Modelling flow in natural soil pipes and its impact on plant ecology in mountain wetlands

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ABSTRACT Marked vegetation patterns in acid moorland in mid-Wales are related to networks of natural soil pipes. Half the discharge of the stream is derived from water draining rapidly along these subsurface networks. Piping is positively associated with two grassland. The phreatic surface is shown to be affected to a limited lateral extent corresponding very closely with transitions from heath to grassland. Modelling of pipeflow confirms that three main processes of drainage feed the pipes, which affect drainage rates, oxidation and supply of nutrients. Suggestions are made as to the significance of piping for conservation and management.

INTRODUCTION

Marked vegetation patterns in mountain moorland in the Cambrian Mountains of mid-Wales appear to follow the lines of subsurface drainage provided by natural soil pipes. In the Maesnant Experimental Basin these pipes vary in size from 90 mm diameter in the ephemeral-flowing pipes on the upper slopes to 240 mm diameter near the outfalls of perennially-flowing pipes on the river terrace edge near the stream. Intensive monitoring of flows shows that ca. 50% of annual stream discharge is derived from pipes (Jones & Crane, 1984; Jones, 1987, 1988).

Three broad categories of flow regime can be recognized in the pipes: perennial, seasonal, and ephemeral. Mapping the pipe networks by dye tracing and ground survey has revealed a remarkable 4.4 km of pipes in a drainage area of 23 ha (Fig. 1). Of this, 1.8 km flow throughout the year. The ephemeral section is activated in about one storm in three. Following an average rainstorm of 30 mm, the ephemeral network yields 600 m$^3$ of water, half of which passes into the perennial network contributing to a gross yield of 2200 m$^3$ from the perennial outfalls. Little overland flow has been observed, except from overflowing pipes.

Pipeflow is therefore the most important single drainage process on the hillslopes of Maesnant. Analysis of the distribution of piping in Britain suggests that it is common throughout the upland zone, particularly on otherwise poorly drained soils (Richardson, 1991).
The potential ecological effects of piping in mountain moorlands therefore demand attention.

VEGETATION PATTERNS

The basin displays obvious vegetation patterns (Fig. 2). *Juncus* dominates along seepage lines and *Sphagnum* bogs develop in holding areas or areas of exfiltration of groundwater. Blanket bog and wet heath occupy gentler slopes (ca. 4°) on terraces, while acid grassland dominates the steeper slopes (over 12°). Areas drained directly by perennial pipes are marked by linear extension of the acid grassland association between communities dominated by *Vaccinium*, *Empetrum* heath and *Eriophorum vaginatum*. The zone of ephemeral pipes is marked by a belt of grassland dominated by *Nardus stricta* flanked by wet heath comprising mainly *E. vaginatum* and *Calluna*.

An intensive programme of field sampling and mapping was undertaken to investigate the relationship between piping, vegetation, and soils. Vegetation associations were identified from 1:2500 colour air photography. Quadrat locations were selected at random within each patch and soils were sampled simultaneously at all 234 sites.

Ordination and monothetic classification of vegetation

Ordination analyses were undertaken on both species and quadrats, using Detrended Correspondence Analysis, and association analysis was based upon the information statistic (Causton, 1988).

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**FIG. 1** Pipe networks and monitoring sites for intensive pipeflow study in the Maesnant Experimental Catchment.
Both species and quadrat ordination indicated the importance of soil moisture status in species distribution. Axis I of the quadrat ordination (Fig. 3) shows an ordered sequence from dry acidic grasslands near the origin (associations A to D and H), through wet heath and bog communities (F, G, I and J) to the very wet Juncus and Sphagnum communities (K to H) at the extreme right. Axis II is less clearly differentiated, but tends to distinguish mesotrophic environments (associations C and H) from oligotrophic (F, K and L).

The relationship between piping and vegetation

Piping is noticeably absent from both the wettest and the driest plant communities. The quadrat ordination diagram (Fig. 3) clearly illustrates the preferred location of piping, concentrating in the mid range of Axis I and the lower to mid range of Axis II. There is a
slight difference between the main pipeflow regimes, with the ephemeral pipes tending to plot a little higher on both axes, i.e. in the direction of wetter and less mesotrophic plant communities. In the field this may be seen in the tendency for the shallow ephemeral pipes, with beds averaging just 150 mm below the surface, to be marked by narrow lines of mosses, particularly Polytrichum commune. In contrast, the perennial pipes, flowing at depths of 0.5 m or more, often cause no differences in vegetation directly above their roofs.

A clear indication of the relationship between piping and vegetation associations was given by contingency analysis, which produced a chi-square value significant at the 1% level. This is largely due to the strong association of piping with just two communities, C and H. C is a dry acid grassland community dominated by mountain mat grass, N. stricta, and containing lichens of the genus Cladonia indicating a relatively dry environment.

Association H is another dry acid grassland in which N. stricta is common. H also contains the bent grasses Agrostis capillaris and A. canina, sheeps fescue Festuca ovina and heath bedstraw, Galium saxatile. A third dry acid grassland group, D, also shows a high frequency of piping although this is not statistically significant.
This leaves two dry grassland communities, A and B, which have very little piping. The vegetational differences between the piped grassland associations and these associations lie primarily in the higher bryophyte component in the piped grassland areas and the higher percentage of raw peat soils or histosols (Peat/Crowdy soil series, see Avery (1980)). Bryophyte differences in these communities require further investigation. Between 37 and 48% of piped grassland areas are developed on histosols, compared with only 25% of pipe-free grassland areas. The latter are predominantly developed on aquods or stagnopodzols of the Hafren soil series. Associations C, D and H appear to be somewhat wetter than A and B. In detail, group H, which has the strongest statistical association with piping, is the only grassland community to lack bilberry, Vaccinium myrtillus. In contrast to the driest grassland community, A, it also contains the sweet vernal grass Anthoxanthum odoratum.

The impression that piped areas are marked by wetter associations of acid grassland confirms the ordination analysis. Figure 3 shows that the main piped associations C and H map into a very similar region, distinctly wetter than A and tending to be lower on Axis II than either B or D.

No pipes are found in the freely draining soils of association G, in which Deschampsia flexuosa is the dominant grass. 83% of quadrats in this association were found to be on the aquod Hafren soil series, and the disassociation with piping is marked, with none of the 30 quadrats containing pipes. Similarly, no pipes were found in the very waterlogged plant communities K, L and M, characterised by very wet flush vegetation containing Montia fontana (group K) or by bog areas of Sphagnum cuspidatum, S. papillosum and S. recurvum. 80% of quadrats in these associations lay on histosols.

As an individual species, Juncus effusus, is particularly associated with piping, occurring in the more marked surface depressions, 1-2 m wide, directly overlying perennial pipes and some of the larger ephemeral pipes (e.g. site 15 in Fig. 1). These narrow linear depressions have significantly thinner peaty O horizons, averaging 10 cm less. Juncus also concentrates in areas where pipe roofs have collapsed or where pipe effluxes issue onto the surface. In all of these microenvironments, Juncus is able to extend roots into perenially or frequently saturated zones and may benefit from the regular supply of fresh nutrients carried by pipe waters.

Some interesting reversals in expected habitats are associated with the development of piping. Acidic grassland associated with the pipes is frequently found on gentler slopes than blanket peat bog, presumably as a result of local drainage by the pipes. This drainage effect is reflected in the very marked striped patterns in the vegetation following the lines of perennial pipes on the lower slopes. Here grassland occupies the broader (ca. 10 m wide) depressions whilst wet heath vegetation occupies the ridge areas rising 0.5-1.0 m above the depressions. As a result, many areas show vegetational transitions from Juncus in the centre of the depressions through dry acidic grassland covering the rest of the depression to wet heath on the microtopographic interfluves. Laboratory analyses of saturated hydraulic conductivity on undisturbed samples and field measurements of soil moisture status taken by quick-pull tensiometer during dry summer weather both indicate that the pattern is due to better drainage in the depressions.
Measurements of hydraulic conductivity in the peat horizon taken in three transects across one of these grassland depressions in the perennial pipe zone shows that, although values are low, peat conductivity is almost twice as high in the immediate vicinity of a pipe as it is 5 m distant; averaging 0.0030 mm s$^{-1}$ against 0.0018 mm s$^{-1}$ 5 m away. The peat is not only less conductive but it is also thicker away from the pipes. This compounds the poor drainage in the rooting zone, even though the trend in hydraulic conductivity reverses within the mineral E/G horizons, from 0.0321 mm s$^{-1}$ near the bed of the pipe to 0.1723 mm s$^{-1}$ 5 m away.

SOILS AND NUTRIENT STATUS

Piping is only associated with two of the eight soil series in the basin. Perennial piping is developed solely within the deeper, oligo-amorphous humidified peat soils of the Crowdy series. Ephemeral pipes are principally located in the shallow loamy ferric stagnopodzols of the Hafren series, with some larger ephemeral and seasonal pipes on Crowdy or intergrade Crowdy-Hafren soils.

Piping is not encountered within eutro-amorphous peat soils, nor in shallow rankers on the higher slopes (udorthents and lithic histosols) or the stony alluvial soils along the stream. In the raw amorphous peat, hydraulic conductivity is too low for erosive development of macropores and they remain too wet for desiccation cracking. The ranker soils, in contrast, are too coarse grained, and the alluvial soils lack sufficient hydraulic gradient (Jones, 1981).

Available nutrient concentrations were measured in bulk samples taken from the top 150 mm root zone in piped and pipe-free sites within the Crowdy and Hafren series. This indicated a number of small but statistically significant differences (Table 1). Concentrations of macro-nutrients were fractionally higher immediately above the pipes in both soil series, with K and Mg being significant in the Hafren and Ca in the Crowdy.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Hafren (aquod)</th>
<th>Significance level (%)</th>
<th>Crowd (histosol)</th>
<th>Significance level (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P</td>
<td>NP</td>
<td>P</td>
<td>NP</td>
</tr>
<tr>
<td>Soil organic %</td>
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<td>55.6</td>
<td>-</td>
<td>83.2</td>
</tr>
<tr>
<td>pH</td>
<td>4.2</td>
<td>4.0</td>
<td>5.0</td>
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</tr>
<tr>
<td>Conductance</td>
<td>28.2</td>
<td>38.8</td>
<td>0.1</td>
<td>30.8</td>
</tr>
<tr>
<td>(μS cm$^{-1}$)</td>
<td>8.0</td>
<td>11.0</td>
<td>2.5</td>
<td>8.6</td>
</tr>
<tr>
<td>K (mg l$^{-1}$)</td>
<td>6.5</td>
<td>7.3</td>
<td>-</td>
<td>8.4</td>
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<tr>
<td>Na</td>
<td>6.8</td>
<td>7.1</td>
<td>-</td>
<td>10.6</td>
</tr>
<tr>
<td>Ca</td>
<td>4.3</td>
<td>5.3</td>
<td>5.0</td>
<td>8.5</td>
</tr>
<tr>
<td>Mg</td>
<td>0.1</td>
<td>0.1</td>
<td>-</td>
<td>0.2</td>
</tr>
</tbody>
</table>

TABLE 1 Comparison of piped (P) and pipe-free (NP) soils.
Indicative through these results may be, a fuller exploration of available nutrient distribution throughout the soil profile is clearly needed. The observed pattern could indicate concentration and replenishment of nutrients around pipe roofs in high flow events. However, it could, perhaps more likely, be related to improved drainage and cyclical oxidation and rewetting around the pipes, which increases organic decomposition and the availability of nutrient cations. The higher organic content above the pipes could help this. Slightly higher infiltration capacities above the pipes could also aid penetration and adsorption of rainfall solutes (Hyett, 1990).

MODELLING PIPEFLOW

Monitoring of pipeflow and phreatic surface fluctuations has provided data on which to base a computer simulation model of pipeflow response (Connelly, 1991). This offers a means of testing:
(a) the sources of pipeflow and, therefore, pipeflow solutes,
(b) the effect of piping on soil drainage,
(c) the size of the micro-catchment areas drained by the pipes.

Monitoring and modelling were concentrated on the perennial and ephemeral network draining to pipe site 4 (Fig. 1). This was chosen as the largest and most diverse of the networks, extending 750 m from its outfall, 60% of this being ephemeral. It contains 1.36 km of ephemeral pipe and 536 m of perennial.

Pipeflow was monitored at four sites (4, 9, 14 and 18 on Fig. 1) and transects of piezometers and dipwells were set perpendicular to the line of pipe at each site. All pipeflow and dipwell sites were logged at 10 minute intervals using Tinylog solid state data loggers for 7 to 15 months. Rainfall was logged at 5 minute intervals. This provided complete data for 49 storms to use in developing and testing the pipeflow model.

The data showed that pipeflow is closely linked to phreatic surface fluctuations in both the perennial and ephemeral sections. This was to some extent unexpected in the ephemeral zone, where it had been thought that relatively rapid access to the shallow pipes through innumerable desiccation cracks at the surface would allow stormwater to enter and use the pipe before the subsoil was saturated. Newson & Harrison (1978) considered that ephemeral pipes lose sizeable volumes of discharge to influent seepage rather than gaining flow by effluent seepage from the saturated zone. Gilman & Newson (1980) describe an experiment in which 50% was lost by leakage within the soil with an artificial input of 1.5 l s\(^{-1}\). Gilman & Newson (1980) also noted from records of natural pipeflow that recession curves did not show the expected exponential decline, but fell more steeply, presumably due to increasing losses to influent seepage as flow levels fall. They tended to follow the view of Weyman (1974) that ephemeral pipes act more as a "runoff maintenance system" transmitting flows released from blanket bogs upslope than as a "runoff generating system". However, none of these workers monitored phreatic levels.

The new evidence from Maesnant indicates phreatic levels rising in the Hafren soils before pipeflow begins and that pipeflow only commences when the phreatic surface intersects the pipe bed. The tendency to very steep recession is confirmed in our records, but this can be seen as due to a combination of a) influent losses through the
beds, once the phreatic surface falls below the bed, and b) the lack of dynamic storage within the pipe system, which is typically of the order of $0.001 \text{ m}^3 \text{ m}^{-1}$. The simulated pipeflow experiments of Newson and colleagues were undertaken in "dry" conditions and we must conclude that they give a misleading impression of normal natural pipeflow events.

In both sections of the network, phreatic surfaces are generally lower towards the pipes, indicating the drainage effect. However, during storm response, phreatic surfaces can rise rapidly adjacent to the pipes, particularly at the lower end of the system (site 4). In the perennial pipes the rise is faster than can be explained by lateral seepage down the local hydraulic gradient towards the pipes. In some cases, the dipwells nearest to the pipes were observed to overflow before any reaction was observed in dipwells to either side. All the dipwells within the microtopographic hollows around the pipes show short-term fluctuations which closely reflect the pattern of discharge in the pipe, with an overall correlation of $r = 0.90$. Only the dipwells on the interfluves, the areas covered by wet heath vegetation (association D) as opposed to acid grassland (association C), fail to show these detailed fluctuations exhibiting only a simple gradual rise and fall.

This suggests a dual support system for pipeflow, with local seepage towards the pipe being supplemented by "ready made" discharge from upslope sources. It also implies that the microtopographic depressions channel waves of throughflow in parallel with the pipe. As these depressions are defined by the contours of both the surface and the Oh/E and E/C horizon interfaces, as well as having greater hydraulic conductivity nearer the pipe in the organic horizons, they confine any influent seepage losses. Hence, influent seepage will tend to be returned as effluent supply later in the storm. Chemical analyses of dipwell water sampled in these depressions during stormflow shows that they are frequently indistinguishable from pipeflow in contrast to samples of peat water from other sites. The situation seems to be similar to bank storage in a river and the return flow must contribute to the reduced rates of recession observed in the perennial pipes compared with the ephemerals. For the vegetation, it means that broad areas of the depressions experience not only similar drainage conditions, but also frequent exchange of nutrients with the pipeflow.

Evidence for the size and nature of the upslope source area is adduced from detailed topographic mapping of surface contributing areas (Jones, 1986), dye tracing experiments and calculations of contributing areas based on discharge measurements at the pipeflow weirs. These suggest that the sources consist of:

(a) an element of "channel precipitation" from rain falling directly onto the saturated surfaces of the mid-slope bogs and draining into the heads of the perennial pipes;
(b) increased groundwater seepage into these bogs during storms;
(c) ephemeral pipeflow, some of which issues into the midslope bogs, operating in about one in three stormflow events; and
(d) overland flow drainage into blowholes or roof cracks along the perennial pipes during the more intense storms.

A FORTRAN 77 pipeflow simulation model was therefore developed to reproduce the observed flow response, based on two source areas:
(a) an upslope supply area, and
limited areas orthogonal to the long axis of the pipe. Orthogonal supply is controlled by the hydraulic conductivity, a variable hydraulic gradient and the area of pipe circumference below the phreatic surface. The latter two parameters are controlled by the rate of water supply from the surface via matrix and macropore seepage, although the matrix component is so slow as to be ignorable on a storm timescale. Since the calculation of macropore seepage rates would require detailed data on macropore distribution and geometry, empirical relationships were established between rainfall and dipwell levels that could be used to calculate hydraulic gradients. The same model is used for the ephemeral network, except that the phreatic surface is allowed to fall below the pipe beds. Antecedent rainfall is used to determine phreatic level, based upon seven-day correlations in the observed record. Output from the ephemeral pipes was used as one element of upslope supply for perennial pipes. A second element comprised calculated "channel precipitation" receipts over the mid-slope bog surface. Groundwater supply to the bog presents a more inscrutable source. This was estimated empirically using flow records for site 9 just below the bog and calculating contributing area, A, from total storm discharge, Q, and storm rainfall, P, using the formula:

$$A = \frac{Q}{P}$$

Finally, the perennial pipe system is divided into segments, each receiving inputs from appropriate sources. These are cumulated at 5 minute intervals and routed downpipe. Routing is based on observed velocities measured by dye dilution, which gave:

$$V = 0.025 Q^{0.743}$$

[FIG. 4 Simulated and observed flow response at pipe site 4.]
The model simulates pipe response well and the goodness-of-fit estimated by the error sum of squares objective function, \( F \) (0.0869 > \( F > 0.0002 \)), indicated a high degree of correspondence between observed and simulated hydrographs, as illustrated in Fig. 4.

The main conclusions that can be drawn from the success of this relatively crude, but physically-based pipeflow model and the field data on which it is based are:

(a) the main sources of pipeflow have been correctly identified;
(b) both ephemeral and perennial pipeflow are essentially generated by the same mechanisms, except for baseflow in perennial pipes;
(c) perennial pipes drain a limited area either side which corresponds to a marked change in vegetation from heath to grassland;
(d) this zone is subject to frequent, rapid oscillations in saturation levels accompanied by nutrient supplies from upslope during storms;
(e) the area potentially contributing nutrients can be very large, reaching a maximum of 3.56 ha for the modelled pipe.

CONCLUSIONS

Kent & Wathern (1980) have shown the importance of soil moisture status in determining the pattern of upland vegetation. The current study has further demonstrated the importance of natural soil piping in controlling both the soil moisture distribution and vegetation patterns in the Maesnant catchment. The pipes are responsible for the development of extensive strips of grassland between the heath moorland associations.

The pipes have two major effects on the vegetational environment:

(a) they improve drainage and aeration by lowering the phreatic surface, and probably also by developing networks of smaller macropores around them due to desiccation, drawdown pressures or improved biotic activity, which improve hydraulic conductivity;
(b) the perennial pipes channel nutrients from large areas of slope, and these are spread by lateral seepage throughout the soil in the microtopographic depressions along the pipe.

Destruction of these natural subsurface networks in land improvement schemes, involving ploughing and reseeding grasslands, has caused waterlogging problems (Gilman & Newson, 1980; Jones, 1981). If ploughing is undertaken, it may be advisable to avoid grassland underlain by extensive piping, even though it may be Nardus dominated.

On the other hand, Hyett (1990) has shown that piping tends to aggravate acidification problems in surface water. By speeding storm drainage, reducing residence times and directing water through upper soil horizons away from deeper mineral weathering sites, pipes reduce the buffering of acid rain (Jones & Hyett, 1987). By increasing aeration of histosols, they also encourage the release of sulphates and organic acids. Ephemeral pipes tend to carry the highest aluminium concentrations, especially of the critical monomeric form; Hyett (1990) measured average values in the toxic range for fish, up to 0.58 mg l\(^{-1}\). In basins dominated by ephemeral piping, destruction of pipes may be a valid anti-acidification measure.

Similarly, the presence of pipe networks has implications for selecting the most effective sites for liming, for minimising the
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impact of afforestation and for preserving natural moorland habitats. Field experiments in Wales have demonstrated the efficacy of liming source areas only as opposed to liming whole catchments (Edwards et al., 1990). These experiments have used TOPMODEL based on a surface topography index to identify source areas (Beven & Kirkby, 1979). However, this is not likely to be an effective basis in the presence of extensive piping (Jones, 1986). Given the evidence that conifer afforestation of the moorlands also aggravates acidification (Edwards et al., 1990), it would be sound planting practice to avoid all source areas, including those created by pipe networks. Since the Maesnant pipe networks double the source area from 6 to 12 ha out of a total basin of 23 ha, the extra area that should remain free of afforestation can be substantial in some basins.

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