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PIPING AND PIPEFLOW IN A DEEP PEAT CATCHMENT

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Abstract

Natural pipes are common in many upland blanket peats yet little is known about pipe network morphology or pipeflow processes. Most information on soil piping comes from the shallow peaty podzols of the Welsh uplands where monitoring suggests that pipes may be important contributors to streamflow. This paper presents information on piping and pipeflow from a deep upland blanket peat catchment in the Pennine Hills of Northern England. Pipe outlets are found throughout the soil profile ranging from the underlying substrate at ~3 metres depth to pipes which are within a few centimetres of the surface. Mean pipe diameters range from 3 cm to 70 cm; some pipes are over 150 m long. Slopes in the catchment are less steep than those usually associated with soil piping. Continuous flow records were obtained from 15 gauging sites on 8 separate pipes. The pipeflow response from deep blanket peat was found to be different to that reported in the shallow peaty podzols of the Welsh uplands; the distinction between 'ephemeral' and 'perennial' pipe types does not appear to be useful within the deep Pennine blanket peat. Response times from all of the pipes are short, even from pipes deep within the peat. At the same time pipes have a prolonged recession limb such that they maintain low flow for longer periods than most other runoff production processes within the catchment. Pipeflow contributes around 10 % of the streamflow volume but can at times contribute up to 30 %. Soil pipes may therefore be far more important in some upland peat catchments than previous work has hitherto suggested.

Keywords

Peat, Piping, Catchments, Hydrology, Discharge, Wetlands

1. Introduction

Many authors have noted the need for increased monitoring and research of soil piping (e.g. Newson, 1976; Jones, 1981; Jones, 1982; Anderson and Burt, 1982; Selby, 1993; Jones, 1994; Jones, 1997b and Bryan and Jones, 1997). Despite this, there have been relatively few studies of pipeflow processes. Laboratory work (e.g. Sidle *et al.*, 1995), modelling (e.g. Stocking, 1981; McCaig, 1983; Nieber and Warner, 1991) and field measurement (e.g. Bryan and Yair 1982; Roberge and Plamondon, 1987; Gutierrez *et al.,* 1997; Zhu, 1997; Carey and Woo, 2000) have shown that piping can be a very important process associated with runoff, sediment and solute yields in many environments, particularly in humid temperate regions (Jones, 1971; Cryer, 1979; Gilman and Newson, 1980; Jones, 1981; Anderson and Burt, 1982; Jones, 1990; Muscatt *et al.,* 1990; Jones 1994; Bryan and Jones, 1997; Jones *et al.*, 1997; Uchida *et al.*, 1999). Most reports of pipeflow are based on either single measurements of discharge for a relatively large number of pipes, or where discharge data are collected through a range of rainfall events, then usually only a small number of pipes are examined (e.g. Gardiner, 1983; Tsukamoto and Ohta, 1988; Uchida *et al.*, 1999). The most comprehensive pipeflow data are limited to two catchments in Wales (the Upper Wye and the Maesnant) where detailed mapping and monitoring was carried out during the 1970s and 1980s (Jones, 1978; Gilman and Newson, 1980; Jones, 1981; Jones, 1982; Jones and Crane, 1984; Jones, 1997a, b).

The Welsh catchments studied have been predominantly in shallow upland peaty gley soils and stagnopodzols. In the Upper Wye for example, the pipes monitored were in shallow soils (*circa* 30 cm) and were all close to the surface (Morgan, 1977; Gilman and

Newson, 1980). Here the soils were dominated by podzols with well developed iron pans over a stony silty clay loam horizon. Any peaty soils tended to be thin and often with a higher mineral content and gleying than the almost totally organic blanket peats of the Pennines which are the subject of this study. Hydraulic conductivities of the Wye soils were of the order of 1.5 x 10^{-3} to 1.5 x 10^{-4} cm s^{-1} (Morgan, 1977). Further details of these soils are provided in Bell (1972). Measurements of pipe cross-sections were taken at the stream bank and by digging pits in the podzols and they were found to average 9.2 cm in diameter (standard deviation = 2.6 cm) within the Cerrig yr Wyn subcatchment (Morgan, 1977). In terms of monitoring, Gilman and Newson (1980) were only really concerned with the response of ephemeral pipes in three storms. The Maesnant catchment, in mid-Wales, is therefore the only one where pipeflow has been heavily monitored. Here over 200 storms have been gauged at up to 17 separate pipeflow, riparian flow and streamflow gauging stations (Jones, 1997a). At Measnant pipeflow contributed 49 % to stormflow and 46 % to baseflow (Jones and Crane, 1984). The soils at Maesnant are thin peats and peaty gley podzols typically of 1 m depth with hydraulic conductivities of the order of 9.4 x 10^{-4} cm s^{-1} (Jones, 1975). Pipes range from 5 - 30 cm in diameter and were found 15 - 80 cm from the surface (Jones, 1982). Thus, because both the Upper Wye and Maesnant contain only shallow organic soils, these areas only provide examples of relatively shallow pipes of small cross-sectional area. The thin soils are subject to deep desiccation cracking during summer and, with the water table falling to the base of the organic horizons, infiltration and percolation can occur readily to reach pipes typically found at the organic-mineral interface. In the blanket peats of the Pennines, however, while cracking can occur on the surface of the peat the water table rarely drops more than a few centimetres below the surface; thus deep desiccation of these peats is restricted.

Nevertheless, piping has been observed in deep blanket peats with Pearsall (1950) and Bower (1959; 1960) both observing deep-seated pipeflow. Gunn (2000) notes that pipes in the blanket peat of Cuilcagh Mountain, Ireland, range from a few centimetres in diameter to those that are large enough to crawl into. Anderson and Burt (1982) report pipe diameters up to 50 cm in Shiny Brook, South Pennines, England and the existence of deep and shallow pipes. One shallow and one deep pipe were monitored with shallow pipeflow closely mirroring the overland flow response and the flow from the deep pipe lagging two hours behind. Anderson and Burt (1982) suggest that pipeflow provided an insignificant amount of storm runoff at Shiny Brook except where very short near-surface pipes (less than 1 m depth) linked pools to the main stream channel. Burt *et al.* (1990) suggest that pipeflow may be more important in shallow peats whereas in deep blanket peats pipeflow from the impermeable lower peat layers will necessarily be restricted. However, this conclusion should be treated with caution as the largest pipes in the Shiny Brook catchment were not monitored. There are no detailed studies of pipeflow or pipe network morphology from deep blanket peat catchments.

Blanket peat covers the headwater catchments of many humid temperate regions. Around 10-15 % of the world's blanket peat exists in the British Isles (Tallis *et al.*, 1998), and yet until recently little was known about the hydrological processes operating in such areas. It is now known that runoff production from these catchments is extremely flashy with short lag times and storm runoff efficiencies often greater than 50

% (e.g. Burt *et al.,* 1990; Burt *et al*., 1997; Evans *et al*., 1999). It has been suggested that two horizons are hydrologically important in peat soils; the acrotelm, which is an upper horizon of roots and decomposing plant material, and the catotelm which comprises dense peat and is anoxic for most of the year (Ingram, 1983). There is typically a discontinuity in hydraulic conductivity reported between these two horizons: Ingram (1983) suggests that typical values are around 1 cm s^{-1} for the acrotelm and values of 10^{-4} cm s^{-1} to 10^{-8} cm s^{-1} have been reported for the catotelm (Rycroft *et al*., 1975).

Evans *et al*. (1999) identified five possible mechanisms for generating rapid flow from blanket peat catchments: a) infiltration-excess overland flow; b) saturation-excess overland flow; c) rapid flow within the acrotelm caused by ponding at the boundary between the acrotelm and a saturated catotelm; d) rapid flow within the acrotelm generated by ponding at the acrotelm/catotelm boundary even though the upper catotelm remains unsaturated; and e) pipeflow. Work by Holden (2000), Holden and Burt (2000), Holden *et al.,* (2001) and Holden and Burt (in press) demonstrates that the flashy runoff response is dominated by overland flow and that saturation-excess overland flow is far more important than infiltration-excess overland flow within these catchments. Figure 1 provides a conceptual model of runoff production in the blanket peats of the north Pennines. Saturation-excess overland flow is quickly generated due to typically high antecedent water tables combined with rapid infiltration into the acrotelm (via matrix and macropore flux). Thus the water table is able to quickly reach the surface. Percolation into the lower acrotelm and upper catotelm is restricted because of the saturated state of the peat and the low hydraulic conductivity of peat below only a shallow depth. Blanket peat typically has a high porosity with values ranging from 85 to 98 % (Bozkurt *et al.*, 2001), but water is generally held in situ throughout most of the peat mass. Once the water table falls below around 5 cm depth in the north Pennine blanket peats then any further fall in water table depth is controlled almost entirely by evapotranspiration; once below 5 cm water table depth remains constant during night hours (Evans *et al.*, 1999). The saturated hydraulic conductivity of the north Pennine blanket peats is highly variable and can range from 10^{-2} to 10^{-8} cm s^{-1} for the peat between 10 and 80 cm depth. Depth is not a significant control on hydraulic conductivity once below 10 cm of the surface and the hydraulic conductivity can vary by several orders of magnitude within only a few horizontal or vertical centimetres (Holden and Burt, in prep). Macropores contribute around 30 % of runoff production within the acrotelm (Holden *et al.*, 2001), but filling of pores due to ponding at shallow depths soon results in saturation-excess return flow. In fact around 80 % of the water flux at the near-surface of the peat seems to occur through less than 1 % of the peat volume (Holden, in prep). Although this work allowed assessment of four of the hypotheses listed by Evans *et al.* (1999) it did not examine the role of soil piping in generating rapid runoff within deep blanket peat. Pipeflow has traditionally required the water table to rise above the level of the pipe before runoff can commence (Jones, 1981; Jones and Crane, 1984; Wilson and Smart, 1984; Jones, 1987). Occasionally pipes have been known to be directly fed from overland flow at the surface via a collapsed pipe roof or through near-surface cracks and macropores (Gilman and Newson, 1980). However, given that overland flow in peats is dominated by saturation-excess mechanisms and Hortonian overland flow is a rare occurrence (Holden and Burt, in press) then it would be expected that water tables would generally remain above pipe levels in deep blanket peat anyway, particularly if they are found at the interface between the organic peat and underlying mineral substrate which is where the podzolic Welsh pipes seem to be found. Therefore the runoff response from soil pipes in blanket peat catchments might be different from those reported in the shallow podzolic soils of mid-Wales or elsewhere.

This paper presents the results of a pipeflow study in a deep blanket peat catchment of the North Pennines, UK. Automated gauging has been done on ten pipe sites (on eight separate pipes), two seepage zones, a drainage ditch, a gully and on streamflow for a five month period from July to December 1999 covering 14 large storm events and a range of high and low flows. It extends the range of catchments where pipeflow has been studied in detail and enables the processes of runoff generation in blanket peat catchments to be more fully assessed.

2. Study site

The location of the study catchment (Little Dodgen Pot Sike (LDPS)) on the Moor House National Nature Reserve, North Pennines, UK, is shown in Figure 2. The reserve is one of the largest areas of blanket bog in Great Britain and is now a World Biosphere Reserve; the site is therefore recognised for its worldwide importance. Lower Carboniferous sequences of interbedded limestone, sandstone and shale provide a base for a glacial till (Johnson and Dunham, 1963). The glacial clay in the LDPS catchment is usually around 30 cm deep, although it can contain coarse clasts resulting in a clayey diamict. The overlying clay has resulted in poor drainage which has led to the development of blanket bog. 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 (Johnson and Dunham, 1963). The vegetation is dominated by *Eriophorum* sp. (cotton grass), *Calluna vulgaris* (heather) and *Sphagnum* sp. (moss).

The climate at Moor House can be classified as sub-arctic oceanic (Manley, 1936; 1942). Mean annual temperature is 5.2^{o}C. Temperatures can be extreme with values below minus 15^{o}C recorded in most winters. Air frosts have been recorded in every month of the year and Moor House generally has over 100 days per year with frosts. Mean annual rainfall is 1950 mm with an average of 247 precipitation days per year. This is very high but can vary considerably from year to year with 1345 mm recorded in 1971 and 2930 mm in 1979. Rainfall intensities in the Pennines are typically low (Holden *et al.*, 2001) with a dominance of low-intensity frontal and orographic rainfall at Moor House with few rainfall intensities recorded above 12 mm hr^{-1}. Westerly and south-westerly moist air masses from the North Atlantic dominate the climate.

Delineation of catchment boundaries is often difficult in blanket peat because of the nature of the gently sloping terrain, and the subsurface pipe networks (Burt and Gardiner, 1982; Burt and Oldman, 1986). In addition, the head of the LDPS catchment emerges from two limestone risings. Sinkholes were found upslope of the outlets. It is notable that these sinkholes were on the other side of the apparent (surface) divide such that estimation of catchment area based on contour maps would not have been sufficient. No detailed work has been done on the limestone drainage systems of this area. By using salt tracing techniques it was possible to identify which sinks were feeding LDPS and which were feeding other catchments. Thus it was possible to more accurately define the catchment area which was larger than the surface topography would have suggested.

The LDPS catchment covers an area of 0.44 km^2 (+/- 0.04 km^2) falling from 570 m to 515 m where it enters the River Tees around 2 km upstream of Cow Green Reservoir. Most of the peat in the catchment is intact, with only three gullies in the main part of the catchment. There is peat-hagg at the head of the catchment which comprises eroded peat with isolated intact islands and which drains into one of the limestone sinkholes (see Figure 3). Examination of aerial photographs combined with ground survey indicates that less than 5 % of the catchment is eroded and floors of gullies in the catchment are vegetated. ‘Flush zones’ or ‘seepage zones’ (Jones, 1981) which are very wet *Sphagnum*-rich areas of peat, are soft under foot, and often occur along topographic drainage lines in peatlands. These seepage zones are common in the catchment and can be identified by the wide areas of lighter-coloured vegetation shown in Figure 3. The blanket peat cover is typically 1.5 – 2.5 m in depth although it is up to 3.2 m deep in places. There is one man-made ditch (‘grip’) running across from the catchment divide to the stream channel. Most of the LDPS basin faces northeast, although the lower third of the river course runs eastwards. Jones (1994) and Jones *et al.* (1997) showed that most piped catchments that have been examined in Britain face south such that piping has been associated with cracking of the peat surface during the summer months. Whilst summer desiccation is common at Moor House prolonged summer dry spells are infrequent and do not appear to be as common as on Plynlimon. Between September 1994 and September 2000 the maximum number of consecutive days without precipitation at Moor House was 14 (summer 1995). Ten days without precipitation was exceeded 8 times during that same monitoring period, with periods of a week or more without precipitation occurring 17 times. Gilman and Newson (1980) note that summer-time desiccation of the peat in the Welsh mountains of the Upper Wye occurs regularly with dry periods of 16 consecutive days having a two-year return period.

3. Stream Discharge

Stream discharge at LDPS was gauged by an Ott R16 stage recorder installed in June 1999 on a rated section 60 m upstream from the outlet to the Tees. A rating curve for this site was derived from repeated flow measurements using a SENSA- RC2 V6C electromagnetic flow meter. A typical discharge response over a 30-day period is shown in Figure 4. The smooth, almost symmetrical hydrograph form with short lag times and rapid rising and falling limbs demonstrates the dominance of quickflow generation within the catchment. Baseflow is of minimal importance. Median discharge for the study period (June 1999- June 2000) was 0.009 $m^3 s^{-1}$ (0.07 mm hr^{-1}) and runoff to rainfall ratio for the catchment was 83 % indicating the limited storage capacity of intact blanket peat. Mean lag time (time between peak rainfall and peak discharge) is 3.2 hours with a mean unit area peak discharge of 5 mm hr^{-1}.

4. Pipe morphology in the LDPS catchment

Figure 5 maps the main soil pipes discovered in the LDPS catchment; they have been coded numerically for ease of identification. These pipes were originally identified by walking along the river channel and observing pipe outlets. The outlets were then traced back upslope where possible by following slight depressions in the surface and watching for occasional collapsed sections which allowed the pipe to become visible.

Often the pipes were easier to map during storm events because jets of water emerging from surface outlets could be seen. Similar jets were observed by Gilman and Newson (1980). The gurgling of pipeflow water could also be heard beneath the peat during some (non-windy) storm events. Nevertheless it was very difficult to accurately map pipe direction, length and continuity. Some of the pipe locations were confirmed through use of ground penetrating radar. This technique is of particular benefit in identifying deeper pipes in blanket peat where no surface expression of the pipe network exists (see Holden *et al.,* in prep. for details). Those pipes that could be identified were mapped using a differential Global Positioning System (GPS) (Higgitt and Warburton, 1999) with submetre planform accuracy but with altitudinal errors often as great as +/- 20 m. However, *relative* surface heights were found to be accurate at the submetre level during one continuous session and this error is small compared to uncertainty surrounding pipe depth within the peat mass.

The four areas where pools are common in the catchment are associated with piping (although it is difficult to assess their direct connectivity) particularly since pipe 18 seems to be ephemeral (see Table 1 and later discussion). Pipes 11, 16, 18 and 19 (pipe identification numbers are given in Figure 5) run downslope from the pool areas; pipe 19 then spills on to a wet *Sphagnum* seepage zone. Several other pipes in the catchment also feed these areas such as pipes 2 and 21. Seepage zones can also feed pipes, as in the case of pipe 1 (fed by S14); McCaig (1984) observed similar features in the Southern Pennines and called these pipe-feeding seepage zones ‘secondary source areas’. Many of the pipes discharged onto the surface generating overland flow which then ran downslope and often back into the pipe system via sinkholes. Both gullies 1 and 2 have pipes entering at their heads. Bower (1960) and Taylor and Tucker (1970) were among the first to suggest that piping in peat could lead to dissection.

Several of the pipes in the headwater area are associated with vegetation changes. Grasses dominate some piped areas, perhaps denoting better drainage, and can be identified on the aerial photograph (Figure 3). Jones *et al.* (1991), Jones (1994) and Jones (1997a, b) describe similar associations of piping and grass 'lanes' in the shallow soils of the Maesnant basin. Notably the pipes associated with the change in vegetation are located in areas of fairly shallow peat in the LDPS catchment (Table 1). In the deeper peat in LDPS, where the pipes are also deeper, no vegetation changes were associated with soil pipes.

The longest flowing pipes extend over 150 m across the 1-3 degree river terrace slopes and have mean diameters ranging from 3 cm to 70 cm. Pipe morphology and site conditions at the outlet of each pipe are shown in Table 1. Nine of the 26 pipes were ephemeral; baseflow in the perennial pipes usually falls to less than 1 litre hr^{-1}. The pipes vary from being shallow within the peat layer, deep but still entirely within the peat, at the peat-substrate interface, or entirely within the substrate. Half of the pipes were at a depth of over 1 m with some being at almost 2 m. Thus, the LDPS catchment is the first blanket peat catchment study with continuous pipeflow monitoring of both deep and shallow soil piping. The ephemeral pipes at LDPS are not like those reported at Nant Gerig (Gilman and Newson, 1980), Maesnant (Jones, 1981, 1987; Jones and Crane, 1984), or Shiny Brook (Anderson and Burt, 1982; Gardiner, 1983) because they are not simply the shallowest of pipes in the peat. Instead both ephemeral pipes and perennial pipes can be found at shallow and deep locations in the soil profile (Table 1). Thus Jones' (1982) theory that ephemeral pipes found at around 15 cm depth on Maesnant were fed by a rising water table would be difficult to support at LDPS because it would already be well above the height of many of the ephemeral pipe outlets. Water tables are typically within a few centimetres of the surface for most of the year in the LDPS catchment. The pipes do not always produce flow because the hydraulic conductivity of the surrounding soil matrix is so low (often of the order of 1 x 10^{-8} cm s^{-1}) that the peat remains saturated and the pipes only very slowly drain surrounding soil.

The distinction between ephemeral and perennial pipes was often difficult to establish for the pipes in LDPS. This is because, during dry periods, most of the pipes almost completely ceased flowing, with less than 1 ml min^{-1} at all but one of the 'perennial' pipe outlets; this is well below the threshold of most monitoring devices (see below). Only pipe 10 continued to produce significant (continuously measurable) flow during rainless periods. For the purposes of this study, ephemeral pipes are taken to be those which completely cease producing runoff. The distinction between the two pipe types widely quoted in the literature does not appear to be very useful in this deep upland peat catchment because it is not often clear whether discharge has truly ceased or not. In terms of dimensions, there are no significant differences between the two types of pipe (Figure 6). A further difficulty is illustrated by pipe 12 which only produced runoff during high discharge conditions (see below). This is likely to be because pipe 12 is connected to another pipe which at high discharge overflows into it. The difference between ephemeral and perennial pipes is again not clear; some ephemeral pipes may simply be extensions of the perennial channel network. These downstream extension pipes seem to be what have been identified as ‘overflow pipes’ on Maesnant (Jones, 1981).

Figure 6 indicates that all but one of the ephemeral pipes are located entirely within the peat; the other, pipe 12, is within the substrate. All of the pipes found at the peat-mineral interface are perennial (although as discussed above flows could fall as low as 1 ml min^{-1}). The six pipes with the largest diameter are perennial. The pipes are generally of a much larger diameter than those reported in the Upper Wye (Gilman and Newson, 1980). While the larger perennial pipes in the Wye were excluded from Gilman and Newson’s (1980) study the difference is mainly because the shallow nature of the soil in the Upper Wye restricts pipe size. In deeper peat it seems that pipes can erode to greater diameters. At LDPS eight of the pipes are located on the interface between the peat and the underlying substrate. Piping is typically found in soils associated with marked reductions in vertical permeability (Jones, 1990) and is often at the interface between organic and mineral horizons (Jones, 1981). Four of the pipe outlets were found to be entirely within the substrate at LDPS.

The pipes at the peat-substrate interface tended to be elongated along the horizontal whereas pipes entirely within the peat are more rounded or tend to be elongated in the vertical; Figure 7 gives examples of these tendencies. This may be related to the difference in the ability of the peat to erode in comparison to that of the clay and till beneath it and to the volume or force of water passing through the conduit. Jones (1981) suggests that there is some evidence to indicate that small rounded pipes evolve to larger flat bedded or rectangular pipes and suggests that ‘horizontally lenticular’ pipes are typical of shallow peats in Britain (Weyman, 1971; Jones, 1975; Morgan, 1977). Jones (1975) found that 37 % of pipes on the bank of Burbage Brook, south Pennines, UK, were flat bedded and horizontally lenticular compared with 12.5 % in Afon Cerist, mid-Wales. This is the type of geometry generally expected in open channels and would therefore suggest non-capacity flow control on the geometry (Jones, 1981). Gilman and Newson (1980) observed smooth beds and rough pipe roofs in Cerrig yr Wyn, Plynlimon. However, the fact that the peat-mineral interface seems to affect pipe geometry at LDPS (generally being associated with horizontal elongation) suggests that erodibility of floor material may be an important factor. There is no relationship between pipe length and pipe cross-sectional area in LDPS. Although this is concurrent with the early findings of Jones (1981), later work on Maesnant suggested that larger pipes and larger discharges were found downslope and down pipe network in some cases (Jones, *pers. comm.*). There is no relation between pipe cross-sectional area and depth or location within the soil profile at LDPS; unlike the findings of Jones (1981), vertically elongated pipes at LDPS were not usually larger in diameter.

The average cross-sectional area of pipe outlets per kilometer length of streambank is taken as the best measure of intensity of piping activity along the streambank (Jones *et al.*, 1997) although many reports of piping are of pipes not directly connected to the stream (e.g. Gilman and Newson, 1980, on Nant Gerig and Cerrig yr Wyn; Jones *et al.*, 1997, who reference an undergraduate dissertation by Humphreys, 1978 on Wansfell; and Stagg, 1974 in the Blackdown Hills). Table 2 shows that LDPS has a relatively low intensity of piping along the streambank compared to other study catchments where pipes connect to the channel. In terms of pipes on the slopes rather than at the streambank again LDPS has lower densities of piping. Jones *et al*. (1997) suggest that soil piping in Britain tends to occur on catchments with steeper stream slopes than average (mean of 7.7° compared to 5.9° national average). The volume and density of piping that has so far been identified on LDPS is much lower than at the other sites tabulated and mean stream slope and valley side slope are much gentler at LDPS (see Section 2). However, there may be a much greater density of pipes than indicated by this preliminary mapping exercise with pipes being more difficult to find than at Maesnant and other sites because they are often deeper. Preliminary GPR survey within the LDPS catchment has indicated that the pipe networks are more dense and complex than could be established from surface survey alone (Holden *et al.*, in prep.). Mapping of small areas using GPR suggests that the length of piping may be more than twice that which surface mapping suggests. The GPR data also suggests that pipes that are deep in the peat at one point along their course may not necessarily be so deep at another location; they can be close to the surface just a few metres upslope.

Evidence from some of the pipes in LDPS suggests that pipes connect the near-surface and deeper peat with the peat substrate. Material deposited at pipe outlets frequently contained a mixture of both peat and inorganic sediment yet the pipe outlets themselves were often entirely within the peat layer well above the substrate. Pipe morphology appears to be very variable such that if a peat face is cut back a short distance, a completely different morphology is revealed. In this way pipe outlet dimensions and depths (such as those given in Table 1) can be misleading. Nevertheless, they have been provided in this paper so that piping in LDPS can be placed adequately within the context of earlier literature and allow comparison between sites. Terajima *et al.* (2000) found through use of a fibrescope that pipe morphologies in a Japanese forested hillslope could change extremely rapidly over very short distances. Pipes are not simple linear channels for the passage of water; rather they are tortuous and constantly changing in cross section. Frequently the pipe floors run counter to the surface topography such that hydraulic pressures are required to transport the water upwards through those sections. In some instances a pipe can become a runnel where for a few metres there is no roof to the pipe. It is notable that Gilman and Newson (1980) still called these open-topped features pipes. Anderson and Burt (1982) suggested that routing of water could occur between cotton grass mounds along runnels. Subsequent growth of the peat could then roof-in the channels.

5. Pipeflow measurement

5.1 Choice of gauging sites

Runoff was monitored at 15 sites. It was impossible to monitor discharge from all pipes and all seepage areas due to limitations on expense, disturbance, and equipment availability. Ten piped sections, one grip (D1), one gully (G1) and two flush zones (S1 and S2) were monitored as well as the main stream gauge just upstream of the Tees outlet (see Section 3). The monitoring sites are shown in Figure 5. Pipe 11 was monitored at three points along its length and discharge was also measured in the gully downslope of the pipe 11 outlet. It was decided not to monitor the pipes and seepage zones downstream of pipe 23 because field observation and preliminary manual measurements of runoff showed that many of these pipes were not major sources of runoff; such measurements also indicated that runoff response was similar to that in the upper part of the catchment. It is hoped that the pipes monitored provide a good cross-section of the response types found over the entire catchment and were the major pipeflow inputs to the stream. One of the main sources of runoff came from hillslopes draining into seepage zone and pipe 8. Approximately 15 % of the catchment fed this zone (shown in Figure 5). However drainage was generally too diffuse to monitor and the pipe was awkwardly located within the peat with no clear outlet to the river for flow monitoring. Pipe 13 was not monitored because its base was on a clayey diamict with a loose gravel base and it proved impossible to prevent water leaking around any measurement device installed.

5.2 Discharge measurement

Pipe discharge was monitored either by insertion of a weir plate into a pipe or, where this was too difficult, water from a pipe outlet was channelled via plastic sheeting and tubing into a plastic box with a V-notch at the front end. The weirs were gauged by the use of a water level sensor consisting of a one-turn potentiometer; this is turned by a float attached to a pulley wheel and counterbalance by 70 kg strain braided fishing wire. The design details are given in full by Jones *et al.* (1984) and improved by connection to solid state dataloggers (Jones *et al.,* 1991). The potentiometer was connected to an available channel on a Campbell CR10X datalogger. The device allowed stage to be recorded with a resolution of +/- 1 mm thus allowing high flow discharges to be recorded to the nearest 50 ml s^{-1}, and low flows to the nearest 50 ml min^{-1}, averaged over 15 minutes. Flows lower than around 100 ml min^{-1} (1.6×10^{-6} m^3 s^{-1}) could not be accurately gauged and tipping buckets would have proven more accurate under these conditions.

Jones *et al.* (1984) note that, although the British Standard (BS 3680 Part 4A) for thin plate weirs should be followed as far as possible, there is no standard to cover small weirs suitable for many applications in hillslope hydrology. For most of the pipes, the sharp-crested weir plates were set directly into the peat where possible and a good length of plate kept either side and below the cut-out portion to limit seepage and erosion around the edge of the plate. V-notches were usually '½ 90°' although where higher flows were likely 90° V-notches were cut. Suitable floats were constructed from plastic cistern ball-floats, or rounded plastic jars part filled with water and antifreeze to float at the maximum diameter when counterbalanced by a metal weight of 120 g. Stage was recorded at 15-minute intervals and converted to discharge using a calibrated rating curve produced manually for each weir. This in combination with stream flow meant that 16 discharge records could be produced simultaneously from July to December 1999.

6. Pipeflow Response

6.1. Pipe blockages

Two days after logger installation, flow at pipe 18 ceased and did not resume because the pipe collapsed blocking the flow of water to its outlet. The collapse seemed to occur several metres upslope of the outlet and was thought to be natural. Zhu (1997) reported frequently blocked pipes in loess soils in China which could re-open in subsequent events; similar findings were recorded by Uchida *et al.,* (1999) in a Japanese cambisol. Therefore the piping had erratic discharges whereby instability of piping was a key factor in determining hydrological response. The pipes in LDPS often produce high amounts of sediment with stilling wells and gauging weirs frequently blocked with fine organic and mineral sediment. Pipe erosional processes and sediment yields are currently under investigation in the LDPS catchment but are beyond the scope of this present study and will be presented elsewhere. Pipe 18 did not re-open in subsequent storms but the pipe networks do seem to be able to change form and flow fairly quickly. However, the pipes are not likely to be as dynamic as in highly erodible loess soils (Zhu, 1997). As no storms were recorded from pipe 18, it will be ignored from the subsequent hydrograph analysis.

6.2. Pipe discharge

Discharge from the LDPS monitoring sites for a 30-day period is given in Figure 8. It is immediately apparent that, although every site displays a flashy regime, there is a marked difference between sites in runoff response. Pipes 9 and 12, which are ephemeral, show different responses with pipe 12 only responding to the larger events. The outlet for pipe 12 is entirely within the clay and the results could suggest that this pipe is connected to another pipe such that it only operates for short periods at the height of a storm when another pipe (as yet undiscovered) overflows. Unlike other reported piping where a necessary pre-requisite for flow is a water table at a height above the pipe level (e.g. Jones, 1982; Carey and Woo, 2000) this does not appear to be the case in blanket peats. This is probably related to the low hydraulic conductivity of the peat and clay below once below the upper 5 - 10 cm of the soil profile. While a small amount of drainage may occur into the pipe from the deep peat layers this is only sufficient to fill depressions on the pipe floor; evaporation within the pipe and at the pipe outlet probably accounts for the rest. Pipe 9 behaves very differently from pipe 12 with much slower recessions and broader peaks. The outlet of pipe 9 is within the peat layer at around 20 cm from the surface although further upslope the pipe may be deeper as the pipe floor sloped steeply down into the soil profile just a short distance back from the outlet.

Pipe 10 behaves as if there is a limited capacity to the pipe such that most storms produce approximately the same peak flows. This was even though the flat-topped 'capacity' hydrographs occurred during maximum rainfall intensities ranging from 3.0 mm hr^{-1} to 9.4 mm hr^{-1} and rainfall totals from 13 mm to 43 mm. Thus rainfall condition was not responsible for producing the similar peak discharge rates from pipe 10. A similar flow response was also found on Maesnant (e.g. Jones and Crane, 1984) where a pipe with a flat-topped hydrograph was connected to a small fountain, around three to five centimetres high in large storms, through a hole in the roof and to an overflow pipe. The effects of capacity flow from pipe 10 are reflected in pipe morphology since the pipe outlet is round in shape (as opposed to horizontally lenticular pipe forms as expected for open channel flow - Jones, 1981). S1 and S2 and pipe 15 display similar discharge characteristics to each other with much broader hydrographs than the other sites. Pipe 15 is immediately adjacent to S1 and the close similarity of the hydrograph form suggests that pipe 15 is linked directly to S1. Adding salt on to the surface of the peat upslope of S1 during a storm event showed that this was the case since increases in salt concentration were detected both at the S1 gauge and the pipe 15 gauge. Pipes 10, 14, 16, 17 and D1 all have narrower storm hydrographs such that response to each rainfall event is much more distinct than from the other sources.

Most pipes at LDPS respond to low-rainfall intensity and low rainfall total events, even after a dry antecedent period. There is no evidence to suggest that there is a 10 to 50 mm rainfall threshold which is required before pipeflow will respond as found in the mainly ephemeral systems examined by Gilman and Newson (1980) and McCaig (1983). Again this demonstrates that water table depth in relation to pipe depth is not important except where the pipe is very close to the surface. It seems clear that the pipes in the LDPS catchment receive drainage far more quickly and in greater volumes than would be expected simply from diffuse seepage through the overburden. Nevertheless flow from the river system itself is more flashy than at any of the sites (except pipe 12) as indicated by the hydrograph intensity index (Table 3). Thus runoff processes other than pipeflow probably dominate the catchment response. Holden and Burt (2000) and Holden *et al.* (2001) show that saturation-excess overland flow and acrotelm flow processes are the most important quickflow mechanisms in blanket peat catchments. Burt *et al.* (1990) suggested that pipeflow may be more important on shallow peat soils whereas on deeper blanket peats pipeflow from the impermeable catotelm will necessarily be restricted. However, the evidence presented from LDPS suggests that pipe outlet depth has little to do with the nature or magnitude of pipeflow response.

6.3. Lag times

The shortest peak lag times (time from rainfall peak to discharge peak) for any of the pipes is for pipe 9 with mean peak lag of 1.8 hours, followed one hour later by pipe 15. Six out of eight of the pipes have peak lag times under 5 hours. Pipeflow lag times are similar to those at Maesnant and several other reported sites (Jones and Crane, 1984; Jones, 1988; Table 4). The initial speed of response from the LDPS pipes and seepage zones (0.2 to 5.8 hours) is much quicker than at Maesnant where start lag times (from rainfall onset to initial rise in hydrograph) ranged from 7.3 to 13.2 hours (Jones and Crane, 1984; Jones, 1988). The low hydraulic conductivity of the peat below 5 or 10 cm depth in blanket peat catchments (Holden *et al*., 2001) means that it is unlikely that pipeflow in the LDPS catchment is derived from diffuse seepage through the peat matrix except when the pipe is very close to the peat surface. It seems much more likely that saturation-excess overland flow and near-surface flow enters pipes where they are open to the surface at sinkholes or where a layer of *Sphagnum* provides the pipe roof. Macropores in the upper few centimetres of blanket peat may provide a by-pass route for water to enter the pipe system if the pipe is close to the surface at some point along its profile. Since many of the pipe systems seem to originate in areas of pools or seepage zones, it is likely that pipes tap surface and near-surface excess water from such collecting areas as the water filters through the surface living *Sphagnum* cover through peats where the acrotelm is locally slightly deeper than in the surrounding peat mass. Hence the extended flow suggested by longer recession times for many of the pipes is probably derived from a larger catchment area with very wet flush or pool features. Jones and Crane (1984, p62) noted that much of the late recession drainage in the Maesnant stream seemed to be coming from 'pools and bogs in the headwaters'.

At 12 of the 14 active monitoring stations discharge starts to rise within +/- 2 hours with respect to streamflow rise (Figure 9). Flow at three of the eight pipes monitored rises, on average, before streamflow. Distribution of peak lag times is slightly positively skewed with a mean of 4.75 being higher than the mode of 4.05 hours. The mean time of pipeflow peak discharge is only 0.02 hours after streamflow peak discharge with a modal value of 0.71 hours after streamflow peak. There is a diversity of response between the pipes and the seepage zones with ‘stormflow’ ceasing in some pipes up to 13 hours before stream stormflow whilst in others it may continue for a further 30 to 40 hours after stream stormflow has receded. Pipes 9 and 12 both have peak lag times around 2 hours shorter than that of streamflow (Figure 9b) and yet start lag times are longer than streamflow (Figure 9a). Flow in pipe 12 falls back to zero on average around 4 hours before the end of stream stormflow (Figure 9c). Figure 9c, however, shows that stormflow in pipe 9 lasts around 14 hours longer than in pipe 12. Generally stormflow in the drainage ditch (d1) ceases around the same time as stream stormflow. Runoff monitoring showed that the ditch was fed mainly by overland flow and near-surface runoff. For pipe 11 there is clear evidence of downslope movement through the system. The upslope site (11a) drains first followed by the sites in order of distance downslope. This is more likely to be related to the downslope drainage of saturation-excess overland flow and near-surface flow feeding the pipe than to slow drainage of the resident pipe water itself. Mean flow velocities of the order of 8 cm s^{-1} were recorded in pipe 11 through salt dilution tracing during storm events. Low flow velocity measurements were not possible since, as discussed above, flow from the pipes almost completely ceased during dry periods with just a tiny dribble emerging from the outlet. For the 115 m length of pipe this would give a mean travel time of 24 minutes during storm events from top of pipe to bottom. This is far too short to account for mean ‘recession times’ 15 hours longer at 11c than at 11a. Notably pipe 11 is a shallow pipe often having its roof within 5 cm of the surface (see Table 1). As demonstrated by Holden and Burt (2000) the source areas producing saturation-excess overland flow in blanket peat catchments will fairly quickly move downslope after rainfall, as the saturated slopes drain from the topslope down. As the hillslopes drain, runoff from the near-surface layers becomes minimal upslope and stormflow in the pipe-head area ceases. Where overland flow and near-surface flow are being produced further downslope, runoff can enter the pipe system through by-pass routes and openings as discussed above.

6.4. Pipe contributing areas

Mean storm discharge divided by approximate pipe length is greatest at site 11a, 15, and S1 (Figure 10). These are all pipes fed by pools or wet seepage areas, and presumably have a larger catchment area. Calculating catchment areas for the pipes is difficult as it is often impossible to tell what areas were feeding the pipes, particularly on the gentler slopes and since occasionally pipes run counter to the surface topography. Comparisons have been made between pipeflow and other hillslope drainage processes in terms of velocity (Jones, 1987) and estimates of the total contributions to stream runoff from various sources in a basin (Jones and Crane, 1984). However, these comparisons lack a clear relationship with basin area that would allow wider generalisations about the relative efficiency and importance of pipeflow (Jones, 1997a).

Dunne (1978) provided a valuable basis for making such generalisations for overland flow and throughflow with collations of American and British data. These data have been plotted and extended by Kirkby (1985), Anderson and Burt (1990) and Burt (1996). In order to map pipeflow data onto these graphs Jones (1997a) advocates the estimation of surrogate pipe basin areas. This requires estimating the micro-catchment area feeding the pipes. Jones (1987) demonstrated that surface depressions are poor indicators of pipeflow contributing areas, probably because piping can develop routes that are at variance with the surface topography. Dye tracing can be used to test links between pipes but is impractical for delimiting catchment areas (Jones, 1997a). Thus Jones (1997a) advocates calculating surrogate 'basin area' through use of storm discharge and rainfall information. The largest contributing areas for each pipe were selected. This was done by calculating the dynamic contributing area (DCA) for each storm as given by Equation 1 for perennial pipes and Equation 2 for ephemeral pipes:

DCA (per) = Total storm discharge in pipe / Total storm rainfall [1]

DCA (eph) = Total storm discharge / Total storm rainfall before end of pipeflow [2]

After the areas had been calculated for each storm, the largest area was taken for each pipe to be a surrogate for basin area. The first of these formulae (Equation 1) was advanced by Dickinson and Whiteley (1970) and used by Calver *et al.* (1972). It is purely an arithmetic estimate of the minimum contributing area of a catchment needed to produce resultant discharge. Equation 2 was adapted by Jones (1997a) for situations where pipeflow ends before rainfall stops. The limitation of applying this technique to the LDPS dataset comes from the fact that only 14 storms were analysed. Thus the largest contributing areas calculated for each pipe are likely to be underestimated. Nevertheless, the data from LDPS probably contain the greatest quantity of continuous pipeflow data outside of Maesnant. Three of the larger storm events during the monitoring period had precipitation totals of 25 mm, 36 mm and 43 mm respectively with 9.4 mm and 7.6 mm and 7.2 mm occurring in one hour. These are near the higher end of typical rainfall events in the North Pennines (Holden *et al.*, 2001).

Area-weighted peak discharges (mm hr^{-1}) calculated from the surrogate area technique outlined above are presented in Figure 10 with actual peak flows for comparison. The distribution of actual peak discharge recorded from the pipes over the monitoring period closely matched the mean storm discharge patterns, except in pipe 12 where storms were peakiest (Figure 10a and 10c). The peak flows found in the seepage zones were lower than expected when compared to the distribution of storm discharges, and seepage zones tended to have less peaky storm hydrographs. Highest flows were reported from gully 1 (site 11d – 13 l s^{-1}) and from the ditch (d1 – 12.5 l s^{-1}). The maximum recorded pipe discharges were at 11c, with 4.6 l s^{-1} and 2.7 l s^{-1} at pipe 10 (Figure 10c). These discharges are lower than those reported for Maesnant but greater than for most other reported pipeflows (Table 4). However, when measured discharge characteristics are compared to area-weighted flows (cf Figure 10c and 10d) results are different. Pipe 12 has the greatest area-weighted peak flows with the gully (11d) having the lowest. The flow at the head of pipe 11 recorded a higher area-weighted discharge peak than further down the pipe. Peak area-weighted flows from the perennial pipes 10, 14, 15, 16 and 17 ranged from 6.4 to 15.9 mm hr^{-1}.

Figure 11 plots peak runoff rates and lag times with catchment area calculated using Jones' (1997a) 'surrogate basin area' technique. The pipeflow data from LDPS can be compared to the diagrams prepared by Jones (1997a) which are based on Kirkby (1985) and Anderson and Burt (1990) and the Maesnant pipeflow data. Uchida *et al.* (1999) fitted their pipeflow response in Japan to these diagrams and found that their monitored headwater ephemeral pipes in a forest cambisol fitted into the Maesnant envelope. Of course, this type of diagram does not take into account rainfall intensities found in different environments nor the variety of soil parameters. Nevertheless they are useful indicators of typical responses.

Figure 11 shows that the estimated catchment area of the pipes at LDPS is generally smaller than on Maesnant. At Maesnant much greater total discharges issue from the monitored pipe systems. As the catchment areas are smaller at LDPS and peak runoff rates are higher, this pushes the main envelope of the LDPS pipeflow dataset to the left of Jones' (1997a) pipeflow envelopes (Figure 11a). Importantly, the peak flow response of the streamflow in LDPS and Trout Beck (Evans *et al.,* 1999) at the catchment level fit into the saturation-excess overland flow envelope on the Anderson and Burt (1990) diagram. This highlights the dominance of saturation-excess overland flow in blanket peat catchments. Similarly, in terms of peak lag times the 11.4 km^2 blanket peat catchment of Trout Beck on the Moor House NNR fits into the saturation-excess overland flow data envelope (Figure 11b). The effect of piping in the LDPS catchment is to move the LDPS mean lag time response away from the saturation-excess overland flow envelope and toward the Measnant perennial pipeflow envelope. The pipeflows at LDPS are thus within the throughflow envelope on the Anderson and Burt (1990) diagram. The slower peak lag times at LDPS when compared to Maesnant may be a result of the much gentler slopes in LDPS. The similarity in lag times (peak or start) between soil pipes, LDPS and the larger Trout Beck catchment suggests that there is much stronger coupling between scales in blanket peat catchments than in other catchments. These data suggest that hillslopes are hydrologically well coupled to the stream channel. Data are not available on start lag times for the hillslope drainage processes compiled by Dunne (1978). However, pipeflow data are plotted in Figure 11c and compare LDPS with results from Maesnant (Jones, 1997a). Given the shallow nature of the Maesnant and Upper Wye pipes on Plynlimon, sites which dominate the literature on storm pipeflow response, one may expect start lag times to be shorter than for the frequently deeper pipes found at LDPS. However, the much more rapid response of the LDPS pipes to rainfall than on Plynlimon means that the LDPS pipeflow response fails to fit the rough limits of the earlier data. Given that catchment area is larger at Maesnant, however, one would expect to find longer lags there. Jones' (1997a) ephemeral pipeflow data suggested that as catchment area decreased lag times increased. This therefore diverged from the more usual trends associated with throughflow and overland flow. At LDPS there is no such evidence.

7. Pipeflow contribution to streamflow

During the monitoring period of July to December 1999 the eight monitored pipes contributed 9.5 % of the total streamflow recorded. The two monitored seepage zones contributed 2.5 %, the ditch 1.9 % and the gully 5.1 %. Frequent manual sampling of the other pipes in the catchment which were not automatically monitored suggested that they may contribute a further 0.5 to 2 % of total discharge.

Total monitored pipeflow contributions to runoff during the 30-day period examined earlier are shown in Figure 12. It is clear that pipeflow is more important for smaller events such as on days 252, 255 and 266, whereas for larger events like those on days 250 and 263 it is probable that saturation of a greater extent of the hillslopes means that saturation-excess overland flow and near-surface acrotelm drainage become more important relative to pipeflow. Peak contributions to streamflow from piping generally occur on the rising limb of stream hydrographs, with a minimum coincident with the streamflow peak. There is then a rise in the proportion of pipeflow contributing to runoff as stream flow recedes. Often there are two or three peaks in the proportion of pipeflow to the streamflow falling limb. This is probably related to the timings of individual pipe recessions relative to that of streamflow. It is clear from Figure 12 that during intermediate streamflow pipes contribute a larger proportion of runoff. The eight separately monitored pipes can at times contribute over one third of streamflow. During both high and low flows, however, pipeflow contributions can fall to below 3 %.

McCaig (1983) estimated pipeflow in Slitherough Clough, Yorkshire. He suggested that as runoff increased, the proportion of runoff from piped areas also increased. However, these results were based on estimations using a mixing model and McCaig (1983) did not actually measure the pipeflow. Jones (1978) and Jones and Crane (1984) presented evidence for the Maesnant to suggest that pipeflow contributions were of reduced significance under very wet antecedent conditions and in the heavier rainstorms. There was also some additional evidence for another fall-off in percentage contribution in drier antecedent conditions and in the lighter storms. The density distribution shown in Figure 13 shows how for LDPS both high and low flows are accompanied by reduced relative pipeflow contributions. The highest contributions are recorded during medium flows of around 0.07 - 0.10 mm hr^{-1}. The highest densities on the plot occur when streamflows are low and therefore pipeflow contributions are low such that most of the time pipeflow contributes less than 15 % to streamflow.

A further important point arises from the very particular nature of the hydrology of blanket peat. In most soil types (other than deep blanket peat), where active piping occurs, including Maesnant, pipeflow may be expected to increase the rate of runoff from a catchment. However, in blanket peat the low hydraulic conductivity of the matrix and high water tables means that saturation-excess overland flow dominates the catchment response. Given the lag times and pipeflow response in comparison to streamflow it therefore seems that soil piping in blanket peat does not increase the rate of runoff production in these catchments. It may in fact be that piping actually supplies more of the recessional and 'baseflow' components which would otherwise be almost non-existent. This probably comes through near-surface (acrotelm) matrix and macropore seepage into the pipe networks, where the pipe roofs are close to the surface; as storm runoff recedes, overland flow ceases but the acrotelm continues to slowly drain. Figure 14 presents a simplified conceptual model of pipeflow supply within blanket peat catchments. High flows are supplied by saturation-excess overland flow and near-surface acrotelm flow as the water table is quickly raised to the surface. After rainfall cessation, as the water table falls over the upper few centimetres of peat, the acrotelm drains at a much slower rate but still provides flow into the pipe networks through matrix and macropore flow where the pipes tap these zones. Once the water table has fallen more than 5 or 10 cm into the peat mass the hydraulic conductivity of the peat is so low that water supply is virtually cut off from the pipes. Once below around 5 cm depth the water table only declines through evapotranspiration rather than throughflow drainage. Only a very small amount of catotelm drainage is supplied to the pipe system and can be accounted for by the very low flows (e.g. 1 ml min^{-1}) at 'perennial' pipe outlets. The pipes respond rapidly to rainfall in blanket peat in that in almost all of them flow begins to rise within two or three hours of rainfall onset. Infiltration rates are high in the upper few unsaturated centimetres of blanket peat allowing the water table to quickly rise to the surface producing saturation-excess overland and near-surface flow (Holden and Burt, in press). Thus pipeflow in blanket peat is probably reliant on water table depth within the acrotelm and on particular parts of the pipe network which tap the near-surface peat layers. The difference between blanket peat piping and other soil piping is that, although pipeflow is quicker in most cases, in comparison to other dominant flow processes occurring within the catchments, pipeflow is no more rapid than the other main flow pathways in blanket peat. In other soil types, however, pipeflow is often comparatively more rapid and will therefore contribute higher proportions of discharges on the rising limbs and peaks of the streamflow hydrograph. In catchments where overland flow is absent, pipeflow will tend to provide a runoff peak before throughflow, as noted in the East Twin catchment (Weyman, 1971). It is clear that more work on pipeflow sources and the complex nature of runoff pathway coupling in blanket peat catchments is required. While these issues have been discussed in the present study, full corroboration is beyond the scope of this paper. Nevertheless, this paper provides a starting point for further work and has allowed a fuller evaluation of the range of runoff production mechanisms in blanket peat catchments.

8. Conclusions

Pipeflow monitoring in the LDPS catchment has provided simultaneous, continuous flow records from a wide range of pipes within a deep blanket peat catchment. Whilst the record is only 5 months long and only 14 storms were analysed, 15 gauging sites were continuously monitored during the study period including 8 separate pipes. This is easily the most extensive continuous record of soil pipeflow outside of the Maesnant on Plynlimon. The pipeflow response from LDPS was found to be different to that on Plynlimon. This is important given the wide citation of the Plynlimon work. Both perennial and ephemeral pipes were found in the LDPS catchment throughout the soil profile. Importantly, the distinction between the two pipe types is often not clear and may therefore not be relevant in deep peat catchments. Pipe outlet depth had little relationship with the flow regime of the pipe in LDPS, although pipe outlet shape appeared to be affected by proximity to the peat-substrate interface. Outlet dimensions are the most commonly reported feature of soil pipes in the literature. However, outlet characteristics are misleading, because the pipe shape, size and depth may be very different a short distance upslope.

Weyman (1975) distinguished between streambank and hillslope piping. He claimed that the small pipes underlying extensive areas of hillslope in the Mendips seem to be connected to the surface through root channels and small cracks and responded rapidly to rainfall. The other pipes seen in streambanks represent the concentration of streamflow from the lower part of the slope and were fed directly from the soil matrix. The LDPS data show that this is not always the case as many pipes issuing into the streambanks can react quickly to rainfall and produce large volumes of discharge. These pipes can also extend up the hillslope for a considerable distance, some clearly fed in part by surface inlets. Direct capture of overland flow through pipe inlets may be a major source of storm runoff resulting in ‘start lag’ times of 2 hours or less. Cryer’s

(1979) water quality analysis of piping at Maesnant led him to agree with Jones (1978) that both soil cracks and seepage supplied the pipes with water.

Calculation of ‘surrogate basin area’ allowed the plotting of the Moor House data onto the generalised graphs of Anderson and Burt (1990) and Jones (1997a). This allowed a simple comparison to be made. The plots suggest that at the catchment-scale, saturation-excess overland flow is the dominant runoff-generating mechanism in blanket peat catchments. This agrees with the work presented by Holden and Burt (2000) and Holden *et al.* (2001). The pipes within the LDPS catchment behave differently to those on Plynlimon (Jones, 1997a). Whilst ‘start lag’ times for pipeflow in the LDPS catchment are shorter than at Maesnant, on Plynlimon, ‘peak lag’ times are approximately the same. Peak runoff rate, peak lag time and start lag time data from LDPS all plot outside the Maesnant data envelopes.

An important aspect of pipe hydrology in the LDPS catchment is that medium flows are sustained for a longer period of time than would otherwise be the case. Unlike the effect of soil piping in most soils (where other subsurface flow processes would dominate), which would be to increase the speed of runoff production within a catchment, soil pipes in blanket peat catchments appear to provide a greater proportion of flow on the falling limb of the stream hydrograph. These flows appear to come from drainage of the acrotelm and of bog pool and seepage zone areas where the acrotelm is slightly deeper. Pipeflow in LDPS, despite accounting for only around 10 % of streamflow in total, can nevertheless be a very important contributor to flow, particularly on the rising or falling limb of the stream hydrograph when pipeflow contributions can be in excess of 30 %.

Thus, although overland flow and near-surface flow processes are more important than pipeflow within LDPS, the dominance of the various processes changes through time and space during a storm event. Hence, in line with Jones (1979), the source areas for runoff within the LDPS catchment may be more dynamic in space than the classical Variable Source Area model of Hewlett (1961) would suggest.

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Table 1. Pipe characteristics in the LDPS catchment. Pipe dimensions, cm, are measured at the outlet. Pipe locations indicated in Figure 5.

Pipe code	Peat depth	Depth of pipe roof	Depth of pipe base	Mean diam	Length, metres	Flow type: eph/per	Automated monitoring, y/n
1	170	168	170	3		P	N
2	150	133	130	4	10	E	N
3	105	60	65	5	30	E	N
4	160	115	165	47	40	P	N
5	160	90	110	16		E	N
6	160	60	77	21		E	N
7	75	73	78	4	20	P	N
8	175				225	P	N
9	180	20	25	12	60	E	Y
10	110	115	130	13		P	Y
12	130	135	147	10		E	Y
13	80	90	75	20	80	P	N
14	110	85	110	19	55	P	Y
15	95	25	37	6	5	P	Y
16	110	105	115	32	150	P	Y
17	60	20	40	47	125	P	Y
18	75	5	10	7	60	E	Y
19	125	30	24	5	17	P/E	N
20	120	115	125	16	20	P	N
21	135	150	135	18	60	P	N
22	220	30	34	4	20	P	N
23	180	183	190	12	15	P	N
24	250	150	180	27	10	E	N
25	200	30	20	20	10	P/E	N
26	220	175	184	10		E	N
D1	100		50		180		Y
S1	95				25	P	Y
S2	90				55	P/E	Y
11a	260	15	35	25	10	P	Y
11b	225	5	50	40	70	P	Y
11c	245	0	90	70	115	P	Y
11d	55					P	Y

D = ditch, S = seepage zone, pipe 11 guaged at three sites with site 11d being near the outlet of the gully partly fed by pipe 11.

Table 2. Identified intensity of piping in LDPS compared to other selected piped sites (after Jones *et al.,* 1997 – calculated using source data from papers and topographic maps)

Catchment	Cross-sectional area of pipes m^2 km^{-1} streambank	Pipe frequency km^{-1} stream bank	Mean diameter of pipes, cm	Pipe volume in main area of piping, m^3 km^{-2}	Pipe density in main area of piping, km km^{-2}	Mean annual ppt, mm	Mean altitude, m	Mean main stream slope, degrees	Mean valley side slope, degrees
LDPS	**0.026**	**9.5**	**19**	**22 (44)^**	**4 (8)^**	**2000**	**540**	**2.2**	**3.0**
Maesnant, Cambria (Jones and Crane, 1984)	0.656	14.5	10^+	2099	98	2200	541	8.1	9.5
Afon Cerist Snowdonia (Jones, 1975)	0.567	80	10			2000	150	1.7	7.5
Burbage Brook, Peak District (Jones, 1975)	0.554	89	9			1000	357	2.0	10.2
Cerrig yr Wyn, Cambria (Gilman and Newson, 1980)	-	56	5	353	180	2200	472	10.3	9.0
Nant Gerig, Cambria (Gilman and Newson,	-	36	10	55.3	44	2200	495	4.4	9.0

1980)									
East Twins, Blackdown Hills (Stagg, 1974)	-	-	4	156.8	142	1100	244	-	2.3
Wolf Creek, Yukon (Carey and Woo, 2000)	-	-	8	70.5	15	260	1175	-	14.0
Wansfell, Lake District (Jones *et al*., 1997)*	-	-	3	124	175	2000	360	-	11.0

+ 10 cm for ephemeral, 24 cm for perennial pipes, *Jones *et al*., 1997 cite an unpublished BSc dissertation by Humphrys, B. 1978, University of East Anglia. ^Preliminary GPR survey over some areas of the catchment suggests that there is up to twice the length of piping than has been mapped from surface features and estimates are given in brackets.

Table 3. Results from hydrograph analysis of 14 storms between July to December 1999

Location	Mean storm Q, m^3	Peak Q, $m^3 s^{-1}$	Start Lag, hrs	Peak Lag, hrs	T_{rec}, hrs	Mean hydrograph intensity, s^{-1}
LDPS	10150	0.60700	1.7	3.3	25.1	32.3
9	48.2	0.00080	2.4	1.8	39.2	15.1
10	157.2	0.00269	3.3	7.8	58.8	13.9
11a	56.9	0.00296	1.5	4.8	25.4	25.2
11b	31.7	0.00198	2.1	4.9	26.7	21.9
11c	103.0	0.00461	1.3	4.8	34.7	26.0
11d	335.0	0.01310	2.2	2.4	40.5	19.7
12*	32.9	0.00202	3.7	1.7	21.3	36.5
14	7.7	0.00021	3.2	3.9	20.6	20.0
15	12.1	0.00025	1.2	2.8	17.5	13.0
16	35.7	0.00251	0.2	2.6	29.9	26.6
17	35.7	0.00128	5.8	8.5	12	26.0
S1	93.2	0.00181	1.1	2.7	19.5	14.1
S2	78.4	0.00116	4.6	3.4	45.5	10.3
D1	266.8	0.01250	3.2	5.9	25.7	22.6

*pipe 12 responded to 10 of the 14 storms analysed

Storm Q = Total storm discharge, m^3
Peak Q = peak discharge, $m^3 s^{-1}$
Start Lag = time from first recorded rainfall to hydrograph rise, hrs
Peak Lag = time from peak rainfall to peak discharge, hrs
T_{rec} = time from hydrograph peak to return to pre-event discharge
Hydrograph intensity = peak flow/10^6, $m^3 s^{-1}$ divided by total storm discharge, m^3 (s^{-1}).

Table 4. Selected pipeflow characteristics recorded in the literature

Source	Soil Type/Location	Peak discharge, l s^{-1}	Flow Type^{+}	Diam, cm	Slope m m^{-1*}	Start lag hrs	Peak lag hrs
Present Paper	**LDPS**	**4.6**	**E/P**	**3-70**	**0.05**	**0.1-3.7**	**1.6-8.5**
Weyman (1971)	Upper East Twins Basin, peaty podzol	1	E	2.5-5	0.04		
Stagg (1974)	Upper East Twins Basin, peaty podzol	0.75	E	2.5-5	0.04		
Knapp (1970)	Upper Wye, Plynlimon, peat	0.67-0.83	E/P	10			
Wilson (1977)	Nant Cwmllwch, Brecon Beacons	1.5	E/P	60	0.10		
Jones (1987)	Maesnant, peat and peaty podzol	59.3	E/P	5-30	0.17	8-13	1-5
Roberge and Plamondon(1987)	Lac Laflamme, nr Quebec, sandy till	1.11	E	'small'	0.2		
Gilman and Newson(1980)	Upper Wye, shallow peat, gley podzols	2.0	E	5-24	0.16	7$^{\#}$	
Muscatt *et al.* (1990)	Afon Cyff	1.5	E	5-10	0.25	5	6
Zeimer and Albright (1987)	Casper Creek, USA	8.5	E	15-45	0.3-0.7		
Tsukamoto and Ohta (1988)	Hakyuchi, Japan	0.5	P	5	0.52	9	5
Koyama (1994)	Hiruzen, Japan	1.85	E	50	0.47	34	28
Woo and diCenzo (1988)	James Bay Coast, Canada	0.7	E	6-7	0.0005	0	1
Elsenbeer and Lack (1996)	La Cuenca, Peru	0.22	E	8	0.51	0	0
Carey and Woo (2000)	Wolf Creek, Yukon	0.26	E	8	0.25	1^	14^
Uchida *et al.* (1999)	Kyoto, Japan, Forest Cambisol	0.18	E	5	0.5	11-12	1.6-3.7

*Ground surface angles at outlet $^{+}$Ephemeral/Perennial $^{\#}$variable depending on antecedence ^Snowmelt dominated, figures given are for two summer rainfall events recorded

Figure Captions

Figure 1. Conceptual model of runoff production in north Pennine blanket peat catchments based on work done by Evans *et al.*, (1999); Holden (2000); Holden and Burt (2000); Holden *et al.* (2001); Holden and Burt (in press), and Holden (in prep).

Figure 2. Location of the study catchment on the Moor House National Nature Reserve, UK.

Figure 3. An annotated aerial photograph of the LDPS catchment. NERC air photograph No 94/9(4) Run 7. 8856 6/8/95. Reproduced with kind permission of the Natural Environment Research Council (NERC (C)).

Figure 4. Discharge and precipitation in the LDPS catchment during days 241-272, 1999.

Figure 5. Main features and pipes of the LDPS catchment. Mapping was done using a Magellan differential GPS. Table 1 gives further details on the features within the catchment. Pipes 9, 10, 11, 12, 14, 16, 17 and 18 are monitored at the gauging stations indicated. The grip (D1), two seepage zones (S1, S2) and gully 1 are also gauged.

Figure 6. Pipe diameter, shape and location in the soil profile at LDPS. Closed = ‘perennial’, open = ‘ephemeral’.

Figure 7. Example pipe outlets. a) vertically elongated pipe outlet entirely within the peat. b) horizontally elongated pipe at the peat-clay interface.

Figure 8. Discharge from the LDPS monitoring stations during days 241-272, 1999 (LDPS discharge over the same period is shown in Figure 4).

Figure 9. Lag time characteristics of the LDPS monitoring stations compared to streamflow lag times, a) Start lag, number of hours greater than streamflow begins to rise, b) Peak lag, number of hours greater than streamflow peak lag, c) Fall lag, number of hours greater than mean streamflow recession (time from rain end to flow back to pre-storm level).

Figure 10. Storm discharge characteristics at the LDPS monitoring stations, a) mean storm discharge, b) mean storm discharge divided by estimated pipe length (no data for pipes 10 and 12 as length undetermined), c) peak discharge recorded during study period, cumecs, d) area-weighted peak discharge during study period, mm hr^{-1}, as determined from calculation of surrogate basin area. Monitoring stations coded as given in Table 1 and Figure 5. d1 = ditch, s1, s2 = seepage zones, 11a-d = monitoring sites along pipe 11.

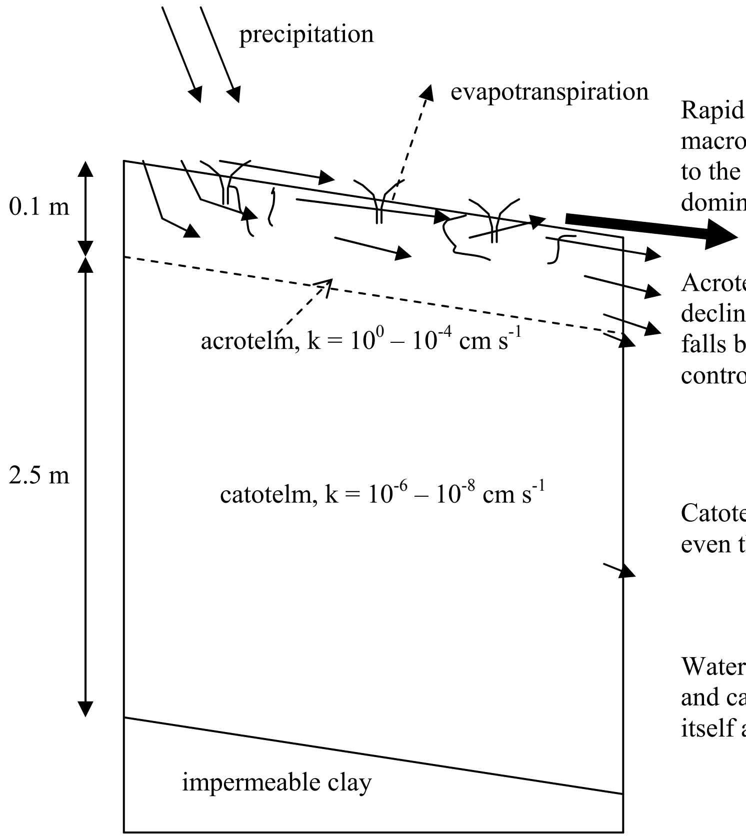
Figure 11. A comparison of the LDPS data with that from Maesnant (Jones, 1997a) and the collations of Dunne (1978), Kirkby (1985) and Anderson and Burt (1990). Peak runoff rates (a), peak lag times (b) and start lag times (c) for hillslope processes. Squares = perennial pipes, open circles = seepage zones, crosses = ephemeral pipes,

triangle = gully 1. (Trout Beck is a 11.4 km^2 tributary of the Tees in the blanket peat moorlands of the Moor House Reserve and is discussed in detail by Evans *et al.,* 1999 – see also Figure 2).

Figure 12. Pipeflow contribution to streamflow in the LDPS catchment during days 241-272, 1999.

Figure 13. Density distribution of the proportion of time pipeflow contributes a given percentage to streamflow in the LDPS catchment, July to December 1999. A darker cell indicates that there are a greater number of occasions when pipes contribute a given percentage to catchment runoff than for a lighter cell. For example, when catchment runoff is 0.1 mm hr^{-1}, pipes contribute between 5 and 10 % of the streamflow volume during less than 0.5 % of the total monitoring time.

Figure 14. Conceptual model of pipeflow sources during a storm event related to water table position in blanket peat. a) water table at the surface, b) water table mid-acrotelm, c) water table near the base of the acrotelm.



Rapid infiltration through permeable upper acrotelm matrix and macropores (root structures, cracks etc) until the water table rises to the surface producing saturation-excess overland flow which dominates the catchment response

Acrotelm throughflow – matrix and macropore flux, declining rapidly with depth. The water table rarely falls below 10 cm depth and when it does it is controlled almost entirely by evapotranspiration

Catotelm throughflow – very restricted even though permanently saturated

Water transfers between the acrotelm and catotelm and within the catotelm itself are very restricted

Figure 1.

Figure 2.

Figure 3

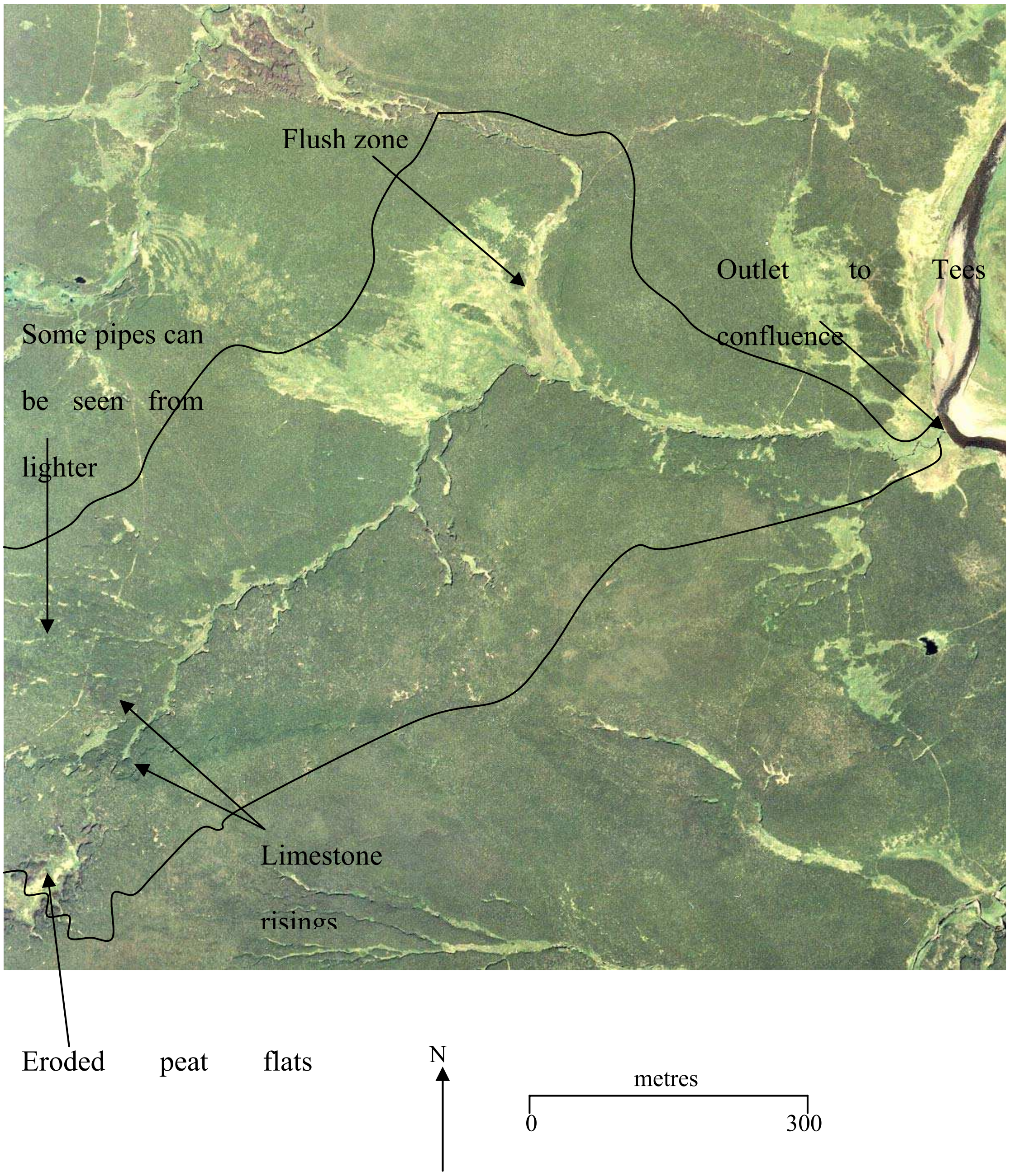
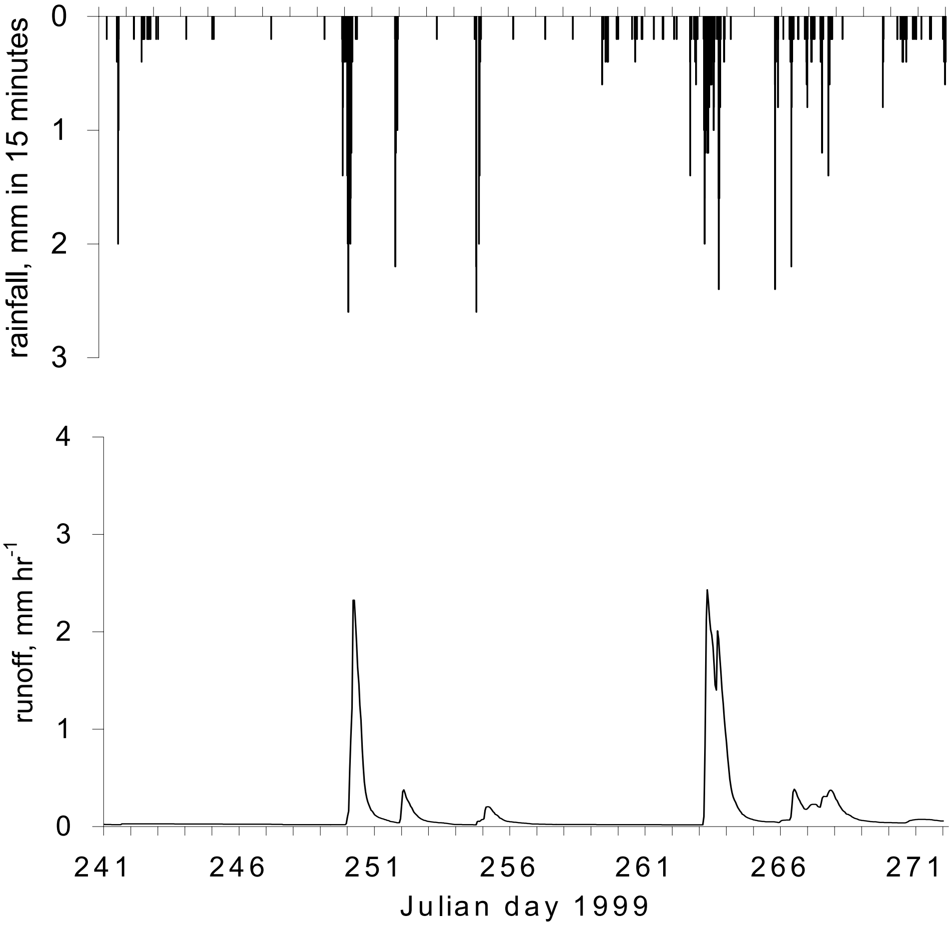

Flush zone
Outlet to Tees confluence
Some pipes can be seen from lighter
Limestone risings
Eroded peat flats
N
metres
0
300

Figure 4.



rainfall, mm in 15 minutes
0
1
2
3
runoff, mm hr^{-1}
4
3
2
1
0
241
246
251
256
261
266
271
Julian day 1999

Figure 5,

Figure 6.

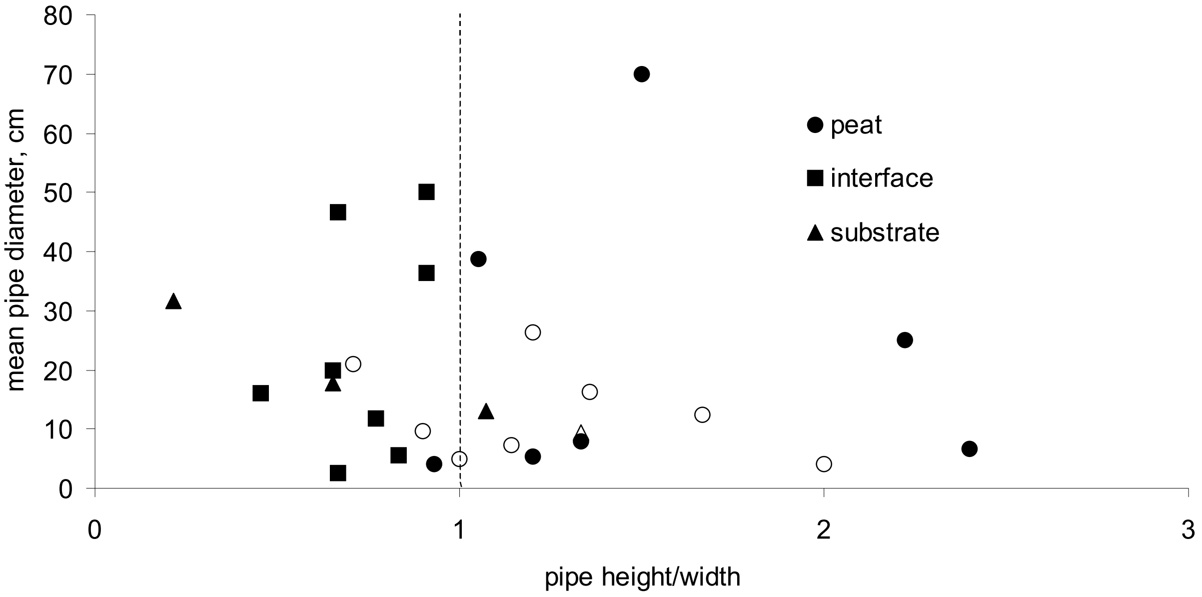

80
70
60
50
40
30
20
10
0
mean pipe diameter, cm
0
1
2
3
pipe height/width
● peat
■ interface
▲ substrate

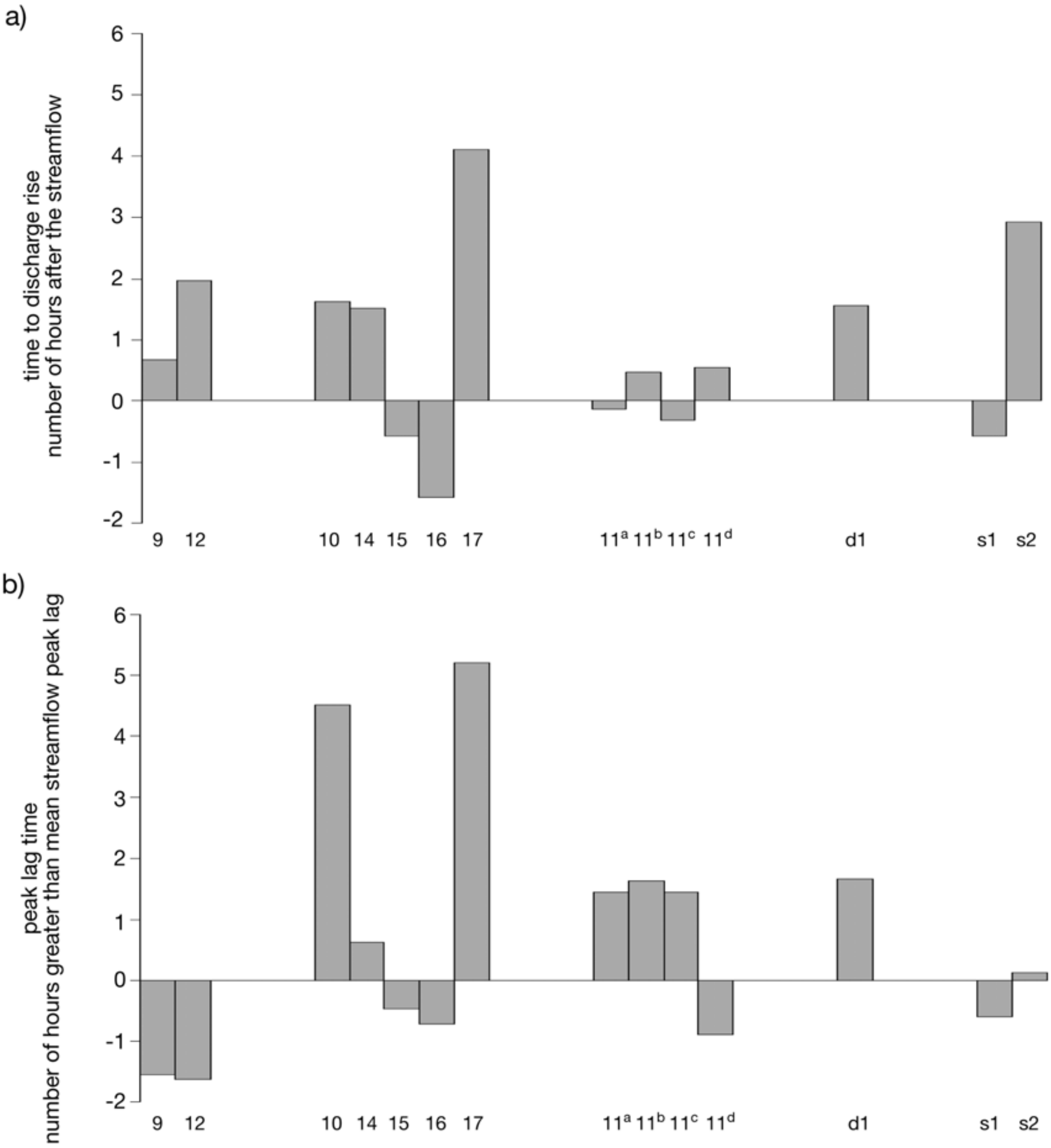
Figure 7.

a)

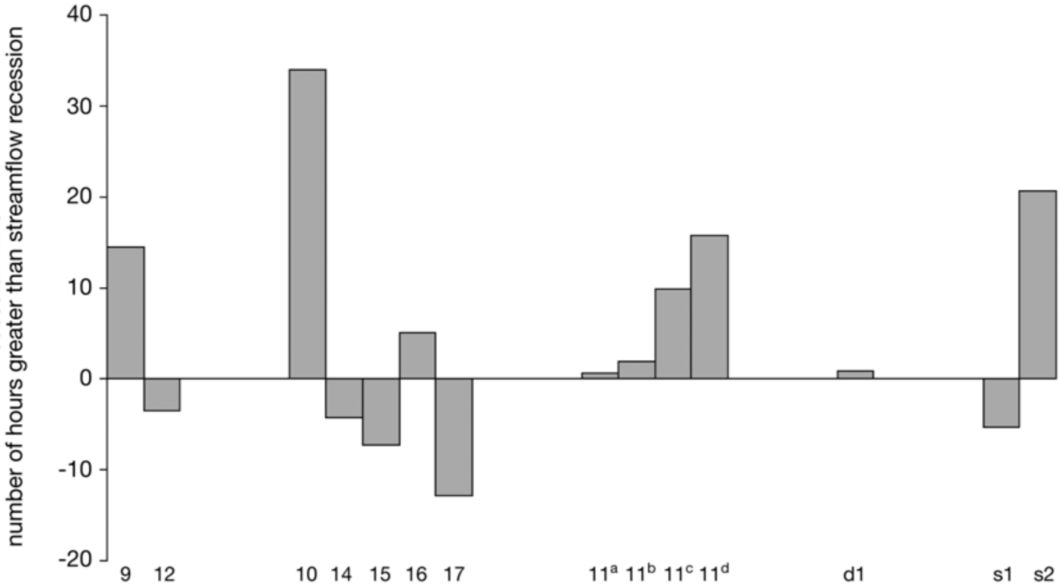
b)

Figure 8.

Figure 9.


a)
time to discharge rise
number of hours after the streamflow
6
5
4
3
2
1
0
-1
-2
9
12
10
14
15
16
17
11^a
11^b
11^c
11^d
d1
s1
s2
b)
peak lag time
number of hours greater than mean streamflow peak lag
6
5
4
3
2
1
0
-1
-2
9
12
10
14
15
16
17
11^a
11^b
11^c
11^d
d1
s1
s2

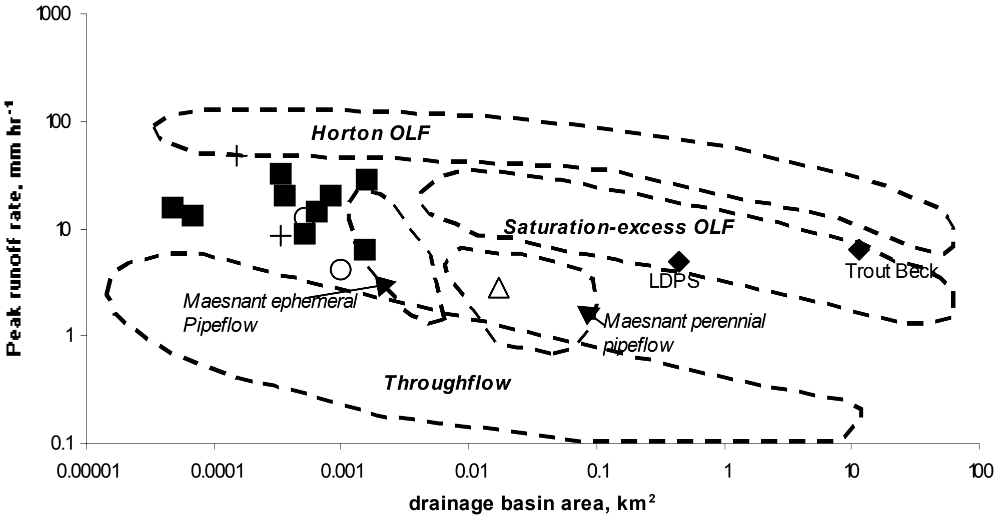
c)



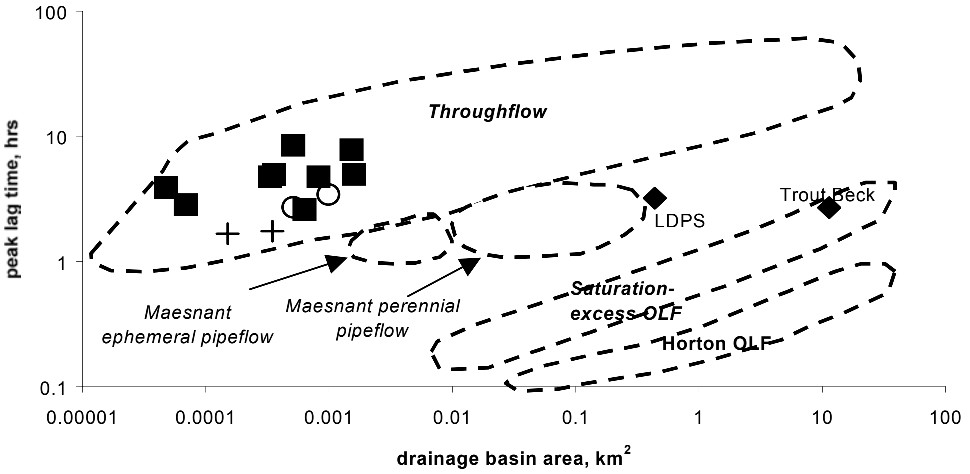
recession time
number of hours greater than streamflow recession
40
30
20
10
0
-10
-20
9
12
10
14
15
16
17
11a
11b
11c
11d
d1
s1
s2

Figure 10.

Figure 11.


1000
100
10
1
0.1
Peak runoff rate, mm hr^{-1}
Horton OLF
Saturation-excess OLF
Throughflow
Maesnant ephemeral Pipeflow
Maesnant perennial pipeflow
LDPS
Trout Beck
0.00001
0.0001
0.001
0.01
0.1
1
10
100
drainage basin area, km^2

b)


100
10
1
0.1
peak lag time, hrs
Throughflow
Maesnant ephemeral pipeflow
Maesnant perennial pipeflow
LDPS
Trout Beck
Saturation-excess OLF
Horton OLF
0.00001
0.0001
0.001
0.01
0.1
1
10
100
drainage basin area, km^2

c)

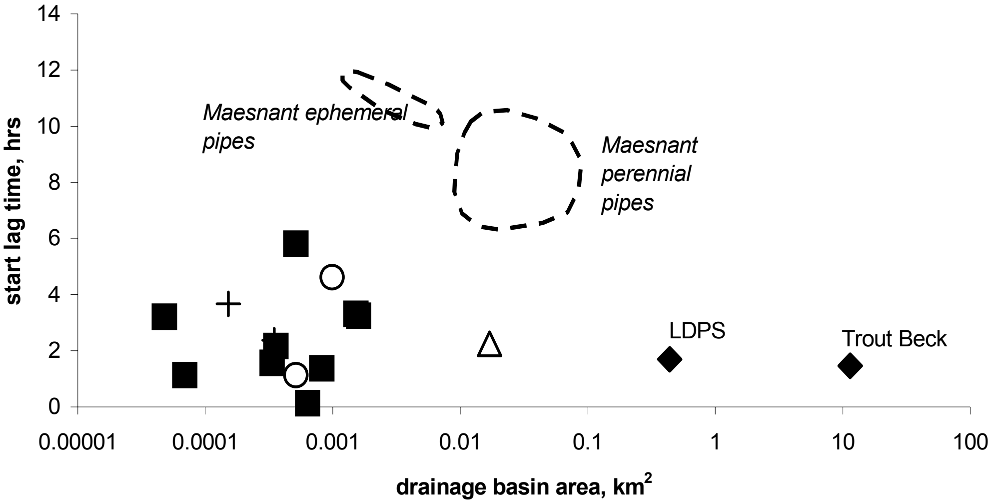

14
12
10
8
6
4
2
0
start lag time, hrs
0.00001
0.0001
0.001
0.01
0.1
1
10
100
drainage basin area, km²
Maesnant ephemeral pipes
Maesnant perennial pipes
LDPS
Trout Beck

Figure 12.

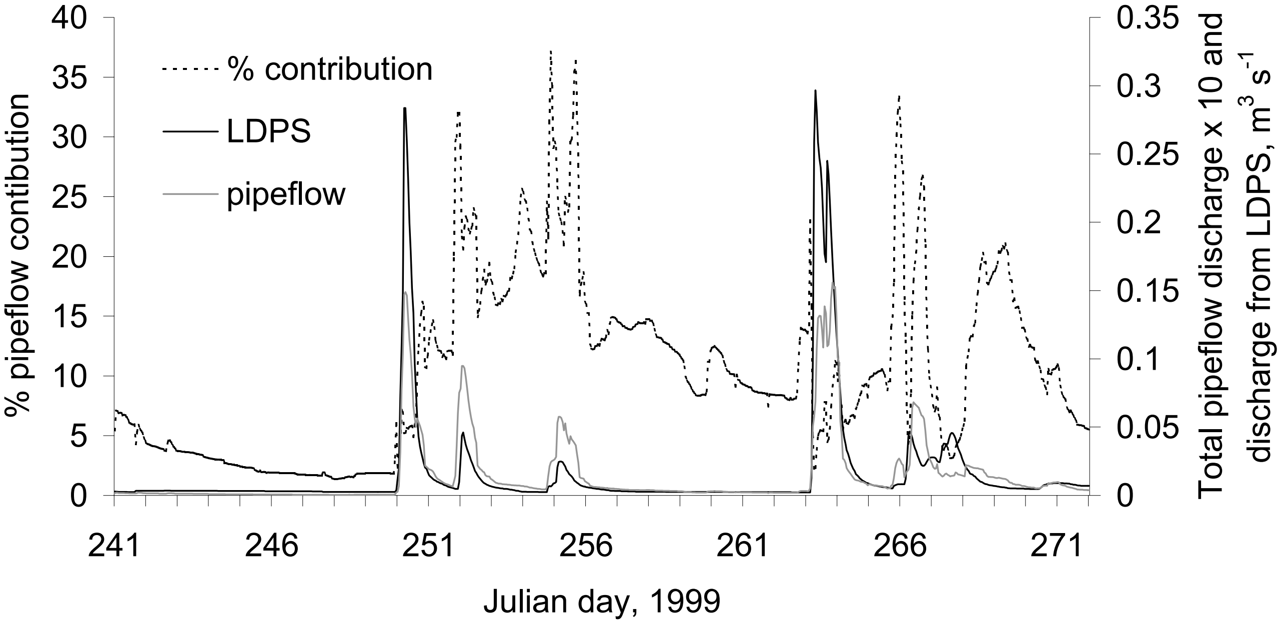

% contribution
LDPS
pipeflow
% pipeflow contibution
40
35
30
25
20
15
10
5
0
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Total pipeflow discharge x 10 and discharge from LDPS, m^3 s^{-1}
241
246
251
256
261
266
271
Julian day, 1999

Figure 13.

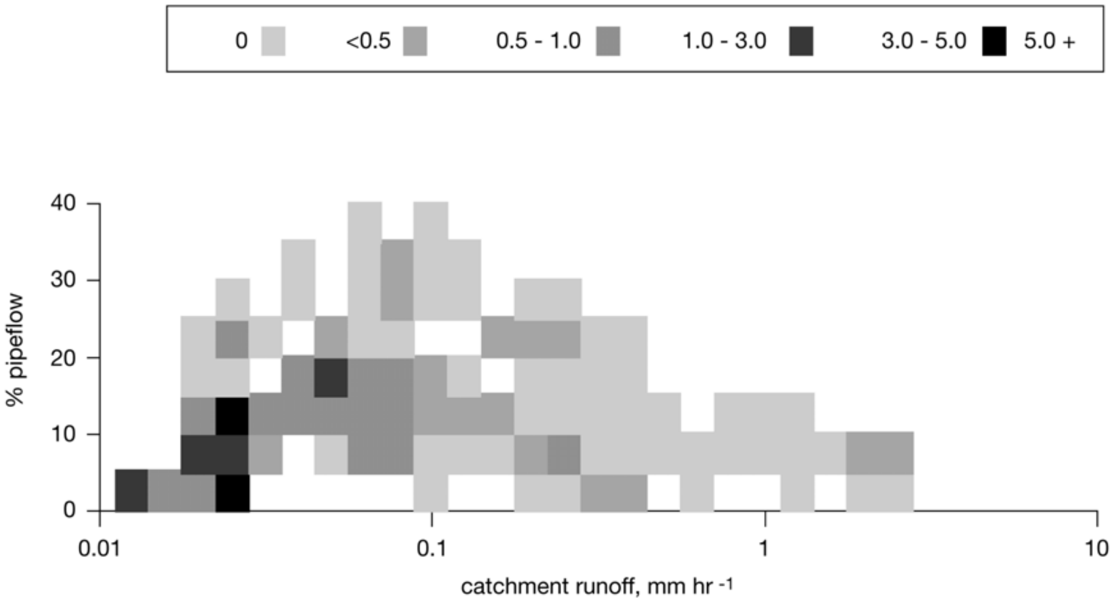
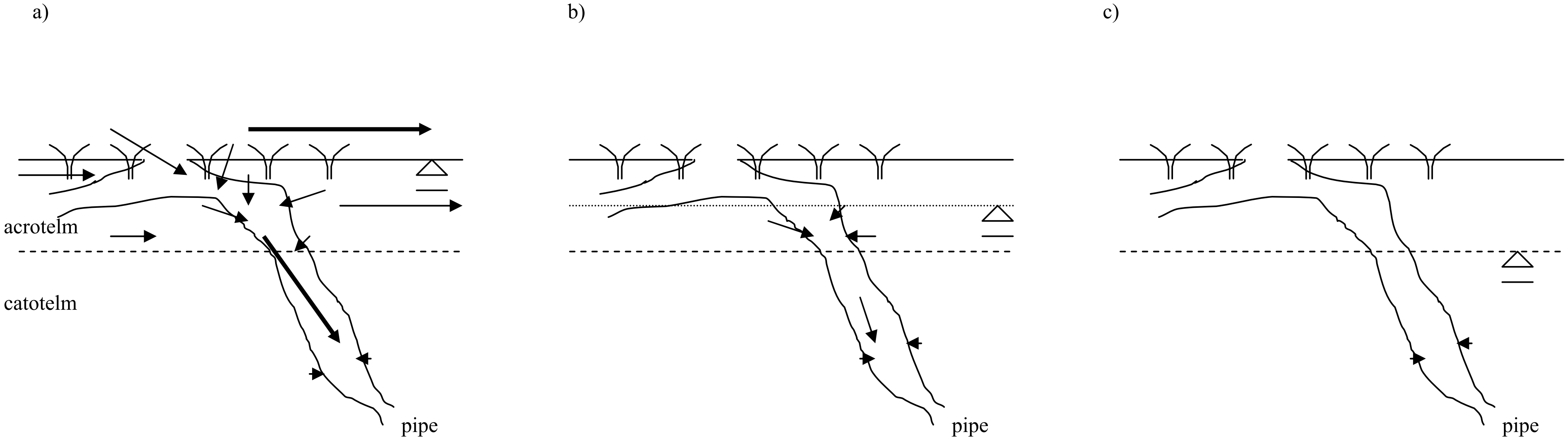

0
<0.5
0.5 - 1.0
1.0 - 3.0
3.0 - 5.0
5.0 +
% pipeflow
40
30
20
10
0
0.01
0.1
1
10
catchment runoff, mm hr -1

Figure 14.



Flow entering pipe as saturation-excess overland flow, acrotelm throughflow, seepage through root structures and near-surface cracks and macropores.

Flow entering pipe as acrotelm throughflow. Recession limb may be prolonged as the pipe drains flush zones, bog pool areas and the deeper acrotelm layers

Pipeflow restricted to catotelm matrix input which is limited by low hydraulic conductivity – thus pipeflow almost ceases.