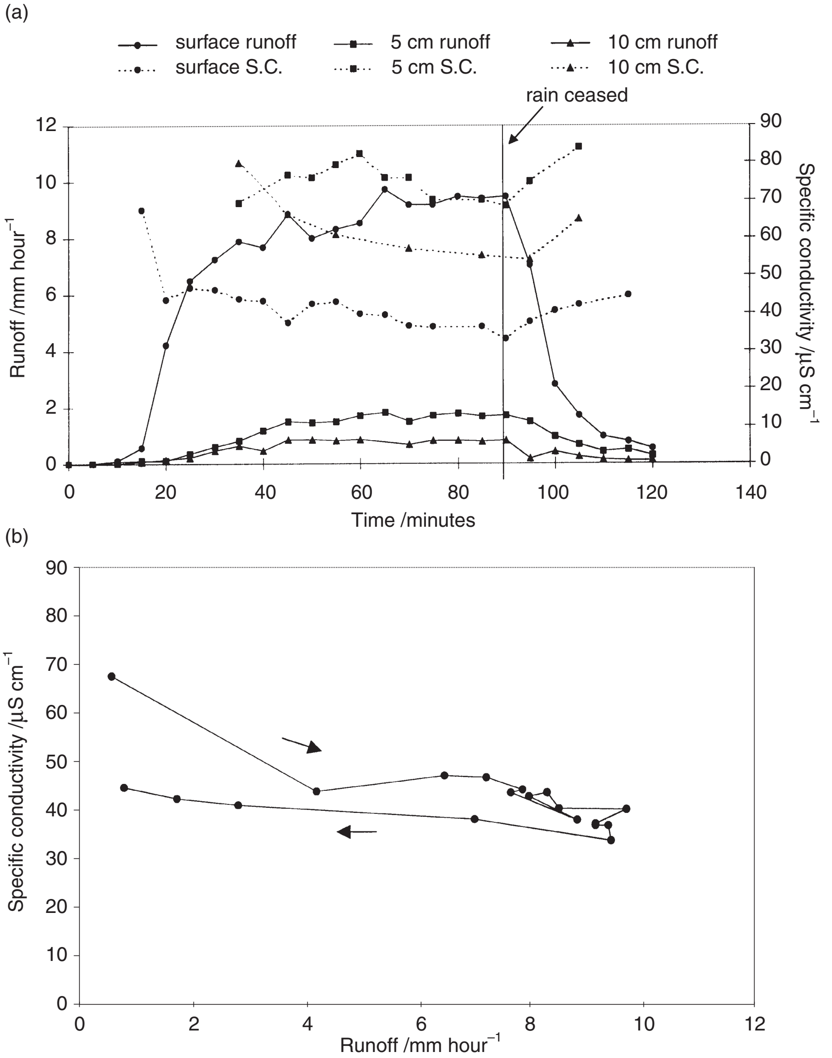

Figure 4 Runoff response and specific conductivity (S.C.) for an *Eriophorum*-covered peat block for a 12-mm-hour^{-1} rainfall event. (a) Runoff rates and conductivity for each layer. (b) Hysteresis plot of specific conductivity against discharge for the surface layer.

Table 4 Specific conductivity of runoff water from peat blocks subject to simulated rainfall; input rainfall at 31.1 μS cm^{-1}

Layer	Mean conductivity /μS cm^{-1}	Standard deviation	Mean maximum conductivity /μS cm^{-1}	Mean minimum conductivity /μS cm^{-1}
Surface	56.5	16.4	103.9	42.6
5 cm	100.2	10.2	106.8	94.5
10 cm	103.1	7.4	112.1	100.4

standard deviations are small. This indicates the slow movement of water through the lower layers and the resulting longer residence times before emergence. Larger deviations in the upper layers represent larger changes during rain, the larger volume of runoff and the importance of new water during rain events. There is also a clockwise hysteresis in the S.C. response (Figure 4b). This, of course, is unusual (cf. Walling & Webb, 1981) and could indicate an exhaustion effect within the peat. On the other hand, it is likely that much of the overland flow produced on the plot at first is return flow produced as the peat becomes saturated. Then, as further ponding develops, the overland flow is diluted with new rainwater.

Tracer response in control and treatment plots. The variations in Lissamine FF and bromide concentration in runoff from a 12-mm-hour^{-1} run on a *Sphagnum* block are shown in Figure 5. For surface flow, variations in bromide and Lissamine FF concentration are similar. However, for the deeper layer, the concentration of Lissamine FF remains much less than that of bromide after breakthrough of the latter to near-input value after 2 hours (input value = 0.2 mg l^{-1}). This indicates that Lissamine

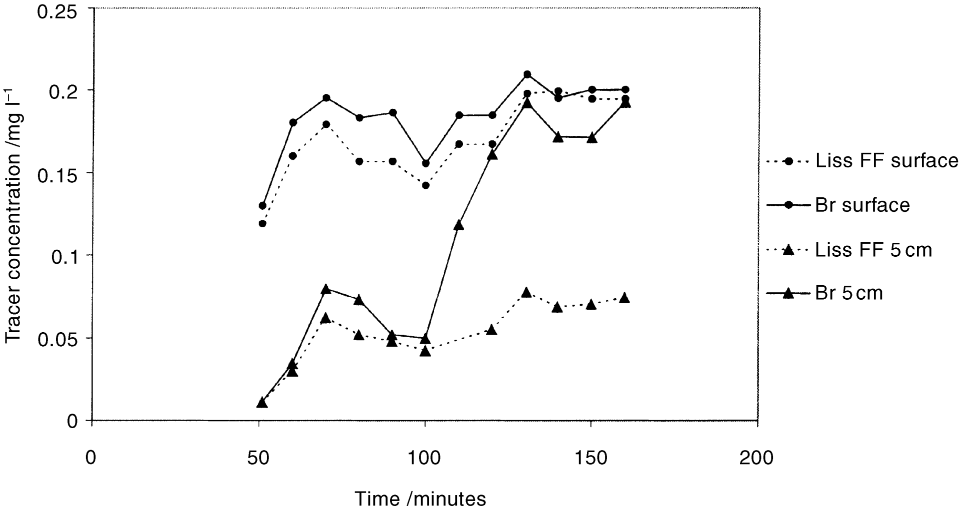

Figure 5 Breakthrough of Lissamine FF and bromide in runoff from a *Sphagnum*-covered laboratory peat block S1, with rainfall at 12 mm hour^{-1}. Input at 0.2 mg l^{-1}.

Table 5 Mean contribution of old water to runoff following watering until steady state and until all runoff produced is new water. Data for 12 control plots and 12 plots subject to a 4-week drought. Tests carried out on the treatment plots on post-drought day 21

	Control plots			Treatment (drought) plots		
Depth /cm	Mean old water contribution to runoff /mm	Standard error	Mean old water contribution /mm per mm peat thickness	Mean old water contribution to runoff /mm	Standard error	Mean old water contribution /mm per mm peat thickness
1	1.03	0.25	0.103	1.14	0.17	0.114
5	0.78	0.12	0.020	0.85	0.12	0.021
10	0.12	0.04	0.002	0.10	0.02	0.002

Table 6 Mean moisture content (% by mass) of peat block layers in peats not subject to drought and peats subject to drought followed by a 21-day rewetting procedure. $n = 12$ in all cases. Standard errors given in parentheses

Layer	Non-drought /%	After drought and rewetting /%
0–5 cm	88.9 (1.0)	77.5 (1.6)
5–10 cm	93.2 (1.1)	81.1 (1.1)
10–15 cm	90.4 (1.2)	84.5 (1.4)
15–20 cm	90.5 (1.2)	82.3 (1.3)

FF is suitable only for identification of flowpaths within the soil rather than for analysis of breakthrough curves, as it is adsorbed readily into the peat. Bromide acts as a more suitable tracer for travel time and mixing analysis. Old water contribution, Q_o, to total discharge, Q_t, can be calculated from the following equation (Pilgrim *et al.*, 1979) if no adsorption takes place:

$$Q_o = Q_t(C_t - C_n)/(C_o - C_n), \tag{1}$$

where C_t is the concentration of bromide at a given time, t, C_n is the applied concentration of bromide in the rain (new water), and C_o is the background concentration.

Table 5 presents the estimated mean depth (volumes have been weighted to produce depth-averages) of old water produced from the runoff troughs for the control and treatment blocks during the experiments. The total amount of rain applied was typically around 18 mm. By the end of each experiment, at steady state, all of the runoff produced from the monitored peat layers was new water. Here 'old water' is defined as water that was present in the peat before the rain began (and hence did not contain the bromide tracer) and 'new water' is the rain from the simulator containing bromide. There was no significant difference between the control and the treatments. Given that 80–90% of the overall mass is water (Table 6), the pore volume should be considerable, and around 40–50 mm of water should have been present in the upper 10 cm of peat at the beginning of the simulation. However, the mean amount of old water produced over 10 cm of peat depth is only 2 mm, and so matrix flow may

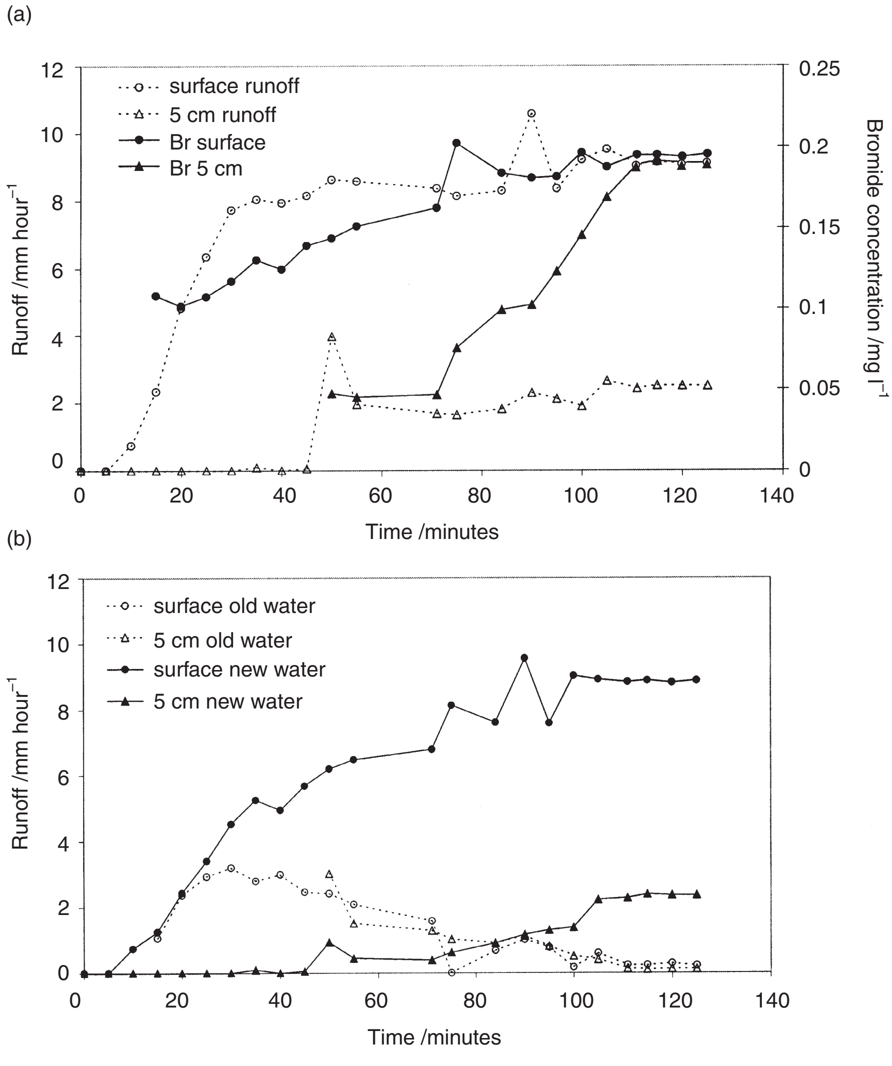

Figure 6 Runoff production from an *Eriophorum*-covered peat block subject to a 12-mm-hour^{-1} rainfall simulation. (a) Recorded runoff and bromide concentration. (b) Calculated old and new water contributions to flow.

be restricted. However, there was no significant difference between drought and non-drought blocks. This suggests preferential flow does not increase following drought.

Analysis of variance showed that the amount of old water in runoff was significantly different between soil layers ($P < 0.005$). Values are given in Table 5 for old water runoff in mm per mm depth of peat. Generally less old water is produced from deep layers than from shallower ones. The mean amount of old water produced over 10 cm of peat is about 2 mm. This is small, but corroborates the findings of Evans *et al.* (1999) at the catchment scale. The peat was not fully saturated prior to rain because several hours were left between each event during which the blocks were allowed to drain.

Results from a 12-mm-hour^{-1} simulation on an untreated *Eriophorum* block are shown in Figure 6(a). Here no flow was recorded from the trough at 10 cm. Steady state was achieved after about 105 minutes from the two upper troughs producing runoff. Mean steady-state runoff was 9.1 mm hour^{-1} for the surface layer with 2.5 mm hour^{-1} for the 5 cm trough. The other 0.4 mm hour^{-1} was produced at the base of the PVC container from the peat between 10 and 35 cm depth. Bromide concentrations stabilized at around the same time as steady-state runoff. The flow of old water decreases over time; early in the event it is produced from the block and later is replaced by new water (Figure 6b). In near-surface peats there is more void space in which mobile water can be stored, whereas in deeper peats there is less space available for mobile water (Boelter, 1964).

The results of bromide tracing suggest that drought has no long-term effect on mixing processes within the peat (and hence part of the rewetting properties of the peat), but other evidence suggests the contrary (Table 6). We measured the moisture contents of the 12 control and 12 treatment blocks after allowing the blocks to drain for 1 hour following the final rainfall simulation and then removing 500 g intact bulk samples (which would therefore include any macropores) from each 5 cm layer of each block and drying it at 105°C for 24 hours. In all four sampled layers down to 20 cm, the moisture content of the peat was significantly less in the drought blocks than in the control blocks, even after substantial subsequent rain ($P < 0.05$). The peat had not regained its original moisture

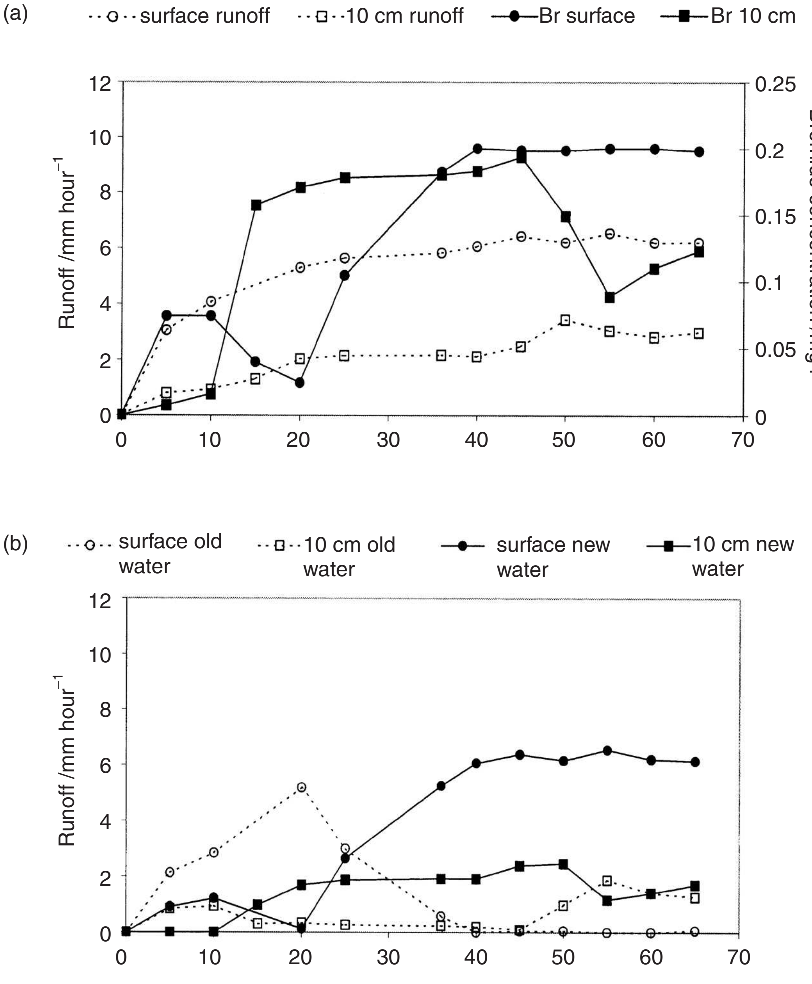

Figure 7 Runoff production from an *Eriophorum*-covered peat block subject to a 9-mm-hour^{-1} rainfall simulation. (a) Recorded runoff and bromide concentration. (b) Calculated old and new water contributions to flow.

content even with nine of the blocks having a vegetation cover and after 21 days of watering. A 4-week laboratory drought under temperature conditions similar to that of summer 1995 had caused physical changes to the peat down to 20 cm depth.

The role of macropores in runoff generation in control and treatment plots

Runoff from some of the blocks to which bromide was applied showed preferential flow. The response from a 9-mm-hour^{-1} watering on an *Eriophorum*-covered peat block is shown in Figure 7. Here surface runoff reached steady state after about 45 minutes (6.1 mm hour^{-1}), with old water contributions (1.1 mm) ending after the first 40 minutes. Initially, runoff was a mixture of old and new water, but at 20 minutes almost all of the runoff from the first centimetre of peat was old water. After this, the remaining mobile old water was rapidly released. Results from the lower layer indicate that the production of runoff is complex, involving mixing and interaction of flows at depth. Initially, bromide concentrations increased rapidly, indicating a quick channelling of new water through the 10 cm trough. Later, after around 50 minutes, bromide concentrations from the 10 cm layer decreased, and old water appeared in greater quantities. This trend suggests some form of preferential flow, with a strong link to the surface, dominating runoff from the lower layer over the first 50 minutes of the run. Later, as the slower response of matrix flow began to dominate, this allowed a larger volume of the peat to act as a source for runoff. These data provide some evidence for preferential flow through the peat blocks. More evidence for preferential flow in the peat blocks comes from Lissamine FF staining.

Figure 8 shows the depth of penetration of applied rainwater as indicated by Lissamine recovery from bulk samples. Only four of the 12 control blocks showed any signs that applied rain percolated deeper than 10 cm. These were three *Sphagnum* blocks and a bare peat block. For the other eight blocks all runoff appeared to take place within the top 10 cm of the peat. For the peat that had been subject to drought the depth of penetration is generally greater than in blocks not subject to drought, with Lissamine detected at 20 cm depth in eight of the 12 blocks.

We computed a recovery ratio, R (Smettem & Trudgill, 1983), given by

$$R = C_m/C_b, \tag{2}$$

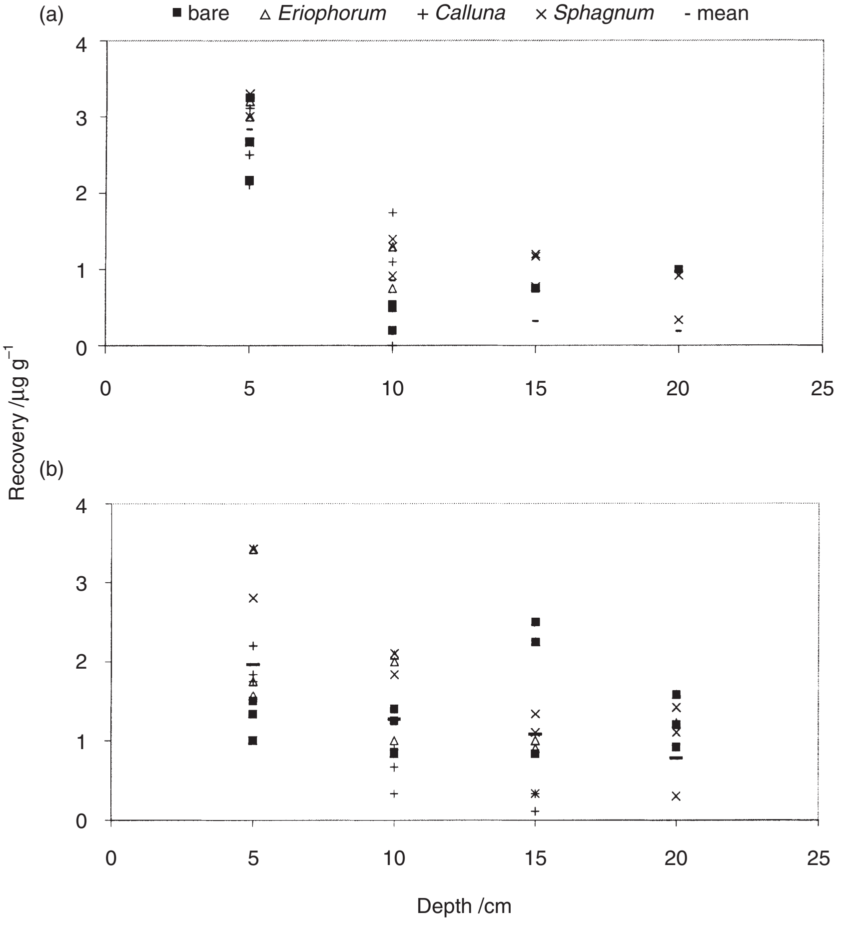

Figure 8 Lissamine FF distribution with depth, bulk sample recovery. (a) Non-drought blocks. (b) Drought blocks.

Table 7 Chi-squared evaluation of R (C_m/C_b) in relation to structural classes. (a) Blocks not subject to drought. (b) Blocks subject to drought. Nine samples per block per layer. No samples taken for layers into which Lissamine did not penetrate

(a)	Number of events					
	Class 1		Class 2			
Depth	$R>1$	$R\leq 1$	$R>1$	$R\leq 1$	χ^2	H_1 acceptance level (one-tailed) (1 d.f.)
5 cm						
Observed	20	9	3	76	53.7	99.9
Expected	6.2	22.8	16.8	62.2		
10 cm						
Observed	27	14	32	26	1.1	Not accepted
Expected	24.4	16.6	34.6	23.4		
15 cm						
Observed	5	11	3	17	1.4	Not accepted
Expected	3.6	12.4	4.4	15.6		
20 cm						
Observed	1	5	15	15	2.3	Not accepted
Expected	2.7	3.3	13.3	16.7		
Total						
Observed	53	39	53	134	22.4	99.9
Expected	35.0	57.0	71.0	116.0		

(b)	Number of events					
	Class 1		Class 2			
Depth	$R>1$	$R\leq 1$	$R>1$	$R\leq 1$	χ^2	H_1 acceptance level (one-tailed) (1 d.f.)
5 cm						
Observed	42	12	13	41	31.2	99.9
Expected	27.5	26.5	27.5	26.5		
10 cm						
Observed	48	10	26	24	11.8	99.9
Expected	39.7	18.3	34.3	15.7		
15 cm						
Observed	30	8	39	22	2.5	Not accepted
Expected	26.5	11.5	42.5	18.5		
20 cm						
Observed	3	5	21	43	0.1	Not accepted
Expected	2.7	5.3	21.3	42.7		
Total						
Observed	123	35	99	130	45.8	99.9
Expected	90.6	67.4	131.4	97.6		

to compare the preferential flows between depths. Here C_m is the microsample Lissamine concentration and C_b is the bulk sample dye concentration at the same depth. Values of R are classified into two groups (>1 and ≤ 1), and interest is directed to the number of occurrences falling into the two structural classifications as described in the Materials and methods section. The null hypothesis (H_0) states that the structural classes have equal frequencies of the occurrence of R; H_1 suggests that there is a significant difference, with R values >1 occurring most frequently in class 1 and R values ≤ 1 most frequently in class 2. The one-tailed χ^2 test yields the significance for the difference between the observed number of occurrences in each class and the expected number.

Values of R for microsamples are given in Table 7(a) for blocks not subject to drought, and indicate that dye penetration is well matched with structural features in the 5 cm layer. Most R values > 1 correspond to class 1 and $R \leq 1$ to class 2. The χ^2 test accepts the difference (H_1) statistically at the 99.9% level for the uppermost sampled layer and for the total block samples. For layers below 5 cm H_0 must be accepted. However, dye penetration was greater than 10 cm in only four cases. This small value may be related to the small number of cases. The number of cases in class 1 is greater at 10 cm than for other layers. Structurally, then, more macropores occur at 10 cm depth, but it may be that these are not sufficiently connected to upper layers to conduct new water.

For blocks subject to drought, the number of samples in class 1 is much greater than in blocks not subject to drought (Table 7b), even at 15 cm depth. This suggests that the simulated drought has induced greater macroporosity in the blanket peat. The hypothesis H_0 can be rejected at 10 cm depth after the drought. Drought appears to encourage the development of functional macropores within the peat. These data provide an important extension to our understanding of the way in which runoff can be affected by droughts in blanket peat catchments. The increased infiltration and lateral subsurface flow that follows droughts on peat may be partly explained by structural changes within the peat caused by lowering of the water table into the normally anaerobic layers and shrinkage of the upper peat. This leads to enhanced functional macroporosity.

Conclusions

Simulated rain on intact peat blocks in the laboratory has shown that runoff is dominated by surface and near-surface flow. Runoff decreased rapidly with increasing depth, increased with increasing intensity of rain and was affected by the type of surface cover. Runoff was flashy, with around 50% of rainwater produced as overland flow. Drought reduced surface runoff, increased infiltration, and led to more flow in the deeper peat.

We could distinguish old and new water from the laboratory peat by using bromide tracing. In total very little old water emerged during watering, though more emerged near the surface than in the lower layers. No significant difference in the old and new water mixing processes could be identified between the control plots and the drought treatment plots. This suggested that the wetting characteristics of the peat had not been affected by drought. However, the moisture content of the droughted peat, even after 3 weeks of rain, was significantly less (by 9%) than that in the control plots. Thus some of the wetting characteristics had been affected.

Macropores were found throughout the control plots, but preferential flow was significant only within the top 5 cm of the peat. Drought simulation suggests that the structure of the peat can change substantially during dry, warm weather. In particular, macroporosity significantly increased in the peat, and preferential flow became significant within at least the top 10 cm following drought. It is unclear whether the reduction in moisture content and structural changes in these peat blocks are permanent, though they appear long-lasting. The experiments suggest that some reversion towards pre-drought infiltration and runoff rates occurred in the first week following rewetting, but this is less likely (or at least much slower) after the first few days of rainfall. Nine of the 12 treatment blocks did not recover to pre-drought runoff and infiltration levels even after 3 weeks of post-drought rainfall simulation. The fact that dried peat rarely returns to its original status upon rewetting (Egglesmann *et al.*, 1993) tends to suggest that changes may be permanent.

This paper has presented results from a set of laboratory experiments. Field conditions are naturally different. Drainage of lower peat layers is probably more delayed than in the laboratory because the water cannot freely flow off. In saturated peat, with less lateral flow, additional macropores created by droughts might not emerge during droughts or may close more rapidly afterwards. Furthermore, rapid flows through macropores under laboratory conditions might enlarge or sustain preferential flowpaths more than under field conditions. However, field evidence presented by Holden & Burt (2002) during the dry summer of 1999 in the North Pennines corroborates findings presented above. Furthermore, pre-drought simulation in the laboratory produced runoff from peat blocks that was not significantly different from runoff under simulated rain in the field (Holden & Burt, 2002). Hence the laboratory blocks seem to replicate field conditions reasonably well. Increased occurrence of droughts in the future might therefore result in changes to hydrological processes in blanket peat catchments.

Acknowledgements

We gratefully acknowledge the assistance of Frank Davies and Brian Priestly in the laboratory. We also thank Brian Whitton and John Gemmill for use of the fluorescence spectrometer, John Adamson (CEH, Merlewood) and English Nature for permission to work on peats from the Moor House Reserve, and two anonymous referees for comments on an earlier draft of our paper.

References

Boelter, D.H. 1964. Water storage characteristics of several peats *in situ*. *Soil Science Society of America Proceedings*, **28,** 433–435.

Bowyer-Bower, T.A.S. 1993. Effects of rainfall intensity and antecedent moisture on the steady-state infiltration rate in a semi-arid region. *Soil Use and Management*, **9,** 69–76.

Bowyer-Bower, T.A.S. & Burt, T.P. 1989. Rainfall simulators for investigating soil response to rainfall. *Soil Technology*, **2,** 1–16.

Burt, T.P. 1996. The hydrology of headwater catchments. In: *River Flows and Channel Forms* (eds G.E. Petts & P. Calow), pp. 6–31. Blackwell, Oxford.

Burt, T.P., Heathwaite, A.L. & Labadz, J.C. 1990. Runoff production in peat-covered catchments. In: *Process Studies in Hillslope*

Hydrology (eds M.G. Anderson & T.P. Burt), pp. 463–500. John Wiley & Sons, Chichester.

Burt, T.P., Adamson, J.K. & Lane, A.M.J. 1998. Long-term rainfall and streamflow records for north central England: putting the Environmental Change Network site at Moor House, Upper Teesdale, in context. *Hydrological Sciences Journal*, **43,** 775–787.

Egglesmann, R.F., Heathwaite, A.L., Gross-Braukmann, G., Kuster, E., Naucke, W., Schich, M. & Schweikle, V. 1993. Physical processes and properties of mires. In: *Mires, Process, Exploration and Conservation* (eds A.L. Heathwaite & K. Gottlich), pp. 171–262. John Wiley & Sons, Chichester.

Evans, M.G., Burt, T.P., Holden, J. & Adamson, J.K. 1999. Runoff generation and water table fluctuations in blanket peat: evidence from UK data spanning the dry summer of 1995. *Journal of Hydrology*, **221,** 141–160.

Hammond, R.F., Van der Krogt, G. & Osinga, T. 1990. Vegetation and water-tables on two raised bog remnants in County Kildare. In: *Ecology and Conservation of Irish Peatlands* (ed. G.J. Doyle), pp. 121–134. Royal Irish Academy, Dublin.

Hawkins, R.H. 1982. Interpretations of source area variability in rainfall–runoff relations. In: *Rainfall–Runoff Relationship. Proceedings of the International Symposium on Rainfall Runoff Modelling held May 18–21, 1981, Mississippi State University*, pp. 303–324. Water Resources Publications, Littleton, MS.

Holden, N.M. 1998. By-pass of water through laboratory columns of milled peat. *International Peat Journal*, **8,** 13–22.

Holden, J. & Burt, T.P. 2002. Infiltration and runoff production in blanket peat catchments: implications of field rainfall simulation experiments. *Hydrological Processes*, **16,** 2537–2557.

Holden, J., Burt, T.P. & Cox, N.J. 2001. Macroporosity and infiltration in blanket peat: the implications of tension disc infiltrometer measurements. *Hydrological Processes*, **15,** 289–303.

Hulme, M. 1998. The climate in the UK from November 1994 to October 1995. *Weather*, **53,** 242–257.

Ingram, H.A.P. 1983. Hydrology. In: *Ecosystems of the World 4A, Mires: Swamp, Bog, Fen and Moor* (ed. A.J.P. Gore), pp. 67–158. Elsevier, Oxford.

Ingram, H.A.P. 1991. Introduction to the ecohydrology of mires in the context of cultural perturbation. In: *Peatland Ecosystems and Man: An Impact Assessment* (eds O.M. Bragg, P.D. Hulme, H.A.P. Ingram & R.A. Robertson), pp. 67–93. University of Dundee and International Peat Society, Dundee.

Omoti, U. & Wild, A. 1979. Use of fluorescent dyes to mark the pathways of solute movement through soils under leaching conditions. 2. Field experiments. *Soil Science*, **128,** 98–104.

Pilgrim, D.H., Huff, D.D. & Steele, T.D. 1979. Use of specific conductance and contact time relations for separating stormflow components in storm runoff. *Water Resources Research*, **15,** 329–339.

Schiff, L. 1953. The effect of surface head on infiltration rates based on the performance of ring infiltrometers and ponds. *Transactions of the American Geophysical Union*, **34,** 257–266.

Smart, P.L. & Laidlaw, I.M.S. 1977. An evaluation of some fluorescent dyes for water tracing. *Water Resources Research*, **13,** 15–33.

Smettem, K.R.J. & Trudgill, S.T. 1983. An evaluation of some fluorescent and non-fluorescent dyes in the identification of water transmission routes in soils. *Journal of Soil Science*, **34,** 45–56.

Tallis, J.H. 1997. The southern Pennine experience: an overview of blanket mire degradation. In: *Blanket Mire Degradation: Causes, Consequences and Challenges* (eds J.H. Tallis, R. Meade & P.D. Hulme), pp. 7–15. Macaulay Land Use Research Institute, Aberdeen.

Walling, D.E. & Webb, B.W. 1981. Water quality. In: *British Rivers* (ed. J. Lewin), pp. 126–172. Allen & Unwin, London.