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RUNOFF PRODUCTION IN BLANKET PEAT COVERED CATCHMENTS

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Abstract

Blanket peat catchments exhibit flashy regimes but little is known about the exact nature of runoff production processes within these catchments. Catchment, hillslope and plot-scale monitoring results are presented from the blanket peats of the northern Pennines, UK. Catchment efficiency for three study catchments with areas of 11.4 km^2, 0.83km^2 and 0.44 km^2 were 72 %, 77 % and 82 % respectively. Mean rainfall peak to discharge peak lag times were 2.7 hours, 2.1 hours and 3.2 hours respectively. Runoff from hillslopes in the catchments was gauged using runoff troughs. Mean hillslope lag times ranged from 0.6 to 2.2 hours and despite large differences in the scale of study there was little difference in response time. This indicates that slopes and channels are strongly hydrologically coupled in these peat systems. Saturation-excess overland flow dominates hillslope runoff, particularly on more gentle slopes, and on footslopes where overland flow occurs most frequently. Overall 81.5 % of the total overland flow and matrix throughflow collected by runoff troughs occurred at the peat surface, with 17.7 % between the surface and 5 cm depth, 0.7 % between 5 and 10 cm depth, and less than 0.1 % from below 10 cm depth, despite the thickness of the peat deposit. Most stormflow is produced as saturation-excess overland flow, whereas most low flow is produced by throughflow from 1 to 5 cm depth. Topography and preferential flow paths are important controls on the spatial pattern of runoff even on low-gradient peat. On steeper midslope regions, more flow occurs within the upper 10 cm of peat rather than at the surface. Preferential flow paths are identified at both the hillslope and plot-scale. Discharge deep within the peat is only produced from small macropore and pipe outlets that are well-connected to the peat surface. Response to rainfall from these macropore networks is rapid and they generate around 10 % of streamflow.

Keywords

Variable source area, overland flow, throughflow, blanket peat, runoff, peatlands, saturation-excess overland flow, wetlands,

Introduction

Until recently little was known about runoff production in blanket peat catchments. The traditional view of peatlands was that they attenuated floods and sustained baseflow in streams and rivers during periods of low precipitation. Blanket peatlands have been viewed as such 'sponges' since at least the mid 18th century (Turner, 1757), because of the high porosity of peat. However, recent studies have demonstrated that intact and degraded blanket peats are extremely productive of runoff and have flashy regimes with little baseflow contribution (e.g. Burt *et al*., 1990; Price, 1992; Burt *et al*., 1997; Evans *et al*., 1999). High water tables indicate that runoff is likely to be dominated by saturation-excess overland flow, or near-surface flow (Evans *et al.,* 1999), but some authors have suggested that infiltration-excess overland flow may also be important in blanket peats (Burt *et al*., 1990; Burt, 1995).

Many studies have reported very low hydraulic conductivities (of the order of 10^{-7} cm s^{-1}) from layers of peat below 40 cm depth despite high porosities of between 60-90 % (e.g. Ingram, 1967; Rycroft *et al*., 1975; Dasberg and Neuman, 1977). However, Baird *et al.* (1997) stated that it is erroneous to assume that the lower peat layers cannot be an important source of subsurface discharge because the peat mass may be sufficiently thick such that, even with low hydraulic conductivity, it may provide significant amounts of water over the long term. Indeed most models of peat hydrology are groundwater based. While models such as MODFLOW (Harbaugh and McDonald, 1996) and DRAINMOD (Skaggs, 1980) can be used to describe groundwater flow they inherently lack any representation of the near-surface conditions which may be important in peat catchments (MacAlister and Parkin, 1999). It is crucial to establish the relative importance of throughflow and overland flow processes in peats and the spatial and temporal distribution of these flow processes so that models of hydrological and biogeochemical processes can be adequately developed. Details of storm runoff processes remain poorly understood in blanket peats and Evans *et al.* (1999) suggested that further work at the subcatchment scale was required to unravel the exact nature of runoff generation in blanket peat catchments.

This paper has two main aims. Firstly to test the Baird *et al*. (1997) hypothesis that throughflow in the deeper peat layers may be an important overall contributor to runoff. The relative importance of overland flow and throughflow (from different parts of the peat profile) will be measured. Adamson *et al*., (2001) suggested that release of SO_4^{2-}, NH_4^+ and H^+ to blanket peat stream water would be controlled by runoff flowpath while water table fluctuations controlled their availability for transport. Similarly results in Adamson *et al*. (1998), Miller *et al*., (2001) and Cole *et al*. (2002) suggest that runoff production may control the release of dissolved organic carbon (DOC) and other solutes into the stream system. DOC production is significantly greater in the upper 10 cm of blanket peat for example (Cole *et al*., 2002).

However, flowpaths are not just a function of soil layering but of topographic drainage. Many wetland restoration practitioners assume that intact and restored peatlands should have a spatially uniform water table with uniform flow production processes across the site (Brooks and Stoneman, 1997; Ginzler 1997; Brulisauer and Klotzi, 1998). Although water table depth may be a good guide for wetland managers, knowledge of spatial and temporal variations in runoff production would allow more accurate management (Heathwaite, 1995). Thus Clymo *et al*. (1995) suggested that there was a need for direct field measurement of peatland runoff characteristics so that improved hydrological and biogeochemical wetland models could be developed. Therefore the second aim of this paper is to provide details of the spatial and temporal variation in runoff generation across intact blanket peat hillslopes. The nested experimental design also allows some analysis of the hydrological coupling of the slopes and channels in peat catchments.

Study Site

Measurements were performed on the Moor House National Nature Reserve (NNR), in the northern Pennine Hills, UK. Lower Carboniferous sequences of interbedded limestone, sandstone and shale provide a base for glacial boulder clay at the site (Johnson and Dunham, 1963). This clay impedes drainage allowing blanket peat to develop. Ninety percent of the Reserve is covered with a blanket peat deposit of up to 3 m thickness. Peat formation began in the late Boreal as bog communities began to replace a birch forest, macro-remains of which are commonly found at the base of the peat. Vegetation cover is dominated by an *Eriophorum-Calluna-Sphagnum* association. Mean annual precipitation at the site has been measured since 1931 and is 1982 mm ranging from 3372 mm in 2000 to 1434 mm in 1973 with a mean of 244 precipitation days per year (Burt *et al*., 1998; Holden and Adamson, 2001). Precipitation is slightly seasonal with 57 % occurring in the winter-half year from October to March. Snow cover is synoptically controlled and a typical winter season will several complete accumulation and melt cycles. On average there are 65 days per year with snow lying on the catchment (Holden, 2001). Further details about site characteristics can be found in Johnson and Dunham (1963), Heal and Perkins (1978), Adamson *et al*. (1998), and Holden and Adamson (2001; 2002).

Measurements

a) Streamflow gauging

Trout Beck, a 11.4 km^2 tributary of the Tees was gauged by a compound Crump weir operated by the Environment Agency (register number 025003) at 535 m altitude (2^{o}23’30”W, 54^{o}41’40”N). The catchment rises on the slopes of Great Dun Fell at a maximum elevation of 848 m and discharge readings were taken at 15 minute intervals. Data used in the present study are taken from October 1994 to December 1999. Figure 1 plots the location of the Trout Beck monitoring site and two other sites where streamflow is automatically recorded within the Moor House NNR. R is gauged by a pressure transducer installed within a sharp-edged rectangular weir and drains the Rough Sike catchment with an area of 0.83 km^2 (Crisp, 1966). L drains 0.44 km^2 of intact blanket peat and is gauged on a rated section. Although L is just outside of the Trout Beck catchment it is included in the present analysis since it is immediately adjacent, and lies within Moor House NNR. Detailed analysis of pipeflow processes within Little Dodgen Pot Sike (L) have been presented elsewhere (Holden and Burt, 2002); here only catchment hydrograph analysis is presented for comparison with other sites.

b) Automated overland flow and throughflow measurement

Runoff was measured on six hillslope plots at the lower end of the Trout Beck catchment. The hillslopes were chosen as they had peat depths, slope angles and vegetation cover representative of the catchment as a whole. Figure 1 plots their location (coded H1-H6) and Table 1 provides details on the characteristics of each site. Surface topography was measured using a total station with a 10 cm diameter base plate providing uniform estimation of the peat surface.

Measurement of runoff production at each of the six slopes was performed using aluminium throughflow troughs channelled into tipping-bucket flow recorders (Knapp, 1973; Atkinson, 1978; Khan and Org, 1997). Anderson and Burt (1978) noted that excavations associated with Knapp's (1973) method of trough insertion may produce errors due to soil disturbance. This may be especially important in a fibrous and anisotropic soil like peat. Rather than digging away from below and inserting the sheet, much less disturbance is achieved if a rigid sheet is simply slotted into the soil. This is easily achieved in an organic peat soil where there is rarely obstruction by rocks or large roots. A trench was dug in the peat, or at suitable locations a peat face was cleaned off, and 50 cm width aluminium troughs carefully inserted at 1 cm, 5 cm, 10 cm, 50 cm, 1 m depth and at the base of the peat layer. A trough was also inserted below the peat-substrate interface. Dividers were inserted flush with the edge of each trough to prevent leakage from upper layers into lower troughs and to prevent lateral flow. Discharge was measured by tipping-bucket flow recorders connected to a Campbell CR10X datalogger. At a 76 m roadside ditch at the foot of slope H2, forty throughflow troughs were inserted into the peat at 5 cm depth and at 2 m intervals. Runoff from the troughs was sampled manually during storm events. Salt dilution gauging was performed along the course of the ditch during storm events using slug and constant rate injection techniques (Burt, 1988).

Digging a pit for measurement in peat may be problematic as the water table may fall close to the peat face resulting in changes in the balance of throughflow and saturation-excess overland flow. Measurement immediately upslope of trough installations showed that the water table did fall close to the peat face, but it is not thought to be a significant effect. Atkinson (1978) states that as a general principle throughflow gutters should ideally be placed on natural faces at stream banks or at the base of slopes as in the study of Weyman (1973) where distortions of the hydrograph and contributing area were at a minimum. Where possible this appraoch was adopted here (Table 1). In order to reduce the effect of flow net distortion on throughflow, dividers were inserted at the sides of the troughs through the profile.

At several stream banks and peat faces, discharge could be seen issuing from subsurface pipes. Discharge from these outlets was monitored using plastic guttering inserted below the outlet and flow was channelled to a tipping-bucket. Results from monitoring discharge from pipe networks in the Moor House blanket peat has been presented elsewhere (Holden and Burt, 2002; Holden *et al.,* 2002) so only a summary will be provided here.

c) Manual measurement of overland flow and throughflow processes

On two of the slopes with automated runoff plots (H1, H2) monitoring of surface detention (and by inference overland flow) and near-surface saturation was done using a network of crest-stage tubes. Entry points were placed at the surface of the peat and at 3, 6, and 9 cm into the peat mass. By burying the tubes to a point where the holes were level with the monitoring height, any flow or ponding to that height resulted in the tube filling with water. This system provided a means of mapping maximum water table elevation during a given period. The tubes were emptied with a large syringe keeping disturbance to a minimum. Networks of thin PVC dipwells and piezometers were also set up at the two sites.

Results

Catchment-scale response

The flashy nature of Trout Beck flow is discussed in detail in Evans *et al.* (1999) and so only a summary is provided here. Figure 2 presents monthly precipitation and runoff totals for Trout Beck. The rainfall:runoff ratio between October 1994 and December 1999 was 72 %. There is a very close correspondence of rainfall and runoff. The lowest ratios occur during February and March 1995, November 1996 and February 1997; this most likely related to drifting snow blowing into the rain gauges leading to overestimation of precipitation (for further discussion of the role played by snowmelt in the catchment see Evans *et al*. (1999) and Bell and Moore (1999)). Seventy two single-peaked hydrographs unaffected by snowmelt and spanning the full range of discharge have been analysed for the Trout Beck catchment**.** The mean peak lag time (from peak rainfall to peak discharge) was 2.7 hours, with the mean time to peak discharge from first recorded rainfall being 6.6 hours. These short lag times indicate that the channel is well coupled to the hillslopes that are generating runoff. These data also highlight the importance of stormflow in the catchment and together with the very high rainfall:runoff ratio indicate that these peats have a limited storage capacity. The hydrographs, both on Trout Beck and on its tributaries, generally have very sharp peaks (Figure 3b and Table 2), and with falling limbs that are nearly as steep as the rising limbs.

Overland flow and throughflow within the Trout Beck catchment

a) Relative contribution of overland flow and throughflow processes

The mean proportion of runoff (as a proportion of total overland and matrix throughflow discharge) collected at each soil depth has been calculated. Flow at the peat surface is responsible for 81.5 % of the total volume (σ = 18.6). Most of the rest of the runoff is generated within the upper 5 cm depth (17.7%, σ = 18.6), with very little from 5-10 cm depth (0.7 %) and even less (0.01 %) from 10-50 cm depth. No runoff was recorded in any of the plots from greater than 50 cm depth to the base of the peat. These data provide important quantitative evidence for the relative importance of surface and near-surface flow processes in blanket peat. Overland flow is the most important runoff pathway. Lateral flow at depths greater than 5 or 10 cm is restricted such that runoff contribution from these layers is low. Holden and Burt (2003) report on results from slug withdrawal tests in the peats at Moor House and found low hydraulic conductivities at relatively shallow depths. Thus, there are minimal flow contributions from most of the peat mass. The results presented here show that less than 1 % runoff is generated from the peat *matrix* below 5 cm depth. Thus, even though the peat may be over 2 m deep, matrix throughflow is insignificant in the Trout Beck catchment. Hence the throughflow-thickness hypothesis of Baird *et al.* (1997) does not apply to these particular blanket peats.

b) Runoff characteristics

A summary of the hydrograph characteristics from the monitored runoff sites is shown in Table 2. It is clear that lag times are very short and, despite large differences in the scale of study, mean lag times from most catchment and hillslope monitoring sites are very similar ranging from 3.2 hours to 1.3 hours. Runoff from deeper peat layers (5 and 10 cm) and from footslopes generally exhibits longer recessions and lower hydrograph intensities. Since plot, hillslope and streamflow characteristics so closely correspond with one another, this suggests that the slopes and channels in blanket peat catchments are hydrologically well-coupled.

The general characteristics of the hydrographs from intact slope H1 seen in Table 2 are illustrated by the examples in Figure 3c-g. Overland flow on the footslope site is more prolonged than on upslope sites. As the hillslope drains, return flow is produced on gentler slopes producing saturation-excess overland flow on the footslopes for a longer period than seen on steeper hillslope sections or at the crest of the hill. When overland flow has ceased on the footslope, the flow record from the 5 cm trough indicates that the near-surface layers of the peat continue to drain. Runoff from 5 cm depth tends to be more prolonged than at the surface with much more rounded and less peaky hydrograph forms. This is indicative of a limited flow capacity of the near-surface layer of blanket peat and of the dominance of saturation-excess runoff generation. Flow from the surface and 5 cm troughs is ephemeral. Given the minimal contribution of flow from deeper layers in the peat (no flow recorded for peat below 10 cm depth on H1) this indicates that peatlands release their gravitationally-free water rapidly following rainfall.

Figure 4 shows runoff dynamics on the H1 slope at different stages of flow recession. Here overland flow (or at least surface ponding) was recorded by a network of 250 crest stage tubes over almost the entire hillslope at the peak of the storm at 0300, day 239 (Figure 4a). Small-scale microtopographical differences could be found on the hillslope but the measurement network allows the general pattern of hillslope runoff production to be displayed. As the hillslope drains following cessation of rainfall, the more gently sloping top and footslope regions continue to produce overland flow with the steeper slopes producing flow just below the surface at 3 cm (Figure 4b). By 1300 (Figure 4c) the surface-saturated zone of peat only exists on the hillslope toe regions whereas steeper areas drain to produce flow down to depths of 6 cm and occasionally 9 cm. After 0900 day 240 (Figure 4d) there is only very slow change. Drainage of free water available in the upper soil layers of H1 is sufficiently rapid such that within 30 hours the hillslope has reached a quasi-equilibrium state with water tables stabilised. Runoff from almost the whole hillslope becomes minimal. The only fully saturated area is on the right flank of the hillslope where monitoring has indicated that the peat is almost permanently waterlogged due to poor drainage. Thus, topography is important for determining dominant runoff process contributions even on low-gradient peat. This should be taken into account by wetland managers. The steeper midslope sections of H1 produce overland flow less frequently than shallower slopes. This suggests that the midslope sections produce more subsurface runoff which collects at the bottom of the slope, and, due to impeded drainage, manifests itself as return flow.

Mean water table levels are shown for H1 (Figure 5). The pattern follows closely the results in Figure 4 clearly demonstrating the role of high water tables in producing surface flow. Thus overland flow development is coincident with saturation of the peat. The dominance of overland flow and flow with the top 5 cm layer of the peat is therefore a result of a saturated peat below. However, the hydraulic conductivity of this lower peat means that despite its saturation, very little runoff is produced from it. Mean water tables are higher on shallower slopes, notably at the crest of the hillslope and at the foot of the slope. The role of non-uniform water tables and corresponding runoff production processes across intact peats should be incorporated into wetland restoration design and denudation models.

Runoff response from the foot of a 230 m slope (H2) is shown in Figure 6 during a 12 day period in 1998. Small amounts of rainfall produce overland flow for the proceeding 24-48 hours at the foot of the slope. The typical response from the 5 cm trough is rounded, with longer recessions than at the surface. As the water table falls, eventually overland flow ceases but shallow throughflow continues to drain. Crest stage tube mapping demonstrates how hillslope saturation changes over time during the rainfall event of day 282-283, 1998 (Figure 7). Much of the slope produces overland flow during the main part of the rainfall event. As the hillslope drains, certain areas of the slope are more likely to stay saturated; consequently these areas become zones where overland flow remains more likely. Given that surface flow is dominant, then some areas are more likely to act as contributing areas than others. Over an 8-month period it was shown that the areas which continued to produce surface flow during the runoff event on day 282-283, 1998, produce overland flow more frequently than other zones (Figure 8a). Hence one side of the H2 slope appears to be a more important contributing area.

Such concentrated lines of flow in peat have sometimes been attributed to small streams which were originally developed in mineral ground, but have become overgrown by peat rather than collapsing later (Tomlinson, 1979). Ingram (1967) also identified ‘water tracks’ in peats where preferential flow seemed to occur. Runoff from the foot of H2 is given for three sampling occasions on 27th July 1998 in Figure 8b (based on trough discharge at the ditch shown in Figure 8a). Trough response is highly variable; the large amount of runoff from the troughs at around 28-32 m along the footslope corresponds with the location where the maximum increase in flow from the slope to the ditch occurs as determined by salt dilution gauging (Figure 8c). Comparison of these results shows that this 28-32 m zone along the transect corresponds with the main contributing area for overland flow identified in Figure 8a. Clearly the spatial pattern of soil saturation has a dominant influence on runoff production in blanket peat.

c) Changing importance of runoff pathways during the recession period

Six throughflow troughs were installed at various depths stacked at 7 sites along the footslope of H2. The relative proportion of runoff produced from each depth category is shown in Table 3. An arbitrary cut-off point has been chosen based on Trout Beck discharge for consideration of ‘high flow’ and ‘low flow’ runoff conditions within the catchment. During storm flow (high flow) most of the runoff is produced from the uppermost layer of peat. However, during lower flow periods most runoff occurs from the 1- 5 cm peat layer. While much variation in complexity and detail in runoff could be masked by examining the peat from 1 - 5 cm depth as a single unit, these data still provide important information on the relative hydrological importance of the surface and near-surface peat. The near-surface peat can fill and overflow rapidly because the peat below it is permanently saturated. On the recession limb overland flow contributions cease but shallow throughflow continues. Thus shallow subsurface peat layers contribute most to discharge during lower flow periods whereas saturation-excess overland flow dominates high flows (and therefore most catchment discharge).

d) Evidence for bypassing flow in the deeper layers of blanket peat

Runoff plot results have indicated that very little flow emerges from peat layers below 10 cm in depth. However, runoff was detected from pipe outlets in the catchment. It is clear from mean lag times of just 1.6 hours and fairly rapid hydrograph recession (see Table 2) that these macropore networks allow water from the surface layers of blanket peat to reach deeper layers rapidly, bypassing the peat matrix. While overland flow is the dominant source of water for the pipes, pipeflow (and hence throughflow) contributes around 10 % to stream discharge in these upland peats (Holden and Burt, 2002). Thus while matrix throughflow is unimportant, bypassing throughflow is important.

Flow at the peat base was monitored at all of the throughflow trough sites; only one site (H5) produced runoff at the interface. Discharge was small with a maximum recorded level of 14.5 ml min^{-1} per metre of contour width. Flow was ephemeral and linked very strongly to rainfall events. Discharge at the peat-clay interface at this site was not therefore a result of continuous slow seepage from the peat mass. No flow was recorded from 10 cm depth to the base of the peat (100 cm) at this plot. It is probable that a macropore network existed to connect the surface peat to the base at this point, bypassing the soil matrix. This may be important for the stability of blanket peat slopes (Warburton *et al*., in press).

Conclusions

Runoff percentages for the Trout Beck catchment are high as rainfall is rapidly transmitted to the channel producing a flashy hydrograph response. Slopes and channels appear to be strongly coupled. Plot-scale monitoring has allowed insight into the detailed operation of runoff production processes in blanket peat catchments. Flow within the upper 5 cm of the blanket peats of Trout Beck significantly dominates runoff response. Despite the thickness of the peat deposit, throughflow from peat matrix below 10 cm depth is an insignificant component of runoff production in the blanket peats of the north Pennines. During high flow, overland flow is dominant; during low flow, flow between 1-10 cm into the peat mass is dominant.

Overall there is a dominance of saturation-excess overland flow, particularly on more gentle slopes with impeded drainage, and on footslopes where overland flow occurs most frequently. On steeper slopes, more flow seems to occur within the near-surface layers of blanket peat, rather than at the surface. Storm mapping of flow processes has elucidated the nature of variable source areas for runoff production in blanket peat. Topography and preferential flow paths are important controls on the spatial production of runoff. No significant discharge emerges from the lower layers of peat except from soil pipes which contribute around 10 % of the discharge to the catchment. These soil pipe networks appear to be well connected to the surface peat such that flow response to rainfall from outlets is rapid. Localised ephemeral flow has also been detected at the peat-mineral interface. The assumption made by some wetland practitioners involved in blanket peat restoration projects that there should be a uniform water table depth across a peatland is clearly not valid in intact catchments. The results from intact peats in this paper are not likely to extend fully to disturbed peats where water tables are lower and peat desiccation has altered the soil structure. Disturbed peats are likely to produce more throughflow from deeper peat layers and a greater amount of bypassing flow through macropore and soil pipe networks.

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Figure Captions

Figure 1. Map of the study site showing monitoring locations.

Figure 2. Monthly rainfall and runoff totals for Trout Beck, October 1994-December 1999.

Figure 3. Runoff production from selected monitoring sites, days 236-241, 1999.

Figure 4. Minimum depth of flow from the peat surface on H1, day 239-240, 1999 as monitored by crest-stage tubes, a) 0300 day 239, b) 0900 day 239, c) 2100 day 239, d) 0900 day 240.

Figure 5. Mean water table depth, cm, on H1, based on bi-weekly sampling, May 1999-November 1999.

Figure 6. Runoff production from Trout Beck and the footslope of H2, day 237-285, 1998, a) precipitation, b) Trout Beck, c) H2 overland flow, d) H2 5 cm depth, e) H2 10 cm depth.

Figure 7. Minimum depth of runoff from the peat surface on H2, Julian days 281-283, a) 1800 day 281, b) 1700 day 282, c) 0600 day 283, d) 1200 day 283, e) 1800 day 283.

Figure 8. Runoff production from H2. a) Frequency of overland flow occurrence on H2 as monitored by crest-stage tubes based on bi-weekly samples, June 1998-September 1999, contours and axis distances in metres, b) Discharge from the foot of H2 as gauged by runoff troughs along a 76 m roadside ditch, 27th July, 1998, c) variation in discharge from the foot of H2 as gauged by salt dilution.

Table 1. Site characteristics and instrumentation where runoff was monitored. See Figure 1 for site locations.

Plot	Location of flow recording	mean slope, m m^{-1}; length, m; mean (intact) peat depth, m	Vegetation (Dominated by *Calluna (C), Eriophorum (E)* and *Sphagnum* spp.(S)) in order of prominence	Manual instruments C/P/W*	Face already present or trench dug
H1	Topslope	0.04, 11, 0.8	S-E-C	U P W	T
H1	Midslope	0.09, 38, 0.6	E-C	U P W	T
H1	Footslope	0.11, 56, 0.9	S-E-C	U P W	F
H2	Footslope	0.07, 230, 1.2	E-C	U P W	F
H3	Midslope	0.07, 170, 1.1	S-C		F
H4	Footslope	0.07, 145, 2.3	E-C		F
H5	Midslope	0.05, 160, 1.0	E-C		F
H6	Topslope	0.02, 10, 1.3	E		T
M1	3 macropores at peat face	0.07,145, 1.2	C		F
M2	4 macropores at peat face	0.06, ?, 0.9	C-E-S		F

* U =crest stage tubes, P = piezometers, W = dipwells

Table 2. Mean hydrograph characteristics (standard deviations in brackets) for storm response of catchment, hillslope and plot runoff.

Source	Peak lag, hrs	Recess lag, hrs	Intensity, s^{-1}	n	Runoff ratio, %
Trout Beck	2.7 (3.1)	28.9 (12.6)	38.8 (27.9)	72	72
R	2.1 (2.2)	25.6 (14.1)	39.1 (23.4)	36	77
L	3.2 (2.6)	24.8 (12.4)	32.3 (21.3)	36	83
*OLF	2.0 (3.5)	10.6 (21.9)	85.3 (73.0)	32	
*5 cm throughflow	1.3 (1.3)	31.4 (25.3)	76.3 (62.1)	38	
*10 cm throughflow	2.2 (2.2)	14.1 (14.0)	54.5 (60.1)	33	
†Macropore outlets	1.6 (2.2)	21.7 (17.0)	41.9 (57.2)	31	
H1 topslope OLF	0.4 (0.3)	18.4 (10.9)	152.7 (93.1)	14	
H1 midslope OLF	0.7 (0.6)	7.6 (7.5)	283.0 (223.8)	14	
H1 midslope 5 cm	0.6 (0.5)	14.2 (7.3)	204.4 (145.0)	14	
H1 footslope OLF	0.9 (0.7)	15.6 (15.8)	149.8 (100.7)	14	
H1 footslope 5cm	1.3 (1.2)	57.3 (11.0)	122.7 (82.3)	14	

*Mean for all runoff plots; †Mean for the seven macropore outlets monitored; OLF = overland flow; Peak Lag = Time between peak rainfall and peak discharge; Recess lag = Time from rainfall cessation to return to pre-storm level; Intensity, s^{-1} = peak flow ($m^3 s^{-1}$) divided by total storm discharge ($m^3 \times 10^{-6}$).

Table 3. Mean flow contributions to total discharge at each site, %, under 'high' and 'low' flow conditions.

Depth, cm	Mean % contribution at high flow	Mean % contribution at low flow
1	84.3	19.3
5	11.6	62.2
10	3.2	13.9
15	0.6	1.6
20	0.4	2.9
50	0.0	0.0

'High' flow was taken to be when flow at the Trout Beck gauging station was greater than 1 $m^3 s^{-1}$, and 'low' flow when discharge was below this level. A discharge of 1 $m^3 s^{-1}$ is exceeded 13 % of the time; 70 % of the discharge volume occurs above this level. Results based on 7 sites, 21 low flow and 25 high flow measurements at each site, separated by at least 6 hours.

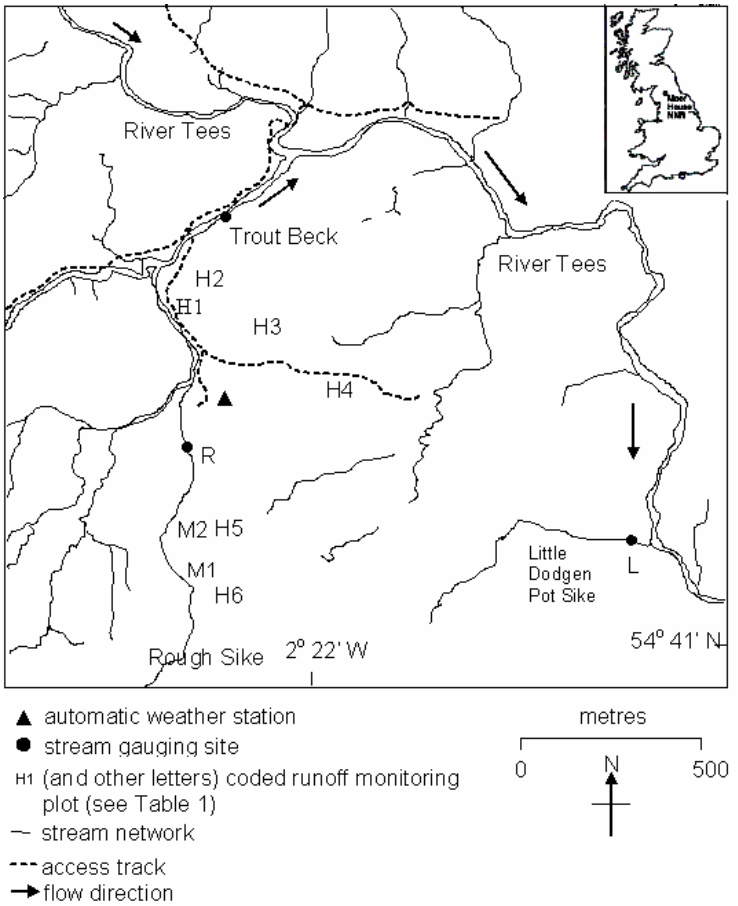
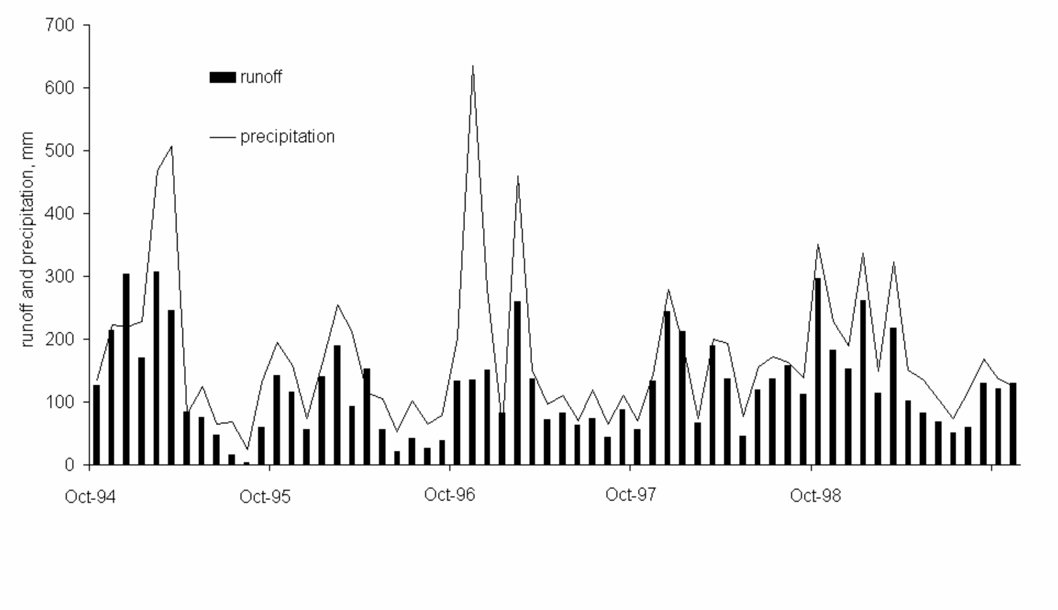

River Tees
Trout Beck
River Tees
H2
H1
H3
H4
R
M2 H5
M1
H6
Little
Dodgen
Pot Sike
L
Rough Sike
2° 22' W
54° 41' N
automatic weather station
stream gauging site
H1 (and other letters) coded runoff monitoring plot (see Table 1)
stream network
access track
flow direction
metres
0
500
N

Figure 1.

Figure 2.



700
600
500
400
300
200
100
0
runoff and precipitation, mm
runoff
precipitation
Oct-94
Oct-95
Oct-96
Oct-97
Oct-98

Figure 3.

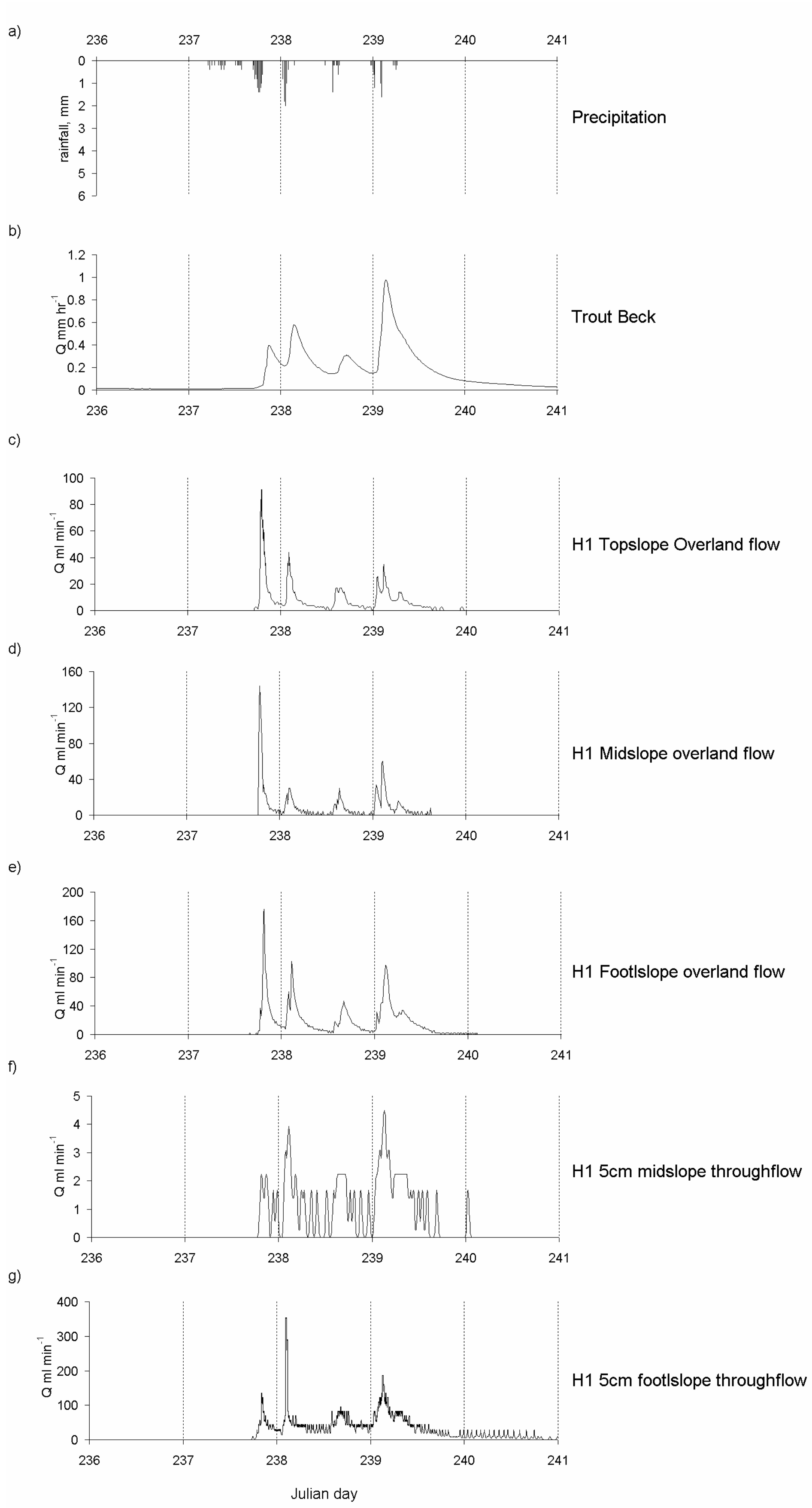

a)
Precipitation
rainfall, mm
b)
Trout Beck
Q mm hr-1
c)
H1 Topslope Overland flow
Q ml min-1
d)
H1 Midslope overland flow
e)
H1 Footlslope overland flow
f)
H1 5cm midslope throughflow
g)
H1 5cm footlslope throughflow
Julian day

Figure 4.

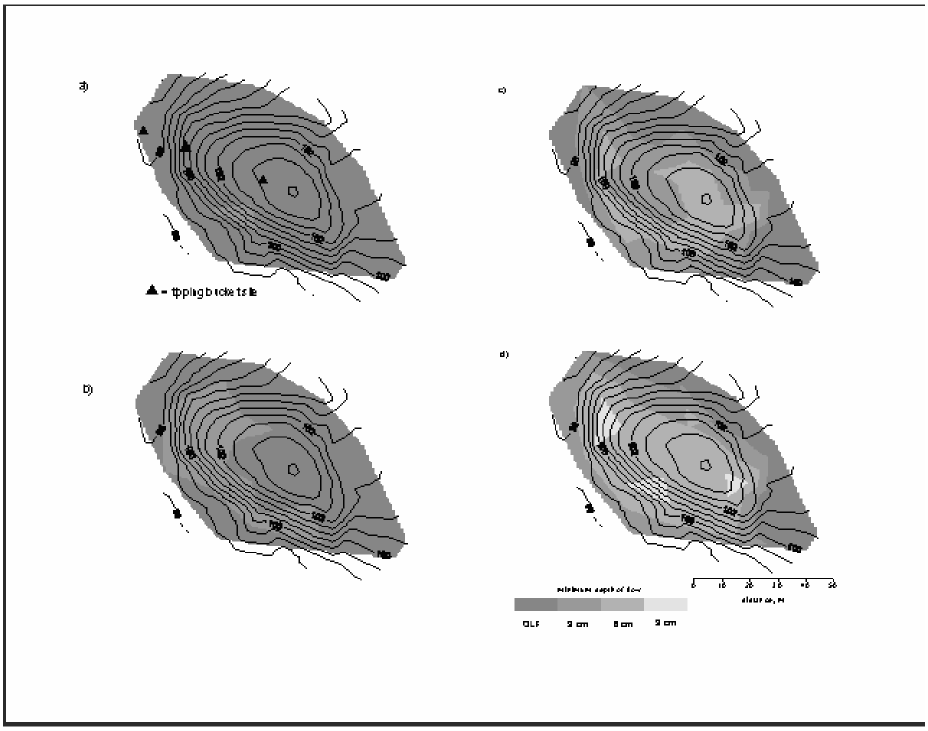


Figure 5.

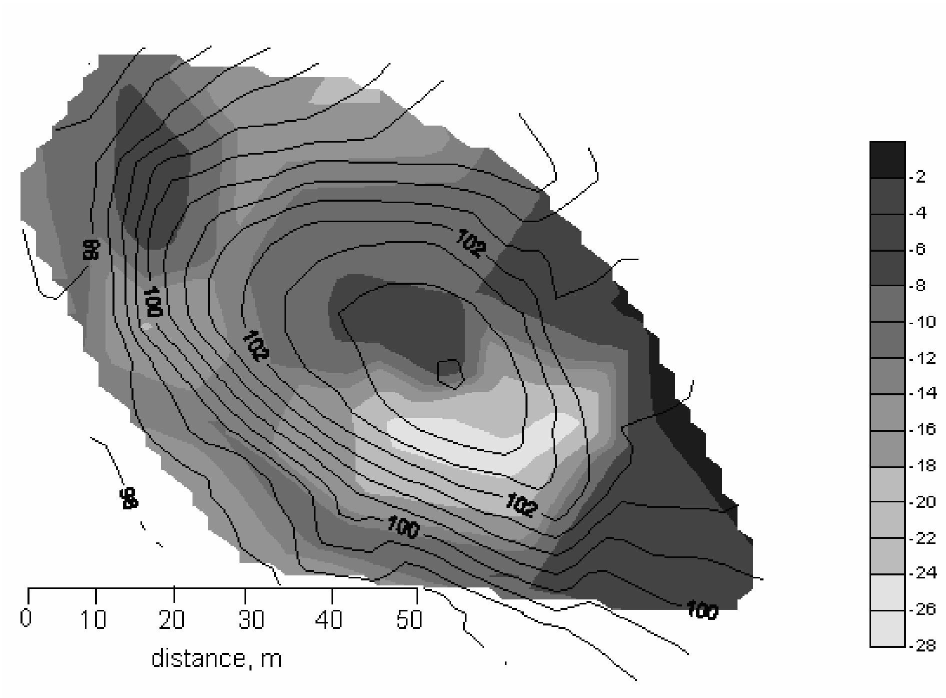

98
100
102
102
102
100
100
98
0
10
20
30
40
50
distance, m
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28

Figure 6.

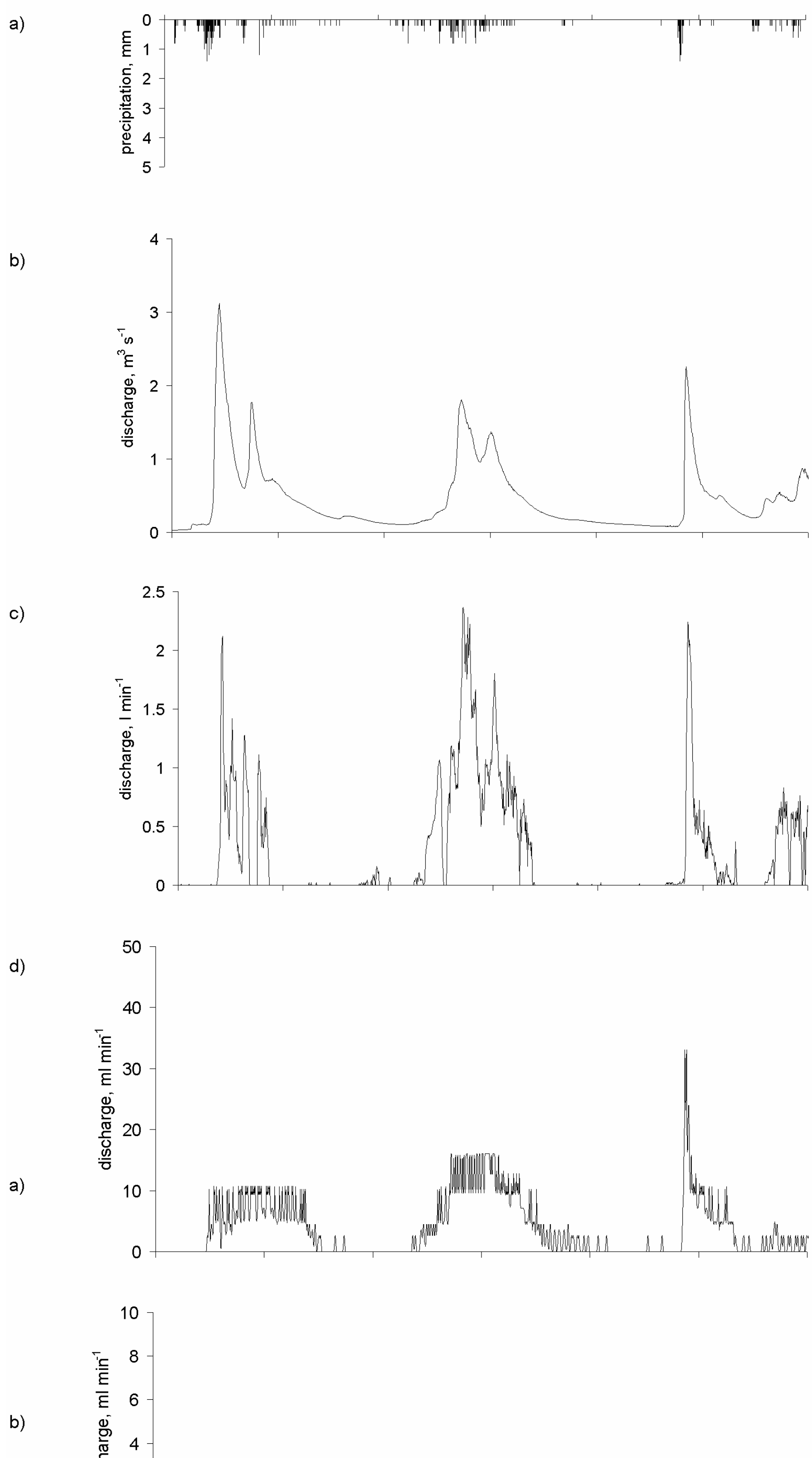
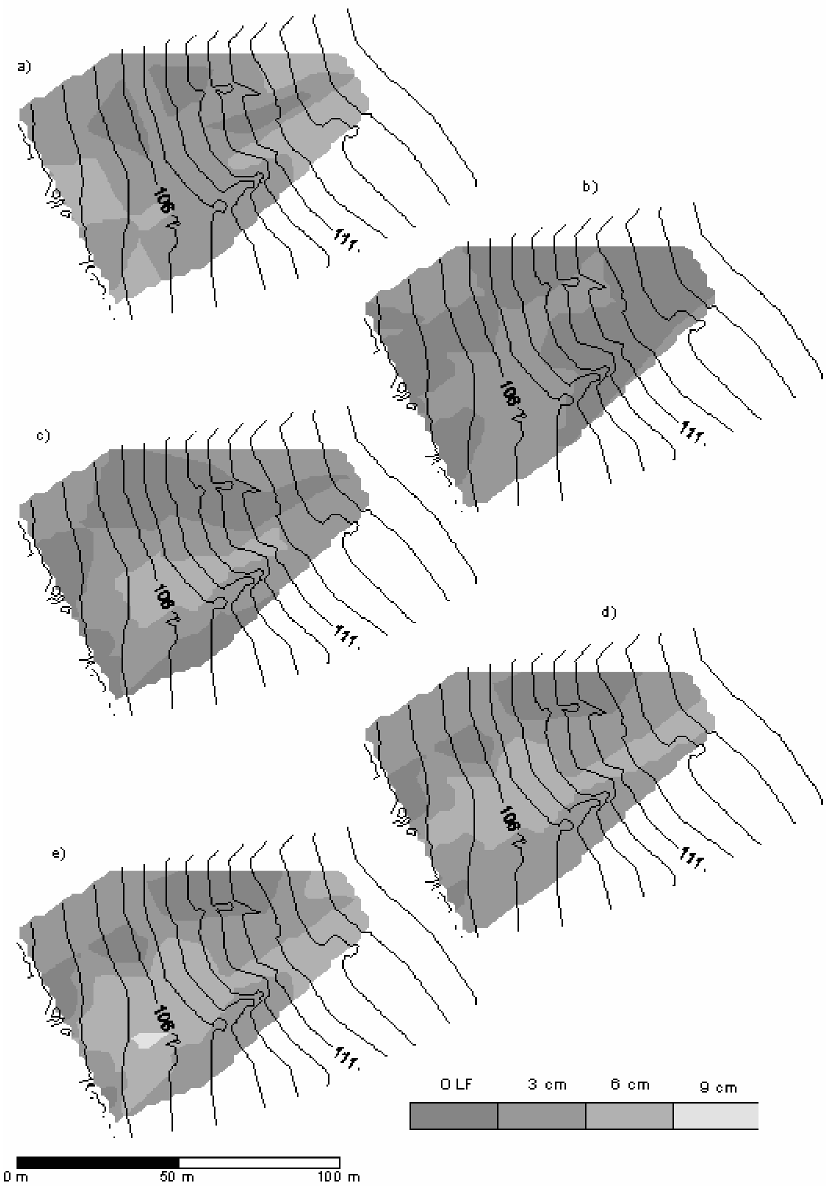
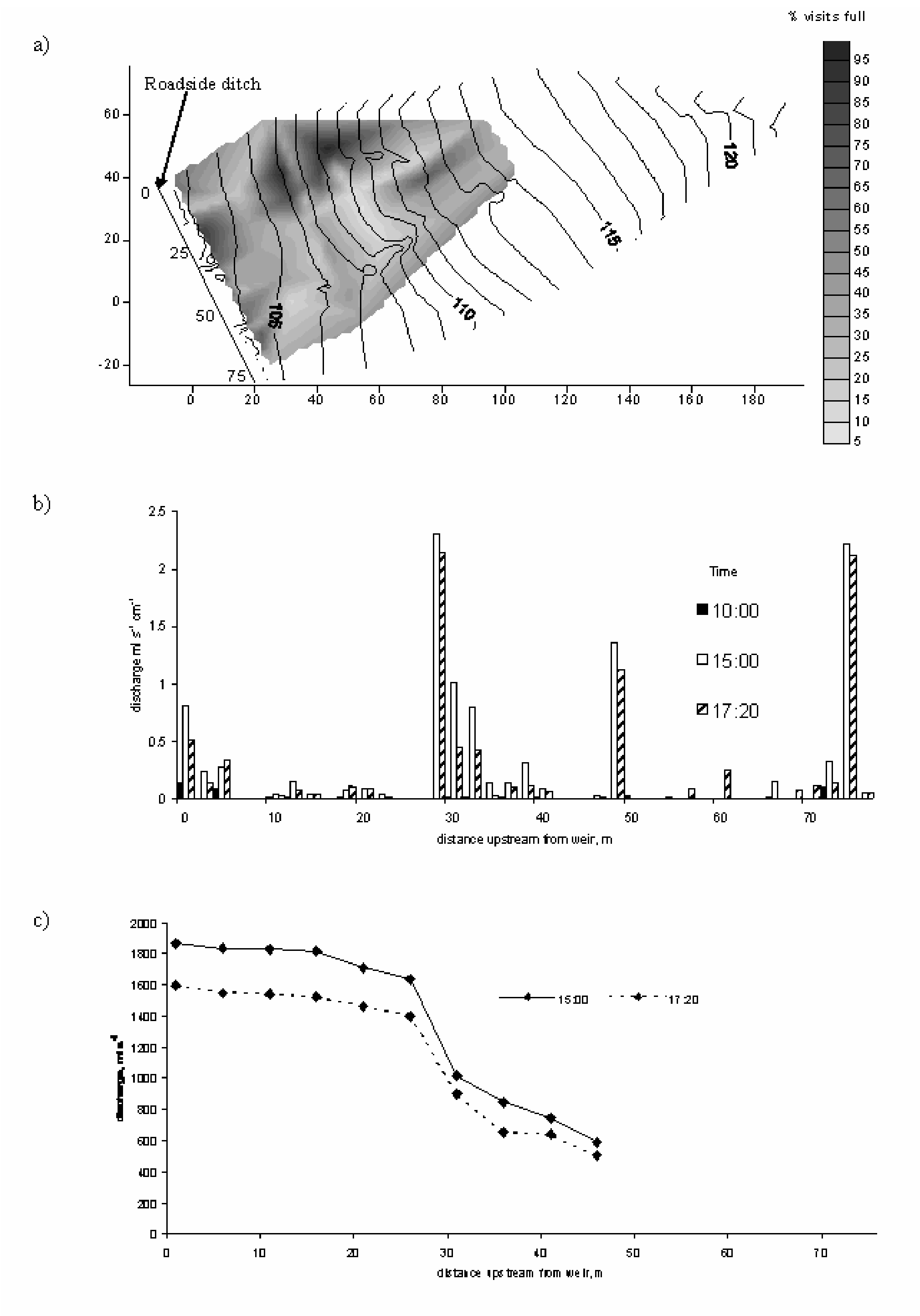

a)
precipitation, mm
b)
discharge, $m^3 s^{-1}$
c)
discharge, $l min^{-1}$
d)
discharge, $ml min^{-1}$
a)
b)
discharge, $ml min^{-1}$
273
275
277
279
281
283
285
Julian day 1998

Figure 7.



a)
106
111
b)
106
111
c)
106
111
d)
106
111
e)
106
111
OLF
3 cm
6 cm
9 cm
0 m
50 m
100 m

Figure 8.


a)
% visits full
Roadside ditch
105
110
115
120
b)
discharge ml s-1 cm-1
Time
10:00
15:00
17:20
distance upstream from weir, m
c)
15:00
17:20
discharge, ml s-1
distance upstream from weir, m