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Full Title:

INFILTRATION, RUNOFF AND SEDIMENT PRODUCTION IN BLANKET PEAT CATCHMENTS: IMPLICATIONS OF FIELD RAINFALL SIMULATION EXPERIMENTS

Short Title:

RAINFALL SIMULATION ON BLANKET PEAT

Keywords:

INFILTRATION, RAINFALL SIMULATION, PEAT, RUNOFF, SEDIMENT PRODUCTION, SATURATION-EXCESS OVERLAND FLOW

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Abstract

Blanket peat covers the headwaters of many major European rivers. Runoff production in upland blanket peat catchments is flashy with large flood peaks and short lag times; there is minimal baseflow. Little is known about the exact processes of infiltration and runoff generation within these upland headwaters. This paper presents results from a set of rainfall simulation experiments performed on the blanket peat moorland of the North Pennines, UK. Rainfall was simulated at low intensities (3-12 mm hr^{-1}), typical of natural rainfall, on bare and vegetated peat surfaces. Runoff response shows that infiltration rate increases with rainfall intensity; the use of low-intensity rainfall therefore allows a more realistic evaluation of infiltration rates and flow processes than previous studies. Overland flow is shown to be common on both vegetated and bare peat surfaces although surface cover does exert some control. Most runoff is produced within the top few centimetres of the peat and runoff response decreases rapidly with depth. Little vertical percolation takes place to depths greater than 10 cm due to the saturation of the peat mass. This study provides evidence that the quickflow response of upland blanket peat catchments is a result of saturation-excess overland flow generation. Rainfall-runoff response from small plots varies with season. Following warm, dry weather, rainfall tends to infiltrate more readily into blanket-peat, not just initially but to the extent that steady-state surface runoff rates are reduced and more flow takes place within the peat, albeit at shallow depth. Sediment erosion from bare peat plots tends to be supply limited. Seasonal weather conditions may affect this in that after a warm, dry spell, surface desiccation allows sediment erosion to become transport limited.

Introduction

Many UK rivers drain headwater areas of blanket peat, yet little is known about the exact hydrological processes responsible for runoff generation in these areas. Recent work has shown that most areas of damaged and undamaged blanket peat are highly productive of storm runoff (in comparison with most other catchments) and, by contrast, generate little baseflow (e.g. Bay, 1969; Burke, 1975; Price, 1992; Burt *et al.*, 1997, Burt *et al.*, 1998b, Evans *et al.*, 1999, Holden, 2000). The suggestion is that this is strongly related to the quickflow response resulting from surface or near-surface flow mechanisms. Infiltration processes and water movement through the upper layers of blanket peat are poorly understood.

Ingram (1983), in his extensive review of mire hydrology, makes almost no reference to the process of infiltration into peat and little information exists elsewhere. Tricker (1977) performed 30 ring infiltrometer measurements on a peaty Derbyshire moorland and found infiltration rates ranging from 0 – 265 mm hr^{-1} (rates after one hour of ponded infiltration). This provides evidence for high spatial variability although not all of Tricker's (1977) measurements were made on blanket peat. Gardiner (1983) and Labadz (1988) both attempted to measure infiltration in blanket peat but comparison is difficult because they used different methods (Table 1). Gardiner's (1983) ring infiltrometer tests suggested that infiltration-excess overland flow was likely to occur on *Eriophorum* moorland since 13 % of hourly rainfall totals exceeded 2 mm hr^{-1} at his field site, whereas the infiltration capacities (final state-state infiltration rate) were likely to be exceeded rarely on *Empetrum* hummocks. Burt and Gardiner (1984) confirmed that overland flow was a frequent occurrence on uneroded vegetated hillslopes but in eroded areas it was only frequent in depressions and on bare peat; the lower water table and interception by crowberry plants and the litter layer helped to restrict overland flow on the hummocks. Rainfall simulation work, however, suggested that *Eriophorum*-covered peat could have a much higher infiltration capacity with very shallow subsurface runoff occurring within the upper few centimetres of decomposing vegetation (Labadz, 1988). Labadz (1988) concluded from her short pilot study that the application of rainfall intensities comparable with those occurring naturally would be vital if results were to be compared with natural runoff events, but this has proved difficult to achieve in temperate climates. Certainly the rainfall intensities used in Labadz's experiments were not typical of rainfall in the Pennines (see below).

Burt *et al*. (1990) suggested that blanket peat catchments may be one of the few natural types in the UK that produce 'Hortonian' infiltration-excess overland flow to any large extent since infiltration rates into peat appeared to be low. However, the limited data available and the typically shallow water tables in blanket peat catchments have made it difficult to decide whether surface runoff is infiltration-excess or saturation-excess dominated. Evans *et al.* (1999) noted that more work at the subcatchment scale level was required to unravel the exact nature of the interaction between infiltration properties of the peat, water table levels and runoff generation. Most flow appeared to occur within the top layer of peat (the *acrotelm* - Ingram, 1983) which was periodically aerated by the lowering of the water table. The lower peat (catotelm) was permanently saturated with a low hydraulic conductivity. The relatively high hydraulic conductivity of the surface layers allowed the possibility of rapid near-surface runoff through this layer. However, there have been very few attempts to quantify runoff from the surface and subsurface peat layers with most measurements relying on estimates of the hydraulic conductivity of the peat (e.g. Ingram, 1967; Romanov, 1968, Dai and Sparling, 1973, Neuman and Dasberg, 1977; Baird, 1995). These tests are generally associated with errors of at least one order of magnitude (Rycroft *et al.*, 1975; Holden *et al.*, 2001) and are most commonly performed at depths well below the peat surface. Indeed, most models applied to peat hydrology have been based on groundwater flow (e.g. Skaggs, 1980; McDonald and Harbaugh, 1988; Armstrong, 1995; Kirkby *et al.*, 1995). This paper seeks to assess the importance of surface and very near-surface flow processes in blanket peat through a series of controlled rainfall simulation experiments.

Rainfall simulators have been extensively used in hydrological and geomorphological research (eg. De Ploey *et al.*, 1976; Lusby, 1977; Imeson and Kwaad, 1980; Bork and Rohdenburg, 1981; Imeson, 1983; Pilgrim and Huff, 1983; Bowyer-Bower and Burt, 1989; Morgan, 1995; Cerda, 1998; Bergkamp, 1998; Foster *et al.*, 2000). Simulators allow the amount, intensity and duration of rainfall to be controlled along with other variables such as drop-size distribution and water chemistry to varying degrees, depending on the system of application (Foster *et al.*, 2000). Runoff can be collected to determine infiltration rates (by subtracting runoff rates from application rates), and sediment erosion can be measured by sampling runoff. Both spray and drip-type simulators have been used in field and laboratory work. Drip systems can generate a constant low-intensity rainfall rate with drop sizes more easily controlled than in spray systems (Bowyer-Bower and Burt, 1989).

Study Site

The experiments were performed at the Moor House National Nature Reserve (NNR), North Pennines, UK (54^{o} 41' N, 2^{o} 23' W). Moor House NNR is a UNESCO Biosphere Reserve occupying 35 km^{2} with an altitudinal range of 290 to 848 m. Lower Carboniferous sequences of interbedded limestone, sandstone and shale provide a base for a glacial till (Johnson and Dunham, 1963). The overlying glacial till provides poor drainage, which has led to the development of blanket bog on around 70 % of the reserve. The vegetation is dominated by *Eriophorum* sp., *Calluna vulgaris* and *Sphagnum* sp. Although there are some areas of bare peat, most gullies have now revegetated with *Sphagnum* and *Eriophorum*. Thus, most of Moor House NNR now consists of intact, undamaged blanket peat; this is in contrast to the deeper peats of the southern Pennine which have suffered widespread damage and where extensive bare areas remain (Labadz *et al.*, 1991). The Moor House peat typically has a high water table with low fluctuations (above 5 cm depth for 93 % of the year – Evans *et al.*, 1999). Unlike the northern Pennines many Scottish and Canadian blanket peats tend to be mantled with a deep layer of spongy poorly decomposed *Sphagnum*-peat; water table fluctuations tend to be greater in these poorly decomposed peats. Also, hummock-pool topography as found in Newfoundland, the southern Pennines or northern Scotland is not as widespread in the north Pennines. The Moor House peats tend to be deeper than in the thinly mantled peaty podzolic soils of the Welsh uplands but are similar to many of the Irish and Finnish blanket peats. Burke (1975), however, found hydraulic conductivities in the Atlantic blanket peats of Ireland generally an order of magnitude higher than in the north Pennine peats.

Maritime air masses from the North Atlantic dominate the climate at Moor House which has been classified as sub-arctic oceanic (Manley, 1936; 1942). Mean annual rainfall is 1930 mm (Burt *et al.*, 1998a) with an average of 247 precipitation days per year (Smithson, 1985). Precipitation totals are very high even by British standards but can vary considerably from year to year, ranging from 1345 mm in 1971 to 3372 mm in the year 2000. Rainfall intensities in the Pennines are usually low (Figure 1), generated predominantly by frontal and orographic processes. Disregarding possible snowmelt events (when apparently high intensities are recorded due to snow melt in a tipping-bucket rain gauge), there were only five occasions during the 1994-1999 water years (October – September) when more than 10 mm of rain fell in one hour, with a maximum of 11.6 mm hr^{-1}. Data from a rain gauge at the study site were logged every 15 minutes between July 1998 and December 1999. Again, disregarding possible snowmelt events, hourly rates based on the 15-minute totals indicated that a rainfall intensity of 10 mm hr^{-1} was exceeded 18 times and 12 mm hr^{-1} six times. On only two occasions rainfall intensity exceeded 14 mm hr^{-1}. The greatest intensity recorded, equivalent to 38.4 mm hr^{-1}, occurred in a manually recorded five minute period associated with the sighting of a funnel cloud on July 31st 1998 (Webb, 2000). Prolonged dry periods are rare in the Pennines. Between September 1994 and June 2000 the maximum number of consecutive days without precipitation at Moor House was 14 (summer 1995). There were eight periods of ten days without precipitation during the same period and 17 periods of a week or more without recorded precipitation.

Catchment runoff and water table conditions have been gauged on Trout Beck, a 11.4 km^2 tributary of the River Tees within the Moor House Reserve. Work has suggested that the flashy runoff response (with minimal baseflow) is dominated by overland and near-surface flow within the upper few centimetres of the peat; lateral flow at depths greater than 10 cm is very restricted (Burt *et al.*, 1998b; Evans *et al.*, 1999; Holden and Burt, 2000 and Holden, 2000).

Methods used

Rainfall simulator design

A drip-type rainfall simulator as described by Bowyer-Bower and Burt (1989) and Foster *et al.* (2000) was used to provide the rainfall. The principal components are shown in Figure 2. Drops were formed by controlling flow through Tygon tubing of 2.3 mm outside diameter (OD) and 0.7 mm inside diameter (ID) through which was threaded 25 mm long, 0.6 mm OD fishing line. The upper perspex plate contained 627 drop formers arranged in a 19 x 33 matrix. A constant head system of two 25-litre water tanks mounted above the perspex drip-screen was used. A manometer board controlled the rainfall intensity and careful calibration allowed a relationship between head difference and rainfall intensity to be accurately determined. Repetition of the calibration procedure showed that as long as the simulator was kept level, accurate simulations of rainfall intensity could be reproduced ($r^2 = 0.98$). The minimum intensity possible with the simulator was 3 mm hr^{-1}. The simulator was supported by a metal frame with adjustable legs for levelling and adjusting the apparatus to the required distance from the ground (1.8 m).

A wire mesh was hung 200 mm below the perspex plate in order to break up water drops into a distribution of drop sizes closer to that of natural rainfall. The dimensions of the mesh used provide a strong control on the distribution of drop sizes produced.

Following Bowyer-Bower and Burt (1989) a 3 mm square mesh was used. Drop size distribution was measured using the flour pellet method (Laws and Parsons, 1943; Costin and Gilmour, 1970; Cerda, 1998; Erpul, *et al.*, 1998). Around 16,000 drop diameter measurements were taken from a 12 mm hr^{-1} rainfall simulation. The modal drop size was ≤ 0.5 mm, with a D_{50} (the drop diameter at which half the sample by volume is composed of larger drops and half of smaller drops) of 1.5 mm. This compares favourably with natural drop size distributions (Best, 1950); low-intensity rainfall is composed mostly of small drops (Laws and Parsons, 1943). Hudson (1971) discusses the properties of natural rainfall including drop-size distribution and terminal velocity: D_{50} increases from around 1.8 mm at 12.7 mm hr^{-1} to 2.5 mm at intensities greater than 65 mm hr^{-1}. On this basis, the simulator's drop size distribution appears acceptable, given that 34 % of drops were between 1 and 2 mm diameter. The range of terminal velocities was almost entirely between 60 and 90 %, with the D_{50} at around 80 %. A.J. Parsons (pers. comm.) calculated that the mean kinetic energy (KE) of the rainfall produced by the simulator at 12 mm hr^{-1} based on the drop size distribution data was 0.069 J m^{-2} s^{-1}. He calculated a KE of 0.089 J m^{-2} s^{-1} using a simulator of the same design at 25 mm hr^{-1}.

Field methods

The rainfall simulator described above was used to provide the rainfall. The legs were inserted into the peat, with horizontal bars preventing the simulator from sinking further. The drip screen was adjusted so that in each case it was 1.8 m above ground level. On the blanket peat moorlands of the Pennines there tends to be significant air movement even on fine days so a protective polythene sheet was used to minimise air movement below the drop formers. Intensities could be easily varied between 3 mm to 140 mm hr^{-1}. Given the low natural rainfall intensities typical of these moorland areas (see above), 3, 6, 9 and 12 mm hr^{-1} were used.

Wherever possible natural rainwater was used for the experiments as differences in the chemistry of tap water may affect soil erodibility through ionic exchange (Hobbs, 1986; Barton, 1994). Rainwater was collected on the Moor House NNR in a large barrel. Occasionally when this source ran out, or when the study plot was too far from the barrel, stream water from peat catchments was used. This was deemed acceptable given its source and low solute concentration. Stream water was passed through a 63 μm filter before being used in the rainfall simulator.

Testing indicated an approximately uniform distribution of rainfall over the 1 m x 0.5 m plot covered by the simulator. The plot was bounded on three sides by aluminium sheets, inserted to a depth of 20 cm and protruding 10 cm above the surface. At the lower plot boundary a small pit was excavated and three runoff troughs constructed of aluminium inserted against the clean front edge of the plot, being slightly inclined to ensure flow into a collecting vessel. The troughs were inserted at 1 cm, 5 cm and 10 cm below the surface and positioned with great care. This was to ensure that no water emerging from upper collection layers could leak down the face to lower troughs to give a false runoff record and to minimise disturbance of the peat (Bowyer-Bower and Burt, 1989). The upper trough was inserted at 1 cm below the surface because it was found to be very difficult to create suitable contact to collect surface runoff above this depth. Hence infiltration rates are indicative of infiltration to depths greater than 1 cm and any lateral flow within 1 cm of the surface contributes to 'surface runoff'. Runoff was measured manually every five minutes from each layer using volumetric measuring cylinders. Surface runoff from bare peat plots was collected and poured into bottles for storage. The suspended sediment concentration was then measured in the laboratory by vacuum filtration through glass fibre filters retaining particles to 1.2 μm in diameter and oven drying at 105°C within four days of collection. Water tables were monitored in the plots using 20 mm diameter PVC dipwells inserted into the peat. A narrow borehole was created with a screw auger and the tube slotted into position. Measurements were made to the nearest 1 mm using an electronic water level sensor.

The pits dug at the lower plot boundary were shallow (20 cm) but kept drained of water to enable flow collection from the troughs. Monitoring of the water table close to the edge of certain pits did suggest a slight decline in the plot within around 5-10 cm of the edge of the pit. Thus there may have been a small amount of error in throughflow rate measurement during the experiments. As the technique is based upon collecting water seeping from a free face the troughs will collect only saturated throughflow (Atkinson, 1978). This is because water at the free face must be at atmospheric pressure in order to leave the pore space of the soil and flow away. This soil at the face must be saturated. Inevitably, if the soil at the face itself is saturated, a wedge of saturated soil will extend upslope, perhaps into soil which would not normally be saturated had an artificial free face not been constructed. This process helps counteract the effect of lowering of water table at the face of a soil. Furthermore, as the throughflow troughs were inserted 5 cm into the soil face from each pit this would also counteract the effect of lowered water table and artificial saturation. Hence the errors associated with the technique should be minimised.

Six plots for each of the four main surface cover types at the study site were selected (bare peat, *Calluna, Eriophorum,* and *Sphagnum*). Each plot contained at least 90 % of the selected cover and had a slope of between 2^o to 3^o. At each site, rainfall was simulated at four intensities (3, 6, 9 and 12 mm hr^{-1}) with the order of the runs varied so as to randomise the effect of antecedent conditions which might otherwise bias results. Experiments were performed during April and May 1999 and rainfall was simulated on the plots until runoff was produced at a steady rate from the three runoff troughs (often this took 1-2 hours, being longer at intensities of 6 and 3 mm hr^{-1}). The rainfall supply was then stopped and the plot allowed to drain. The plot was left for several hours before the next run began. Runoff from the three layers generally fell to an extremely low rate within 30 minutes of rainfall stopping. Two of the plots for each vegetation type (8 in total) were revisited in August 1999 during a dry period to see if surface desiccation and water table drawdown had any impact on infiltration and runoff processes from the acrotelm. In total, 128 rainfall simulation runs were conducted. This represents a considerable increase in data on infiltration and runoff production processes within blanket peat compared to previous studies.

Calculation of infiltration and runoff rates

Runoff rates were measured as the volume of runoff from the plot per five minutes, and then converted to mm hr^{-1}. Infiltration rates were calculated by subtracting surface runoff rates from rainfall intensity. This neglects any possible influence of evaporation and, more importantly, the effects of surface depression storage and storage on vegetation surfaces. As Slattery (1994) noted there are several difficulties in applying the theoretical infiltration curve of Philip (1957). Here it was found more appropriate to assess final steady-state runoff and infiltration rates as a mean value of the readings taken over a time period when the runoff was considered to be steady. An example is shown in Figure 3 which shows a typical decline in infiltration rate up to about 40 minutes. After 40 minutes there does not appear to be any long-term change in infiltration rate, simply oscillation around a mean value. In such cases the infiltration rate can be considered as effectively constant. Observation of the surface runoff processes suggests that oscillation occurs as a response to waves of water movement linked to surface ponding; episodic cut and fill of micro-topographical features causes water to flow out followed by a period of pool refill and micro-channel change. In a sense, these fluctuations are not a direct response to changes in infiltration rate at the peat surface, but an artefact of the method of data collection. As the last data point may be affected by the oscillation effect, it was felt more appropriate to use the quasi-steady state average rather than apply the Philip equation.

Results and Discussion

Nature and timing of runoff response

The runoff and suspended sediment response from a bare plot with a rainfall intensity of 12 mm hr^{-1} is shown in Figure 4a. At the plot scale, some of the catchment-scale characteristics demonstrated by Evans *et al.* (1999) can be seen. There is a very rapid response to rainfall from all three layers. Only 20 minutes after the onset of rain, runoff response from all three layers rises rapidly. Runoff is greatest near the surface and declines with depth. Steady-state rates of runoff are achieved within 80-100 minutes for all three layers. The recession appears even more rapid than the rising limb for surface runoff, although the hydrographs are fairly symmetrical in appearance. Surface runoff recession is also faster and more dramatic than at depth. This is a result of continued percolation of water into the peat mass from the surface depression storage after rainfall input has ceased. The drainage of the lower layers slows once the excess water has drained from above.

On average, for all runs, steady-state runoff is reached in 59 minutes, but steady-state is achieved more rapidly at higher intensities (Table 2). The time to steady-state is about the same for all soil layers which suggests that there is a close connection between the layers. The time to maximum ponding (and surface flow) and hence the development of saturation-excess overland flow coincides with the saturation of the surface layers.

Figure 4b plots water table depth during the 12 mm hr^{-1} rainfall simulation run shown in Figure 4a. The water table responds rapidly to rainfall suggesting that infiltration rates can be high when the peat is not saturated to the surface and when water tables are shallow. Overland flow is only recorded once the water table has reached the surface. Importantly, only four of the rainfall simulator plots produced overland flow when the water table was below the surface. This suggests that overland flow generation occurs as a result of saturation of the peat rather than through Hortonian infiltration-excess mechanisms. Non-uniformity of plot surfaces (e.g. ponding in depressions when the peat surface at the dipwell location in the plot was above the level of the depression) may explain the four exceptions. Furthermore, in these four cases, the water table was within 10 mm of the surface when overland flow began.

Infiltration rates

Mean steady-state infiltration rates for each intensity of rainfall are shown in Table 3. Infiltration rates are low but increase with rainfall intensity. Some runs produced no surface runoff as the infiltration rate was greater than the application rate for these tests. Nevertheless, for most runs, overland flow was produced even at low rainfall intensities. Thus overland flow can develop at low rainfall intensities even on vegetated blanket peat. These infiltration rates are generally lower than those recorded by Labadz (see Table 1); however, given the tendency for infiltration rates to increase with rainfall intensity, any comparison must be qualified with respect to rainfall intensity data. Figure 5 shows how mean steady-state infiltration rates vary with intensity for each vegetation type. For lower intensities, mean rates of infiltration into bare peat are slightly greater than for vegetated mire. At the 9 and 12 mm hr^{-1} intensities, the infiltration capacity of bare peat is slightly less than for *Eriophorum* or *Calluna* surfaces. However, there is little overall difference in rates between an *Eriophorum*- or *Calluna*-covered surface and a bare surface. Mean infiltration rates into peat below a *Sphagnum* cover appears to be lower than for other vegetation types, which may relate to the types of peat which form beneath different vegetation covers.

Significance of rainfall intensity, vegetation cover and peat depth on runoff production

Runoff was collected from the surface layer and at 5 cm and 10 cm depth from all plots. These data have been combined for subsequent analysis. Data for runoff rates from all layers at different intensities are highly variable and positively skewed, ranging from 0 to 9.99 mm hr^{-1} with a mean of 1.77 mm hr^{-1} and a skewness of 1.49. Given this last result, it is not surprising that the variance within subsamples defined by depth, vegetation and rainfall intensity categories is not even roughly uniform, as required for application of ANOVA. The square roots of runoff rates are less skewed with a range from 0 to 3.16 $\sqrt{(mm\ hr^{-1})}$, a mean of 1.05 $\sqrt{(mm\ hr^{-1})}$ and a skewness of 0.35. More importantly, variances for the depth, vegetation and intensity categories are now nearly equal. The ANOVA results (Table 4) show that the depth and intensity controls are overwhelmingly significant as the calculated significance levels are less than 0.00005. Hence, both controls can be regarded as genuinely influencing runoff rates. Runoff significantly decreases with depth and increases with intensity. As suspected during examination of infiltration rates above, surface cover is of some importance to the model but its influence is not as strong as depth and rainfall intensity controls.

A similar data transformation was required for comparison of runoff efficiency data. For the purpose of the present study runoff efficiency has been defined as the proportion of rainfall received at the ground surface that is being generated as runoff by each soil layer. Here raw data ranges from 0 to 85.3 % with a mean of 23.2 % and a skewness of 0.78. After transformation, skewness was –0.01 with a mean of 3.90 √ %, and values ranging from 0 to 9.24 √ %. Again, variability with depth, vegetation and intensity categories is now similar. ANOVA indicates that for runoff efficiency, of the three controls, only depth can be accepted as a major factor (Table 5). Rainfall intensity can be disregarded as a control on efficiency and vegetation cover is of limited importance, although it can again be argued that some influence has been identified. Results from ANOVA have allowed the significance of rainfall intensity, peat depth and surface cover in controlling runoff production to be established. Discussion will now focus on the significance and role of each controlling variable.

Rainfall intensity control

Table 5 shows that rainfall intensity exerts very little influence on runoff production volume as a proportion of incoming rainfall. This is probably a reflection of saturation-excess runoff development since this can occur at much lower rainfall intensities than is required for infiltration-excess overland flow (Burt, 1996). Thus, if the peat becomes saturated to the surface even under low-intensity rainfall, then overland flow is likely to be produced no matter what the rainfall intensity is, as long as there is enough water supply to keep the peat saturated. The rainfall simulator results suggest that blanket peat runoff production is just as efficient for low-intensity as high-intensity storms. This evidence corroborates catchment-scale work at Moor House where all rainfall events with intensities greater than about 1-2 mm hr^{-1} produce an efficient runoff response with a steep rising hydrograph (Evans *et al.*, 1999). Given that infiltration rates also increase with intensity, this suggests that a mechanism operates by which a similar proportion of rainfall can infiltrate into the peat, to some extent independent of intensity (over a 2 mm hr^{-1} threshold).

Since most rainfall simulation studies use only one intensity of rainfall there are few reports of relationships between rainfall intensity and infiltration. In semi-arid soils the greater energy of high-intensity rainfall disrupting the soil crust in response to wetting, so that finer material produced by slaking and splash is kept in suspension instead of blocking pores has been cited as potential mechanism for increasing infiltration rates

(Bowyer-Bower, 1993). Kneale and White (1984) found that the proportion of applied water emerging from the soil as bypassing flow increased from 0 to 55 % as water application rates onto a clay-loam grassland increased from 2.2 to 21.2 mm hr^{-1}. The depth of surface ponding is likely to be important on blanket peat. Higher rainfall intensities tended to induce a greater depth of ponding, and thus an increased head of water and a resultant increase in percolation rates and subsurface runoff (Schiff, 1953). Philip (1958) found infiltration rates increased by 2 % for every extra centimetre of ponded water on a light clay soil. This is a relatively small amount but importantly the effect was predicted to be greater in wetter and non-homogenous soils. No work of this type has been done on peats and, because the infiltration models are based on infiltration into unsaturated homogenous soils, it is difficult to establish how important ponding depth may be on blanket peat without field experimentation. Observation showed that ponding across the surface of bare peat was not always uniform or widespread and often only occurred locally in depressions. The non-uniform nature of a soil over a $0.5m^2$ plot may result in the surface of one part of the plot having a higher infiltration capacity than the rest of the plot. Therefore, as Hawkins (1982) demonstrated numerically, mean infiltration rate over a plot will increase with rainfall intensity simply because a greater flux of water is occurring through the parts of the plot surface that have the higher relative infiltration capacities. In other words it must be acknowledged that only a fraction of the area within small plots need contribute to overland flow and that infiltration rates are being calculated as a plot mean value.

Depth control

Mean steady-state runoff rates from all three runoff-collecting troughs are shown in Figure 6. Standard deviations indicate the variability within the dataset. There is a large amount of overlap but ANOVA (see above) demonstrated that the differences were significant. The greater the rainfall intensity, the higher the overland flow runoff. Lateral flow between 5-10 cm depth accounts for only 7.2 % to 13.0 % of incident rainfall volume (depending on intensity), compared with 21.7 % to 25.5 % from the peat layers between 1-5 cm depth and 31.6 % to 40.8 % at the surface. Mean runoff significantly increases in all layers with increasing rainfall intensity, a result of increased infiltration followed by enhanced lateral flow. For the 5-10 cm layer, the gradient of the rise in runoff with intensity is significantly less than for the overlying layers (U test, $p<0.0005$). Mann-Whitney U test results indicate that the gradient of the rise in runoff with intensity is significantly greater at the surface than for the 5 cm layer ($p = 0.002$) which also significantly greater than the gradient for the 10 cm layer ($p = 0.001$). This is obviously linked to the larger proportion of overland flow occurring, but may also be to some extent a reflection of a limited capacity for lateral flow within this layer restricted by a lower hydraulic conductivity and reduced percolation rates.

Surface cover control

ANOVA demonstrated that there was a minor vegetational control on runoff generation. It is not necessarily surface cover that is the control; rather the surface cover is indicative of the properties of the peat below that cover. It is well known that particular vegetation types prefer different water table conditions, with height and fluctuations being important for example (Ingram, 1983). Furthermore, the vegetation may interact with the peat structure by rooting, litter deposition and building up of the peat deposit.

Figure 7 provides further information on the role of surface cover in controlling runoff production. Standard deviations are included in an inserted table. For *Eriophorum*-covered peat, the mean runoff at 1-5 cm depth is just as great as that at the surface, but between 5-10 cm only 1.2 % of the rainfall input is collected as throughflow from this layer. So peat below *Eriophorum* clearly allows rapid flow within the top 5 cm but below this layer very little lateral flow occurs at all. This is similar to the findings of Labadz (1988): on the one *Eriophorum*-covered plot throughflow was rapid just below the peat surface. Unlike Labadz's results, however, the results presented here indicate that *Eriophorum* peat is capable of producing overland flow as well as near-surface flow. There may be some difficulties in comparing data sets due to different definitions of the peat surface. For the present data the surface is defined as the first centimetre of intact peat and any very loose leaf litter layer is not considered as the peat 'surface', although often the distinction is very difficult owing to the partially living nature of the upper peat profile. Ingram and Bragg (1984) suggest that the acrotelm itself possesses the essential characteristics of a layer which suppresses sheet flow. At the same time results from the rainfall simulator tests presented here show that widespread overland flow does occur on vegetated peat hillslopes often to depths of more than 1 cm. Not only will definitions of the surface vary but it is also likely that acrotelms of different natures, and hence different surface properties, exist and are distributed throughout the areas of study described in the literature and indeed throughout small catchments. Ingram and Bragg (1984), for example, view the acrotelm as comprising poorly-decomposed, high hydraulic conductivity, *Sphagnum* peat often 50 cm thick. Such an acrotelm is uncommon at Moor House except in localised flushes or hollows. Hence the nature of the peat surface and upper peat layers are likely to be very important factors in determining runoff production processes within blanket peatlands.

At Moor House for vegetated surfaces runoff decreases with depth, but for bare peat the mean proportion of runoff between 5-10 cm is 8.0 % greater than that between 1-5 cm and only 2.4 % less than surface runoff. Bare peat therefore plots differently on Figure 7 from vegetated peats at depth. This may be related to desiccation: drying of an unprotected peat surface may lead to the development of a more permeable upper peat mass and any such effect is reduced with depth. Percolation-excess is again evident at 10 cm depth such that lateral flow occurs more readily at this level. Ingram and Bragg (1984) noted that on a bare peat surface where there is downwasting and removal of the acrotelm, the result is a mire with restricted infiltration leading to enhancement of sheet flow on the surface. Results presented here, however, indicate that bare peat has equivalent infiltration rates to those of vegetated peat. In this way a dynamic feedback mechanism may operate because the peat itself changes its hydraulic properties as the emerging bare surface becomes susceptible to drying or frost heave, and to aeration. Hence, the bare peat surface degrades and allows infiltration to take place, such that the near-surface peat that was once the catotelm now in effect becomes a thin acrotelm. More work is required to examine this possible mechanism. An indication that the surface properties of the bare peat are very different from that of the peat below comes from an analysis of the dry bulk density (DBD) of bare peat with depth (Figure 8). The top 10 cm of bare peat has a much lower DBD than the peat below, with a sharp transition after about 10 cm to a much denser peat. As well as desiccation of the surface, erosion may lead to reworking of the surface peat, probably through a mixture of water and wind-driven mechanisms, such that the top layer of peat may in certain locations contain a depth of unconsolidated deposited peat. In this case it is likely that bulk densities are decreased and this will allow increased infiltration to a shallow depth just below the reworked layer where lateral runoff can take place. For *Eriophorum*-covered peat DBD increases gradually with depth and is lower than that of the bare peat. The bare peat was more humified near the surface (H7 on Von Post, 1922 scale) than peat below *Eriophorum* (H1-H3). The emergent and weathered bare peat surface, having lost peat from above, was formerly at a greater soil profile depth and was therefore older than the recently generated and less humified vegetated surface peat.

Effect of summer desiccation on runoff processes

Part of this study involved looking at the effect of warm, dry periods on blanket peat during the summer of 1999. Out of the 24 plots examined in the spring, 8 were revisited during a warm dry period of the summer, two from each of the original surface cover types. It is unusual in the blanket peat catchments of the North Pennines to experience periods of more than 10 days without rain which coincide with warm weather (see above). Figure 9 illustrates the dry bulb air temperature and rainfall characteristics for July and August 1999 (Julian day 183-242). Only 19.2 mm of precipitation occurred between day 203 and 225, with only 0.2 mm of precipitation between day 186 and 195 and none between 206 and 216. Total precipitation for June, July and August 1999 was 294.8 mm, which compares with the mean for this time of year of 384.7 mm (mean at Moor House since 1953). Daytime temperatures were frequently above 20 ^{o}C. During this dry, warm period, cracking on the surface of bare peat was observed. Maximum crack widths and depths (up to 28 mm and 145 mm respectively) occurred on Julian day 214, after 10 days without rain and when summer temperatures were at a maximum. The surface took many months to recover, with cracks still evident in late summer. The cracks usually filled with re-deposited material rather than closing up by complete re-swelling of peat. Rainfall simulation plots were revisited from Julian day 209-216 during the height of the surface desiccation period.

Paired T-tests demonstrate that there is a significant difference between the runoff production in the plots during the original runs in the spring and the runs during the summer period ($n = 96$, $t = 2.03$, $p < 0.03$). However, for *Sphagnum*-covered plots there was no change in the runoff production rates. The *Sphagnum* cover may protect the surface from damage. Furthermore, because *Sphagnum* species tend to grow in wetter areas which have higher water tables, such as in topographical hollows which are very poorly drained, these areas may be less likely to become dry, unless the drought is very severe. For the other plots infiltration rates are greatly increased for all intensities such that surface runoff is reduced in the summer test. An example is shown in Figure 10 where, for a *Calluna*-covered plot, surface runoff is reduced and lateral flow from the 5 cm trough is greater as a result. It may be that both matrix and macropore flow increased within the acrotelm as evidenced by the increasing fluxes measured from the 5 cm layer during the summer tests. On bare peat where flow through the desiccation cracks was visible, some absorption into the peat was noticed before any runoff occurred. This was followed by a period of ponding in depressions on surface crusted sections. The ponds then overflowed into cracks to be channelled away. Eventually, the cracks themselves filled with water as flow capacities were exceeded and as some blockage by sediment and perhaps some re-swelling occurred. Only at this stage could overland flow be collected from the runoff trough. In some plots, the total steady-state runoff collected from the upper 10 cm was reduced such that more runoff was being produced from the lower layers of blanket peat.

Sediment movement

Results from spring 1999 indicated that rain splash was an important agent of disturbance and entrainment on bare peat as particles were often splashed up to the top of the plot boundary boards (10 cm in height) and up to 15 cm against the rainfall simulator legs and on the internal sides of the wind proofing around the plot. Suspended sediment concentration was measured during the 24 spring experiments on bare peat. The sudden decline in sediment concentration coinciding with rainfall cessation (Figure 4a) provides evidence for the strong erosional role of rain splash. As runoff decreases rapidly after rainfall cessation the effect is combined with transport-limiting flow reduction. This is similar to the findings of De Ploey (1984) who worked on loess loamy soils. Surface wash was observed to be the main agent of transport with individual particles and fibres of peat easily observed moving in micro-rills. Sediment supply to the runoff troughs oscillated in relation to micro-pool and micro-rill, cut and fill processes. The supply of available sediment was, in most cases, found to be limited as concentrations decreased during a run, very quickly at first, and more slowly later, typically producing clockwise hysterisis loops. This effect may in part be related to the development of a pool of surface water which attenuates the erosive power of rain

(Klove, 1998). The trends in sediment concentration during the runs are similar to those reported by Klove (1998) who examined a degraded mined peat surface in Finland.

Peak sediment concentrations were generally recorded during the rising limb of surface hydrographs (Table 6; mean concentrations also shown). Values of peak concentration of sediment were between 33 and 3852 mg l^{-1}, generally increasing with intensity on a particular plot. These values are somewhat lower than those found by Labadz (1988) who found peak values ranging from 947 to 9110 mg l^{-1}. However, Labadz used very high intensities (39 to 92 mm hr^{-1}) and hence a greater total raindrop impact energy would have been supplied to the peat surface allowing increased detachment and entrainment.

Bare peat areas are frequently surrounded by vegetation, such that sediment may become trapped, so that sediment yield measured at a particular outlet is therefore a result of differential production, storage and deposition within the catchment (Walling, 1983). For the Rough Sike catchment, (a tributary of Trout Beck), within which many of the rainfall simulator tests were performed, Crisp (1966) estimated an annual sediment yield of 93 tonnes with an estimate of about 10-20 % of the catchment as eroding. The eroding peat is concentrated in gullies corresponding to Bower's (1960) late stage of development. Re-instrumentation of Crisp's weir has shown that most of the peak sediment concentrations occur on the rising limb of the hydrographs (Burt *et al.*, 1998c). This is indicative of sediment exhaustion whereby the supply of readily mobilised material is quickly depleted (Webb and Walling, 1984). The rainfall plot studies reflect these catchment-scale effects. Peak suspended sediment concentrations from the catchment outlet were found to be around 50-60 mg l^{-1} (Evans and Burt, 1998) with peat fans at the end of gully networks reducing direct peat supply from the eroding source areas to the main channel. The rainfall simulator tests were, of course, performed on isolated plots. On a hillslope, sediment will be transported, deposited and stored several times and supply of sediment from upslope will be an important feature. The mean concentrations of suspended sediment produced on bare peat plots indicate that loads are spatially highly variable. Over the 3-12 mm hr^{-1} range the mean suspended sediment concentration was 224 mg l^{-1}. The very low density of the peat (0.1 g cm^{-1} compared to 1.2 g cm^{-1} for mineral soil peds and aggregates and 2.6 g cm^{-1} for typical quartz grains) means that this represents a significant volumetric load (Burt *et al.*, 1997).

Burt and Gardiner (1984) note the importance of desiccation in creating a peat surface that can provide high sediment supply. Because of this, sediment loading may vary with aspect (Bower, 1959; Francis, 1990) and with season (Tallis, 1973; Francis, 1990). It is possible that results reported here are at the lower end of the scale when winter frost activity has been reduced and before summer desiccation has occurred. Observations of weir pools on the Moor House NNR indicate that maximum supply of eroded material to streams occurs in early spring due to frost action; the weir pools had to be cleared of sediment frequently during the spring but very infrequently at other times of the year. Tallis (1973) showed that substantial peat erosion occured during snowmelt and during heavy rain, when stream flow rates were high. Francis (1990), however, found that peat supply to streams was much greater in the autumn and early winter; the suggestion was that summer desiccation had prepared the peat for removal, but as the winter progressed sediment exhaustion occurred and frost action was of minimal importance. The two opposing results may be related to sediment storage and release mechanisms, and to the nature of the coupling between bare peat areas and streams in the area of study. It can also be noted that the sediment peaks found by Francis (1990) were for late autumn and early winter of 1983 and 1984; both years were atypically dry years.

Sediment loading from the two bare simulator plots revisited during summer 1999 was lower during the summer runs (Table 6). It is possible that the summer crusting of the surface prevents removal of sediment in the first instance, but as wetting-up occurs, and significant ponding and runoff begin to disturb the crust, then more sediment erosion can occur. For the summer runs, peak sediment concentrations were coincident with peak runoff; the sediment supply now appears to be transport limited, whereas during the spring sediment delivery was supply limited.

Conclusions

The use of low-intensity rainfall has allowed a more realistic evaluation of infiltration rates and flow processes than previous studies. The rainfall simulation experiments on blanket peat have suggested that infiltration rate increases with rainfall intensity. Small-scale spatial variation within plots, as well as surface ponding depth, are likely to be the main reasons for this. This has important implications for inferences drawn from infiltrometers and simulators alike. Ring infiltrometer tests do not provide adequate information on typical infiltration rates in blanket peat because they are not dependent on any rainfall intensity control and operate by imposing a constant-head of water on the peat surface. Inferences from rainfall simulation experiments with very high rainfall rates may also provide inadequate information since they must be intensity specific. These factors are often ignored by workers using rainfall simulators and too frequently results are presented from experiments using unrealistically high intensities. Results drawn from a single rainfall intensity may well be specific to that intensity and not necessarily general.

The rainfall simulator results have shown overland flow development on vegetated and bare peat surfaces over the 3–12 mm hr^{-1} rainfall intensity test range. This could suggest that blanket-peat infiltration rates are low. However, the work has demonstrated that low steady-state infiltration capacities are not due to inherently low surface permeability but are more to do with low percolation rates below the surface resulting in saturation of the near-surface layers. Water tables in the plots were rarely below the surface when overland flow was produced. This therefore corroborates the results of Holden *et al.* (2001) who demonstrated through use of a tension infiltrometer that infiltration-excess overland flow was likely to be a rare occurrence in blanket peat catchments. Runoff production decreases rapidly with peat depth and not much vertical percolation takes place to depths greater than 10 cm such that most of the runoff production is within the upper layers of blanket peat. Overland flow occurs readily on both vegetated and bare peat surfaces. Thus, the low infiltration rates measured using the rainfall simulator are a result of surface saturation of the peat and saturation-excess overland flow can develop even during very low-intensity rainfall simply because the peat is saturated. Overland flow is therefore rapidly generated and storm runoff efficiently produced in blanket peat catchments; this helps to explain why catchment-scale storm response is extremely flashy even during low-intensity rainfall events.

From bare peat plots, sediment loading tends to be supply limited. Seasonality may affect this relationship such that after a warm dry spell, surface desiccation allows sediment supply to become transport limited. Much more work is required on linking process mechanisms and rates of erosion in blanket peat areas. Rainfall-runoff response at the plot-scale may also vary with season. Where any change occurred, rainfall more readily infiltrated into the peat during the summer tests, than during spring. This suggests that less overland flow may be expected after warm dry spells. Not only is this related to a lower water table and water table recharge in the first instance, but as these tests ran to steady-state such that the water table had time to rise, the evidence suggests that alteration in hydrological properties of the peat at and near the surface has occurred. Klove (1998) used high-intensity rainfall simulation (35 – 260 mm hr^{-1}) using a spray nozzle on large 100 m^2 plots of heavily disturbed (mined) peat in Finland. Work concentrated on sediment erosion processes but overland flow was often found not to occur below rainfall intensities of 30 mm hr^{-1}. This peat surface would have been heavily disturbed and this result probably represents the important effect of changing environmental conditions on runoff generation in peatlands. The effect of vegetation removal and of exposing peat more readily to the processes of surface desiccation is to increase infiltration rates and promote lateral subsurface flow. When peat dries its structure is permanently altered such that it becomes hydrophobic (Egglesmann *et al.,* 1993). It is not known how much permanent change can occur due to droughts on bare and vegetated peat hillslopes and what effect this will have on hydrological flow pathways, hydrochemical processes, ecological processes and erosion. With an increasing number of hot dry summers predicted for many upland blanket bog areas

(Marsh and Sanderson, 1997), peat desiccation may increase and more work is required to establish possible catchment-scale effects.

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Table 1. Mean, maximum and minimum measured infiltration capacities, mm hr^{-1}, of blanket peat; data from Gardiner (1983) and Labadz (1988).

Gardiner (1983)
single-ring constant-head infiltrometer – 20 measurements

	Eriophorum	Empetrum hummocks
Mean	2.1	28.7
Maximum	8.3	100.0
Minimum	0.0	9.2
n	10	10

Labadz (1988)
rainfall simulation – intensities from 39 to 96 mm hr^{-1} on 5 0.25 m^2 plots, short duration.

	1 Eriophorum plot	4 bare peat plots
Mean		
Maximum	No OLF produced	17.7*
Minimum	90.0+	52.5
n	-	3.0
	4	8

* five of these measurements where in the range 7.3 – 6.8 mm hr^{-1}

Table 2. Means ($\bar{x}$), standard deviations (σ) and number of runs (n) in each case of time to steady-state runoff production from the rainfall simulation plots, minutes

depth, cm		rainfall intensity, mm hr^{-1}				
		3	6	9	12	mean 3 to 12
0	$\bar{x}$	70	76	50	45	60
	σ	24	19	20	40	34
	n	21	22	22	23	88
5	$\bar{x}$	67	74	49	40	58
	σ	29	18	17	26	31
	n	21	21	21	21	84
10	$\bar{x}$	57	81	45	50	58
	σ	30	26	21	48	38
	n	13	13	14	15	55
mean	$\bar{x}$	69	77	49	45	59
0 to 10	σ	24	25	34	30	34
	n	55	56	57	59	227

Table 3. Mean and standard deviations (in brackets) for infiltration rate, mm hr $^{-1}$ and runoff rate for field rainfall simulation experiments, Spring 1999.

Intensity, mm hr^{-1}	3	6	9	12
Mean infiltration rate at steady-state, mm hr^{-1}	2.04 (0.73)	4.02 (1.21)	5.51 (1.78)	7.02 (2.42)
Minimum infiltration rate at steady-state, mm hr^{-1}	0.89	1.31	2.40	3.52
Mean % of applied rainfall infiltrating at steady-state	67.94 (24.35)	67.02 (20.19)	61.22 (19.83)	58.51 (20.21)
Mean % overland flow rates at steady-state	32.06	32.98	38.78	41.49
Number of runs with no overland flow	3	3	2	1

n = 24 for each intensity

Table 4. Analysis of variance of steady-state runoff rates from bounded rainfall simulator plots, square root data.

Source	d.f.	F	Prob > F
Model	8	21.84	0.0000
Depth	2	54.40	0.0000
Intensity	3	19.44	0.0000
Vegetation cover	3	2.49	0.0600

$R^2 = 0.39$

Table 5. Analysis of variance of percent runoff at steady state as a proportion of incident rainfall from bounded rainfall simulator plots, square root data.

Source	d.f.	F	Prob > F
Model	8	14.15	0.0000
Depth	2	52.10	0.0000
Intensity	3	0.48	0.6960
Vegetation cover	3	2.52	0.0590

$R^2 = 0.29$

Table 6. Mean and peak suspended sediment concentrations from unvegetated rainfall simulation plots, spring and summer 1999.

Plot	Intensity	Infiltration rate	Time of run, mins	Mean sediment concentration, mg l^{-1}	Peak sediment concentration, mg l^{-1}
1	3	2.71	55	61.13	98.5
	6	5.18	50	72.75	111.4
	9	7.48	50	39.25	149.2
	12*	8.51	100	73.58	210.5
2	3*	2.03	150	23.34	50.1
	6	3.94	90	43.21	77.5
	9	5.88	90	36.67	90.1
	12	6.76	90	47.65	100.9
3	3	2.57	90	21.43	33.4
	6*	2.82	125	32.13	70.7
	9	5.56	90	36.43	100.2
	12	7.45	140	53.28	232.0
4	3	2.15	50	204.62	635.1
	6	5.14	95	226.82	1028.6
	9*	6.08	55	1220.24	2096.1
	12	7.31	75	2377.48	3852.5
5	3	3.00	180		
	6	5.02	250	84.34	156.3
	9	2.40	200	99.85	301.2
	12*	4.40	100	149.65	555.4
6	3	2.98	180	45.12	67.2
	6*	4.70	85	72.12	111.2
	9	5.70	75	56.43	145.2
	12	7.98	120	71.22	189.4
2a	3	1.02	240		
	6	3.13	200	17.2	26.3
	9*	5.64	140	24.2	45.1
	12	8.58	120	32.4	67.2
5a	3	2.93	150		
	6	5.79	150	8.5	14.3
	9	8.03	150	15.6	23.4
	12*	10.80	160	17.3	23.5

* = first run on the plot
a = summer run

Figure captions

Figure 1. Relative frequency of hourly rainfall intensities recorded at Moor House, 1994-1999 water years.

Figure 2. Design of the rainfall simulator used in the study a) main frame components, b) drop former.

Figure 3. Comparison of infiltration rate determination over time with actual values, fitted Philip curve and mean quasi-steady value.

Figure 4. Plot response to rainfall simulation during a 12 mm hr^{-1} experiment on a bare field plot. a) Runoff production, infiltration and suspended sediment concentration, b) water table fluctuations.

Figure 5. Mean infiltration rate against rainfall intensity for surface cover types on field plots exposed to rainfall simulation.

Figure 6. Mean steady-state runoff from field plots by depth against rainfall intensity. Plus and minus one standard deviation from the mean indicated by the error bars.

Figure 7. Proportion of input rainfall produced as runoff by depth for surface cover type.

Figure 8. Variation in dry bulk density with depth below an *Eriophorum* cover and a bare peat surface.

Figure 9. Dry bulb air temperature and precipitation recorded at Moor House, July and August 1999.

Figure 10. Steady-state runoff by rainfall intensity for a *Calluna* dominated plot visited during spring and summer 1999. a) surface runoff, b) runoff from the 5 cm trough, c) runoff from the 10 cm trough. Full trendlines = spring 1999, dotted trendlines = summer 1999.

Figure 1

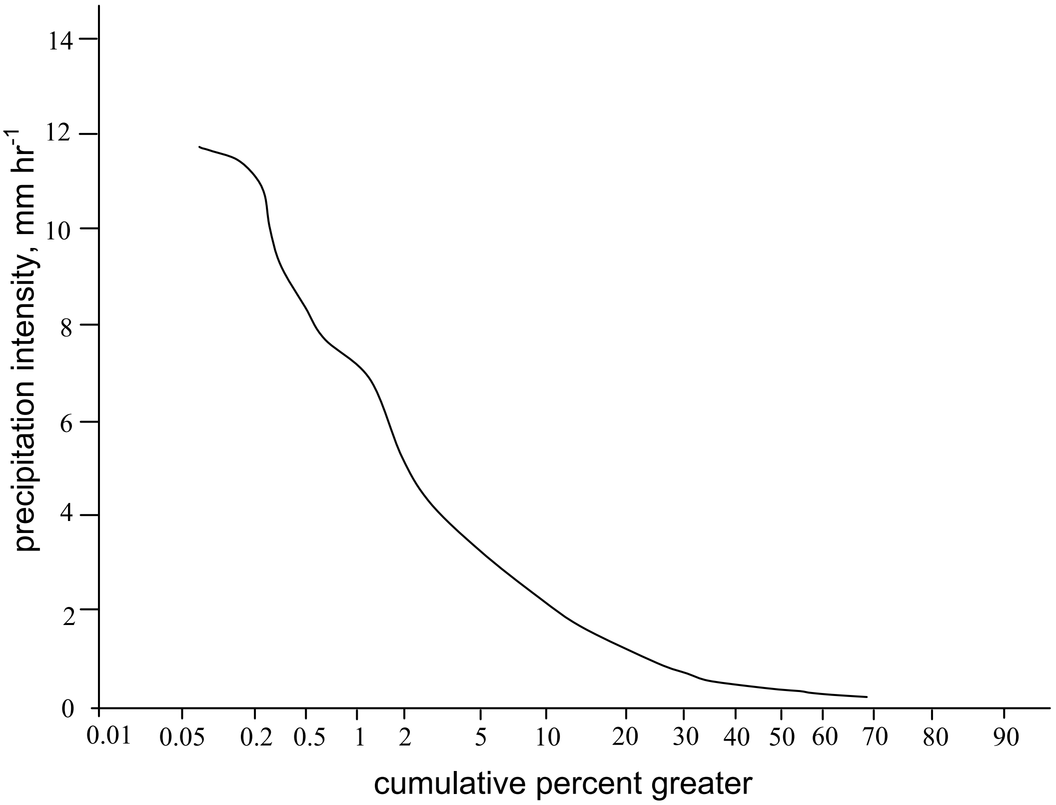

precipitation intensity, mm hr^{-1}
14
12
10
8
6
4
2
0
0.01
0.05
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
cumulative percent greater

Figure 2.

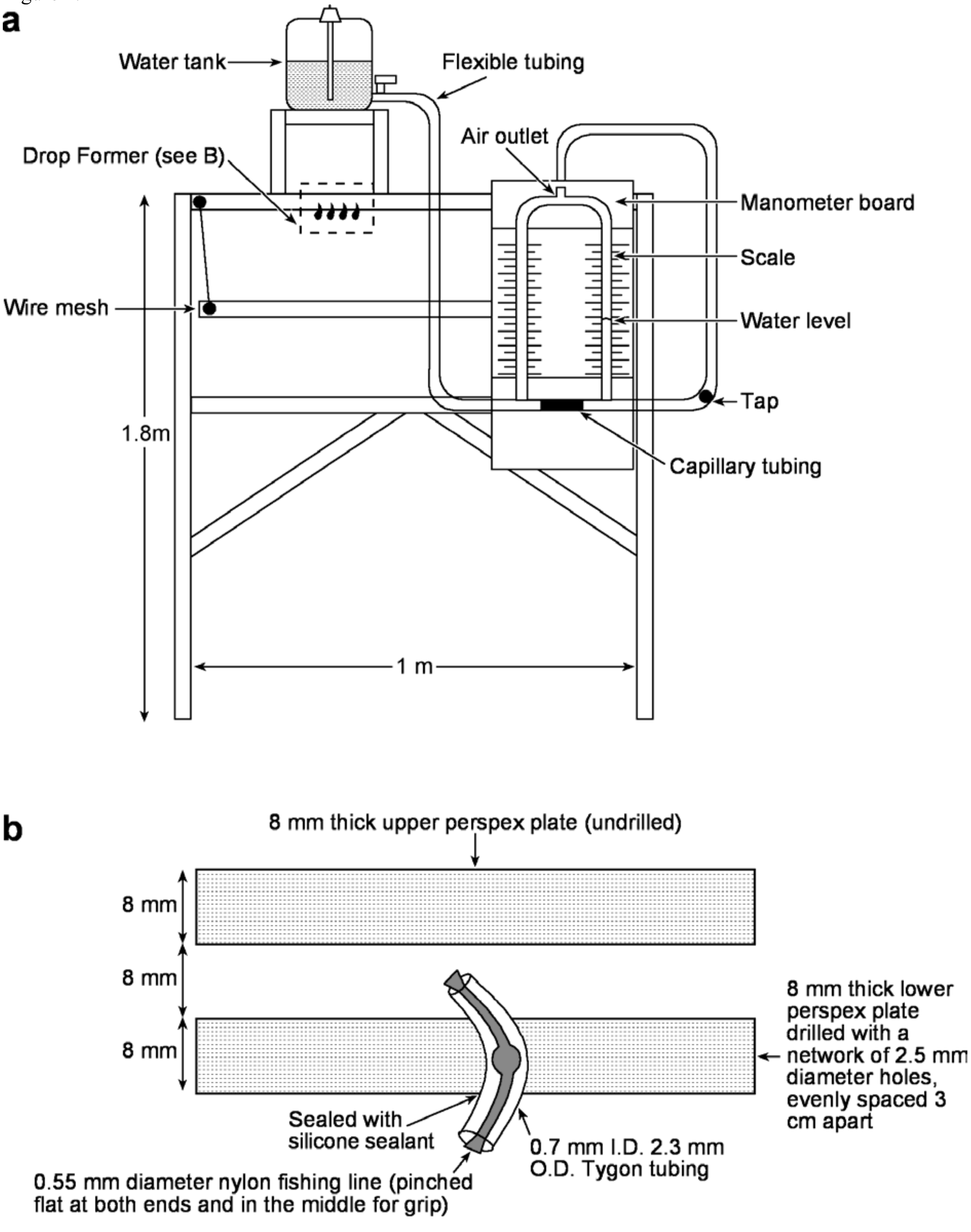
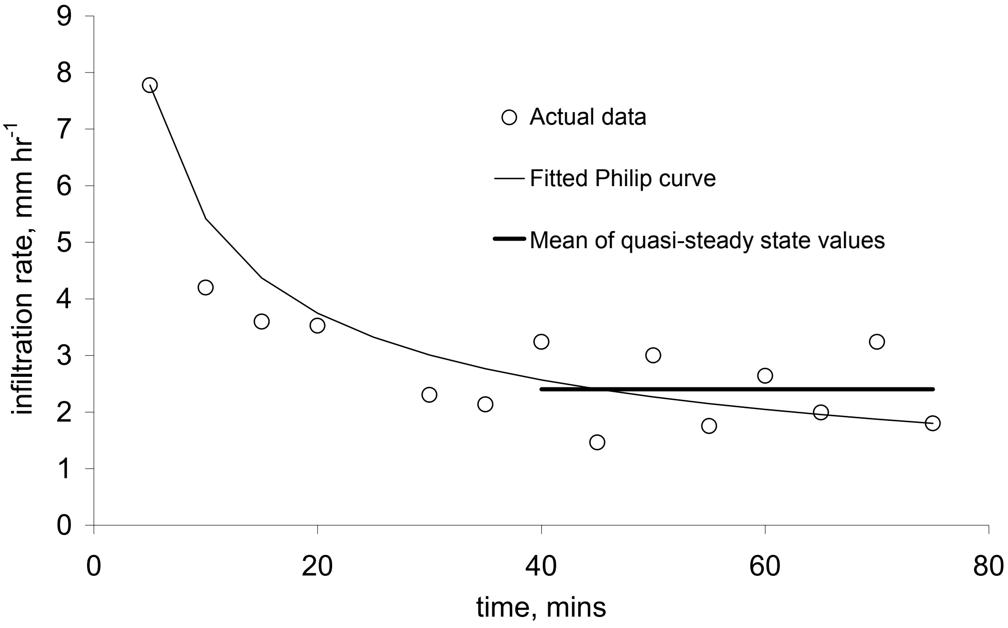

a
Water tank
Flexible tubing
Air outlet
Drop Former (see B)
Manometer board
Scale
Wire mesh
Water level
Tap
1.8m
Capillary tubing
1 m
b
8 mm thick upper perspex plate (undrilled)
8 mm
8 mm
8 mm
8 mm thick lower perspex plate drilled with a network of 2.5 mm diameter holes, evenly spaced 3 cm apart
Sealed with silicone sealant
0.7 mm I.D. 2.3 mm O.D. Tygon tubing
0.55 mm diameter nylon fishing line (pinched flat at both ends and in the middle for grip)

Figure 3



9
8
7
6
5
4
3
2
1
0
infiltration rate, mm hr^{-1}
0
20
40
60
80
time, mins
○ Actual data
— Fitted Philip curve
▬ Mean of quasi-steady state values

Figure 4.

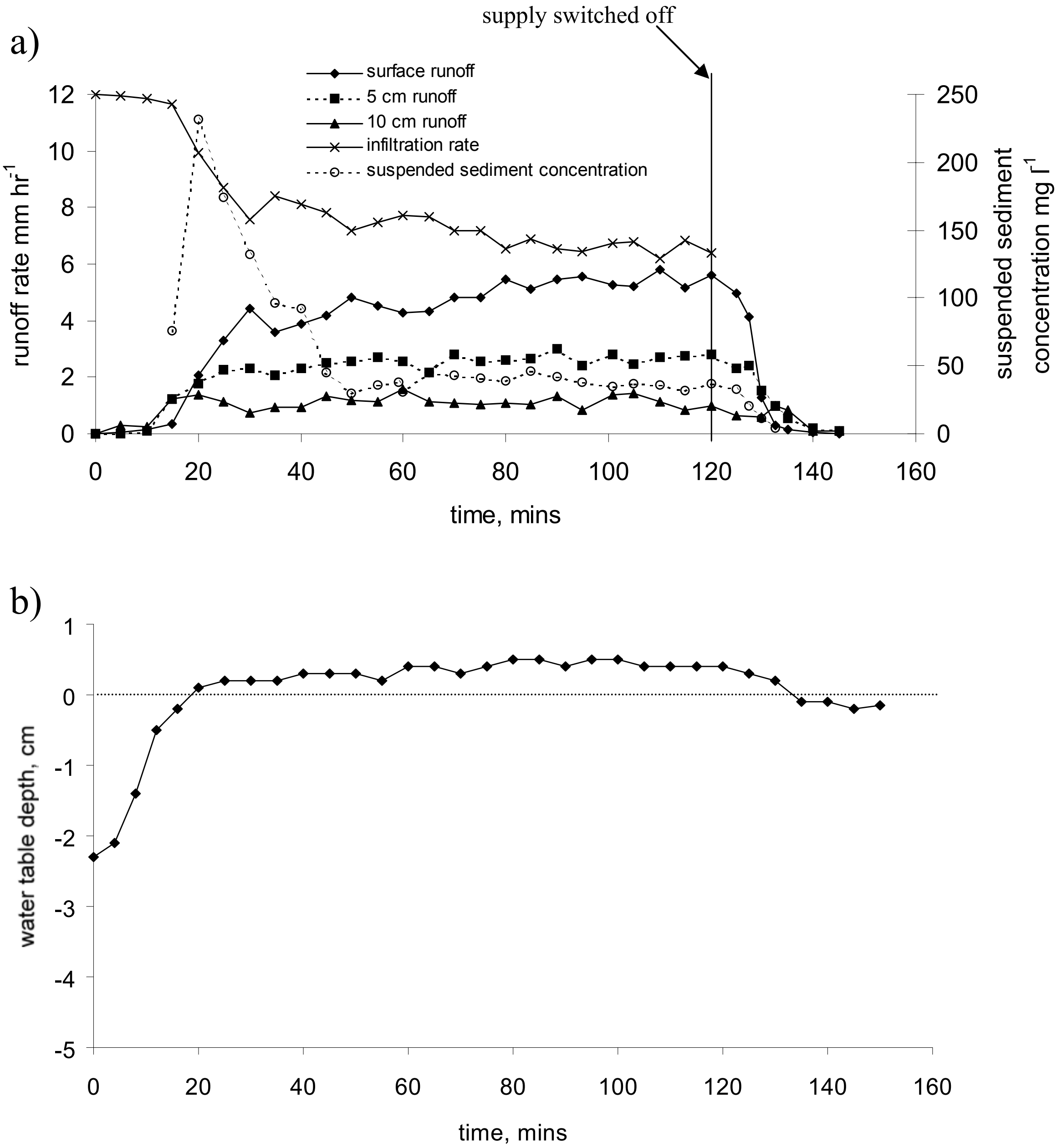

a)
supply switched off
surface runoff
5 cm runoff
10 cm runoff
infiltration rate
suspended sediment concentration
runoff rate mm hr^{-1}
suspended sediment concentration mg l^{-1}
0
2
4
6
8
10
12
0
50
100
150
200
250
0
20
40
60
80
100
120
140
160
time, mins
b)
water table depth, cm
1
0
-1
-2
-3
-4
-5
0
20
40
60
80
100
120
140
160
time, mins

Figure 5.

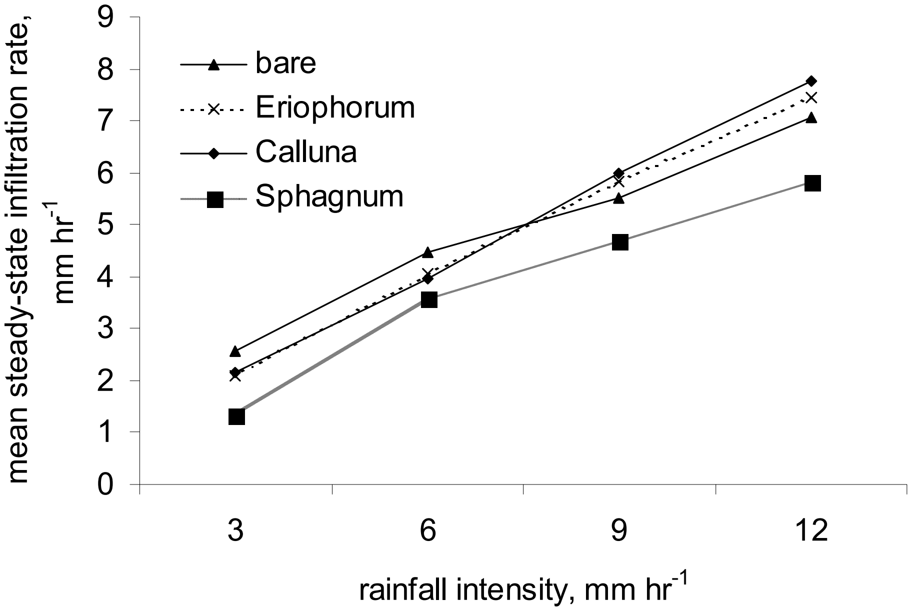

mean steady-state infiltration rate, mm hr^{-1}
9
8
7
6
5
4
3
2
1
0
3
6
9
12
rainfall intensity, mm hr^{-1}
bare
Eriophorum
Calluna
Sphagnum

Figure 6.

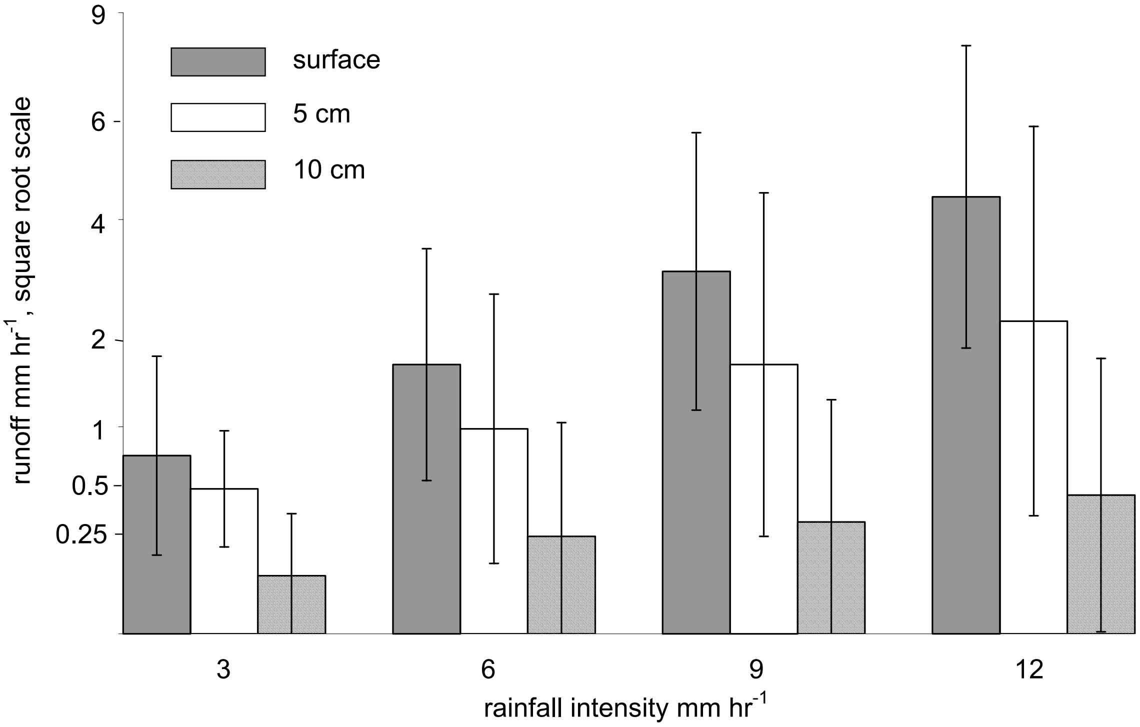

runoff mm hr-1, square root scale
9
6
4
2
1
0.5
0.25
surface
5 cm
10 cm
3
6
9
12
rainfall intensity mm hr-1

Figure 7.

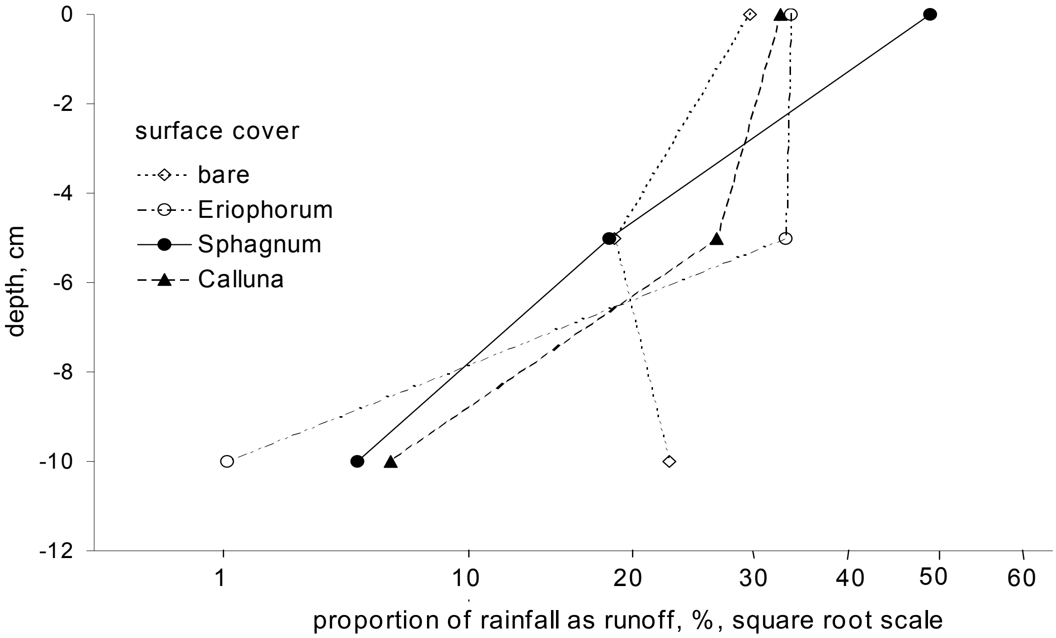
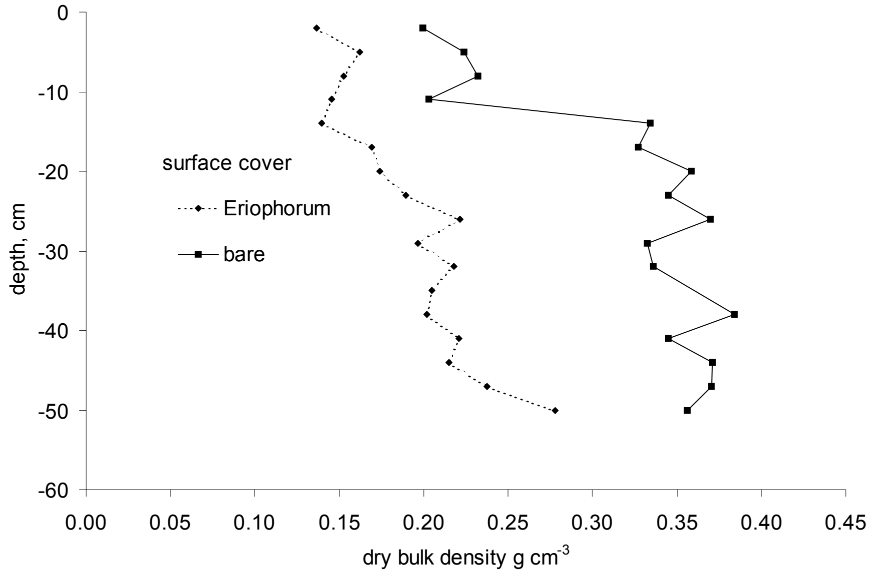

0
-2
-4
-6
-8
-10
-12
depth, cm
surface cover
bare
Eriophorum
Sphagnum
Calluna
1
10
20
30
40
50
60
proportion of rainfall as runoff, %, square root scale

Figure 8.



0
-10
-20
-30
-40
-50
-60
depth, cm
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
dry bulk density g cm-3
surface cover
Eriophorum
bare

Figure 9.

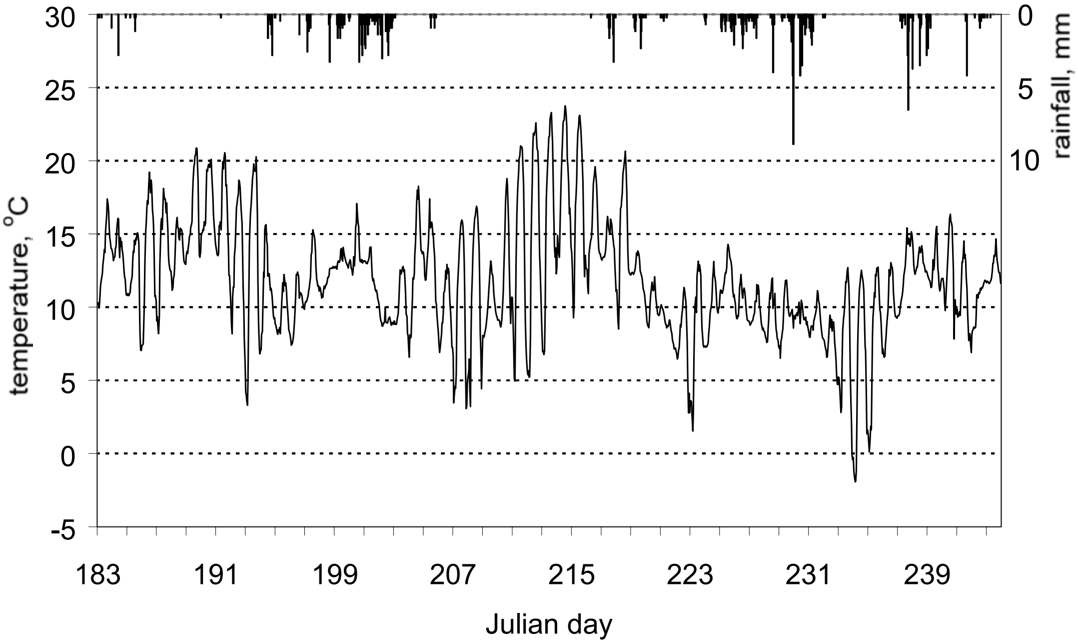
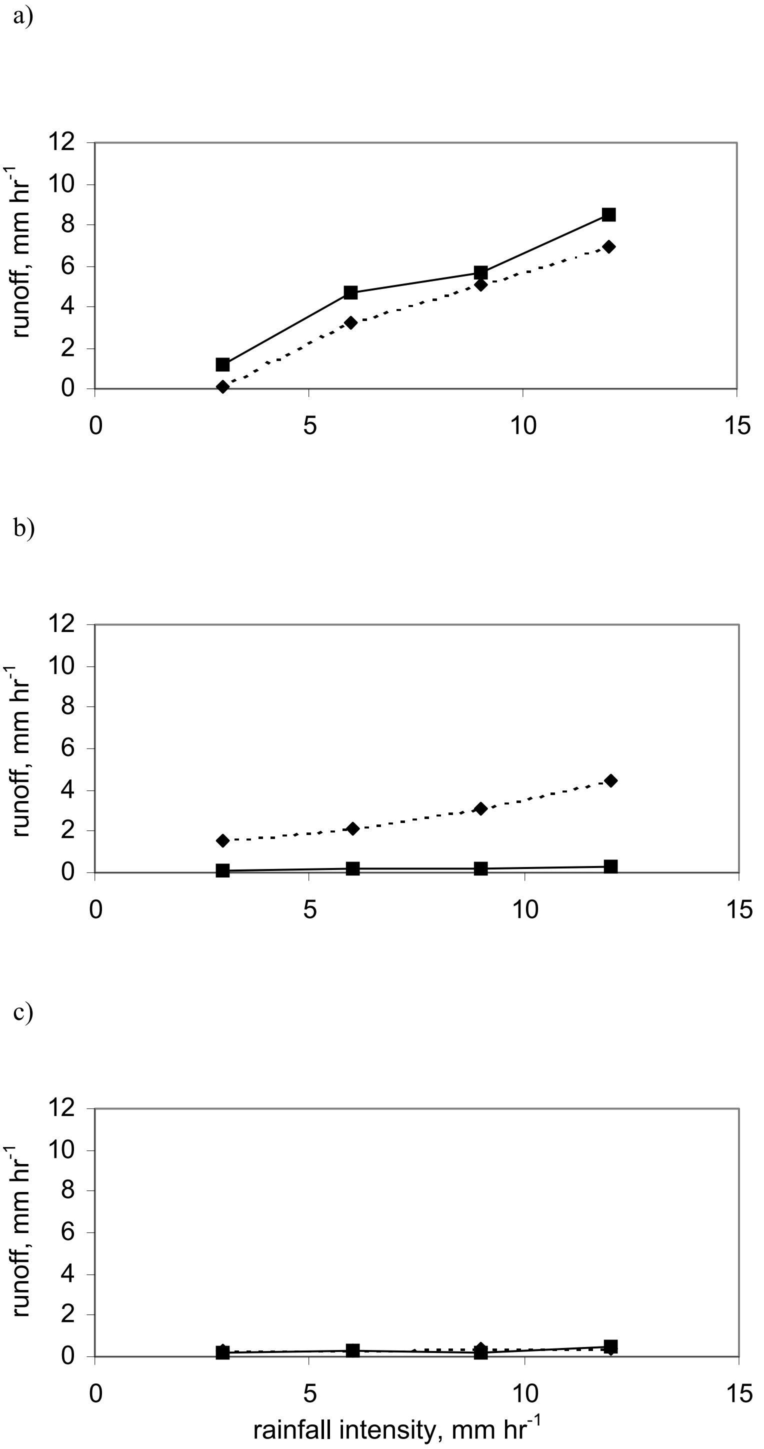

30
25
20
15
10
5
0
-5
temperature, °C
0
5
10
rainfall, mm
183
191
199
207
215
223
231
239
Julian day

Figure 10.


a)
runoff, mm hr^{-1}
0
2
4
6
8
10
12
0
5
10
15
b)
runoff, mm hr^{-1}
0
2
4
6
8
10
12
0
5
10
15
c)
runoff, mm hr^{-1}
0
2
4
6
8
10
12
0
5
10
15
rainfall intensity, mm hr^{-1}