Cuaternario y Geomorfología, 8 (3-4), 1994, pp. 77-102

SOIL PIPING AND ITS HYDROGEOMORPHIC FUNCTION

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Abstract. Piping is shown to be a widespread phenomenon with important implications for practical as well as theoretical considerations. Its occurrence in most climatic regions testifies to the common existence of sufficient causal factors, as well as to a variety of initiating processes. Nevertheless, there are preferred climatic and pedogeomorphic environments for pipe development, and it is in these environments that piping is most important as an erosive agent and as a source of runoff. Channel extension and slope failure are the main geomorphic products, emphasising the potential role of subsurface flow and subsurface properties in these processes. Hydrologically, piping has been found to increase direct runoff, expanding stormflow contributing areas and affecting acidification processes by reducing the time of residence of water in the soil.

1. Introduction

Soil piping is a much neglected process. Whilst it is not universally important, it is important in certain localities. Wherever it has been observed, the evidence seems to indicate that it performs a function in drainage and erosion that is often far more significant than its frequently small or hidden nature might suggest. Even where piping may play only a minor role, it has considerable significance for general theory, because it is the exception to so many 'rules' and theories.

Piping takes many forms and performs a variety of functions. But most fundamentally for both geomorphology and hydrology it provides a rapid means of subsurface flow, which is barely, if at all, considered in standard theories of erosion and runoff generation. Average velocities of pipeflow recorded in the field exceed overland flow by almost an order of magnitude, 0.3 m s^{-1} compared with 0.04 m s^{-1} (Jones 1987a). Admittedly, overland flow tends to occur over wider areas, with a broader cross-section of flow, so that discharges, as opposed to velocities, are higher. In contrast, pipeflow is more localised on the hillslope. Nevertheless, this concentration can give pipeflow the advantage in erosional power and in speed of delivery to the stream. Part of this advantage arises because pipeflow and erosion are largely unhindered by vegetation; the channel beds are bare and vegetation normally only restricts erosion on the tunnel roof.

Some of this advantage may be lost, however, if, as Whipkey & Kirkby (1978) suggested, it takes a long time for rainwater to infiltrate down as far as the level of the pipes. In general, this does not appear to be the case. Hydrological observations all indicate rapid to moderately rapid delivery of rainwater to the pipes through cracks and macropores (Jones, 1978; Gilman & Newson, 1980; Jones & Crane, 1984; Roberge & Plamondon, 1987; Jones et al., 1991), with the exception of piping in allophane latosols and kaolin soils under tropical rainforest in Dominica (Walsh & Howells, 1988). Recent British evidence based on isotope analysis which suggests that pipes may transmit predominantly 'old' water, i.e. water from previous storms and richer in deuterium, during stormflow (Sklash et al., in press a and b) does not prove slow delivery. It could be displaced by the translatory or piston flow mechanism (Hewlett & Hibbert, 1967). Even so, in an adjacent catchment, Hyett (1990) found strong chemical evidence that stormflow in the pipes is dominated by fresh storm rainfall.

These properties give piping three main functions within the hydrogeomorphic system. First, it provides a means of channel extension, by subsurface erosion and roof collapse. Secondly, it adds another component to hillslope drainage that is capable of contributing stormflow to the stream. And finally, it can contribute to a variety of hillslope erosion processes.

2. Spatial distribution of piping.

Global distribution: To a large extent, the overall hydrogeomorphic importance of piping processes depends on how widespread and common piping is around the world. Surveying the published reports of piping over the last 50 years or more certainly indicates that it is extremely widespread. At one time or another, piping has been reported from all the climatic regions of the world: piping, if not strictly 'soil piping', is even found in glacier ice (Shreve, 1972). This latter case only serves to emphasise the diversity of processes that can result in the development of extended water-sculpted voids within media like soil, ice, sediment and sedimentary rocks. Restricting our survey to soil piping in the strict sense, we can largely ignore processes of solution and melting and concentrate on the removal of solid particles of soil.

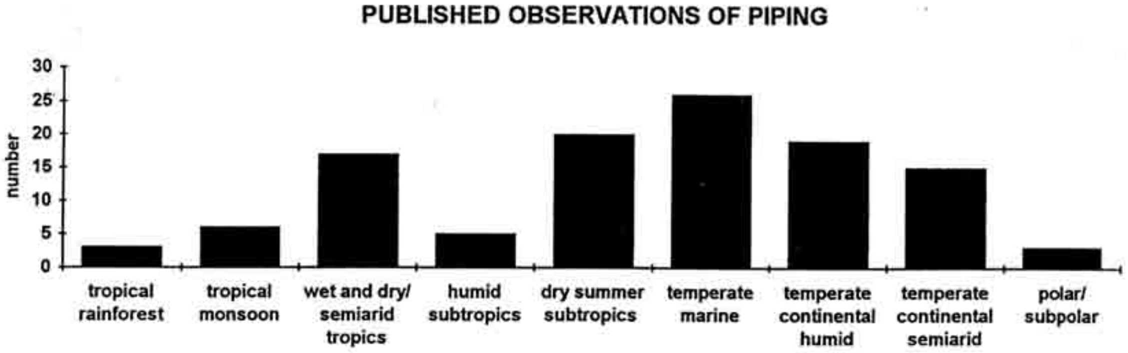

Fig. 1. The global distribution of published reports of piping, according to major climatic region.

These processes are controlled by a variety of physical and chemical parameters. It is this wide variety of causative factors that has produced the widespread distribution of piping. Chemical parameters are more evident in the development of piping in dryland soils. These principally relate to the dispersive properties of the soils. High exchangeable sodium percentages or sodium adsorption ratios in alkaline soils containing clays of the smectite-montmorillonite group produce the highest susceptibility to piping in the drylands (cp Gutiérrez et al., 1994). Even so, physical factors also play an important role in dryland piping. In common with piping in humid lands, four properties dominate these physical factors: (1) the potential for crack development, (2) an erodible soil structure, which may or may not be chemically determined, (3) an horizon with lower permeability in the lower soil profile, which acts as an impeding layer and concentrates throughflow within a limited section of the profile, and (4) sufficient hydraulic gradient to cause erosive velocities of flow. If the concentrated throughflow, or miniature 'perched water table', occurs in an horizon with crack development or erodible soil structure on a moderate slope, then pipe development is highly likely (Jones, 1981). There are cases where climatic change may have created soils within presently humid regions which retain a dispersive clay chemistry from a drier phase that makes them additionally susceptible (Charman, 1970; Jones, 1990).

Figure 1 is an attempt to represent the global distribution of piping, based on reports published to date. It is clearly inadequate in a number of ways. It must partly reflect the distribution of interested observers, and it is impossible to quantify remarks like 'piping is common in this region'. For these reasons, the 74 piped basins in Britain discussed below have not been recorded as separate observations. Multiple publications relating to the same site have also been counted as only one observation.

Despite these problems, the graph does seem to reflect the distribution as generally perceived today. Most notable is the low incidence of piping in very wet climates and in polar regions. It also shows latitudinal peaks in the drier tropics and subtropics, and in the midlatitudes in general, but particularly the wetter temperate regions. The Mediterranean climate is represented by the dry summer subtropics. Figure 2 summarises the distribution further, and suggests overall that the various roles of piping are least important in very wet climates. This is supported by the very limited hydrological evidence from such regions, which suggests that overland flow is dominant (Bonell & Gilmour, 1978; Walsh & Howells, 1988; Jones, 1990). The contrasting peak in moderately wet climates is very marked and suggests that this may be the region of maximum environmental impact, at least in terms of hydrology.

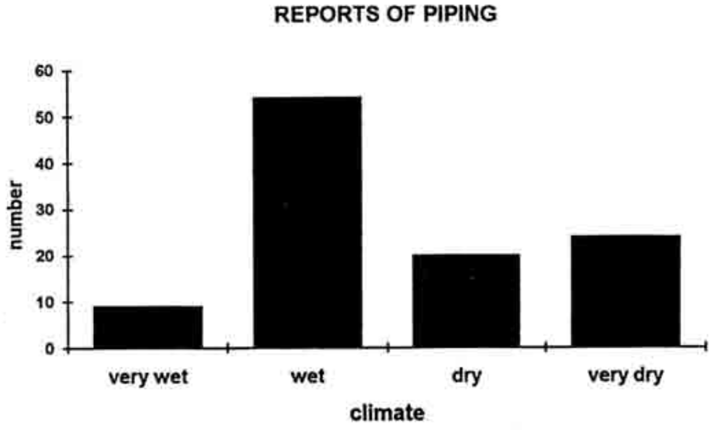

Fig. 2. A summary of Figure 1 showing the distribution of piping reports according to the general level of humidity or aridity. Tropical rainforest and monsoon climates are 'very wet'; arid and semiarid are 'very dry'.

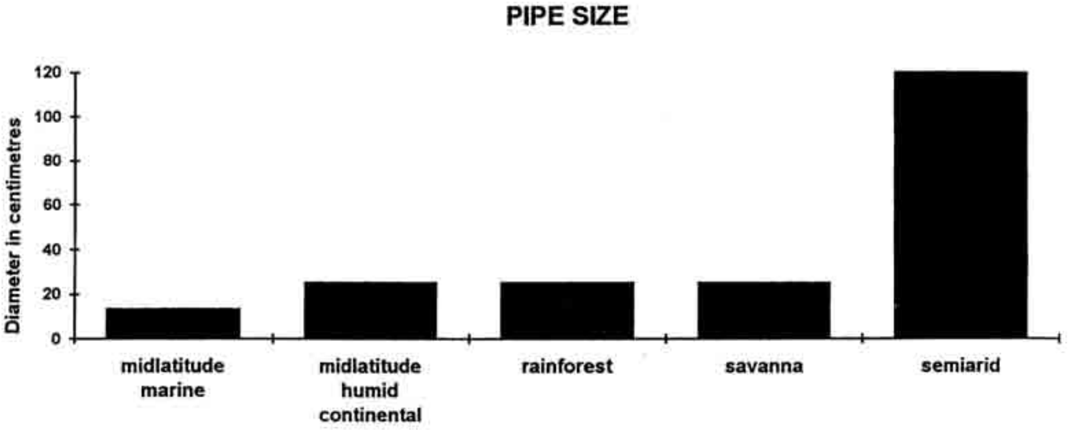

Fig. 3. The average diameter of piping in major climatic regions. Semiarid regions are also characterised by a high range of sizes.

The drylands in general also show ample evidence of piping, with the sole exception of hyperarid regions. Indeed, this is the 'classic' region for piping reports, so much so that piping used to be regarded as a feature specific to these climates (Parker, 1963; Bryan & Yair, 1982). Piping certainly presents the most obvious geomorphic impact in these areas.

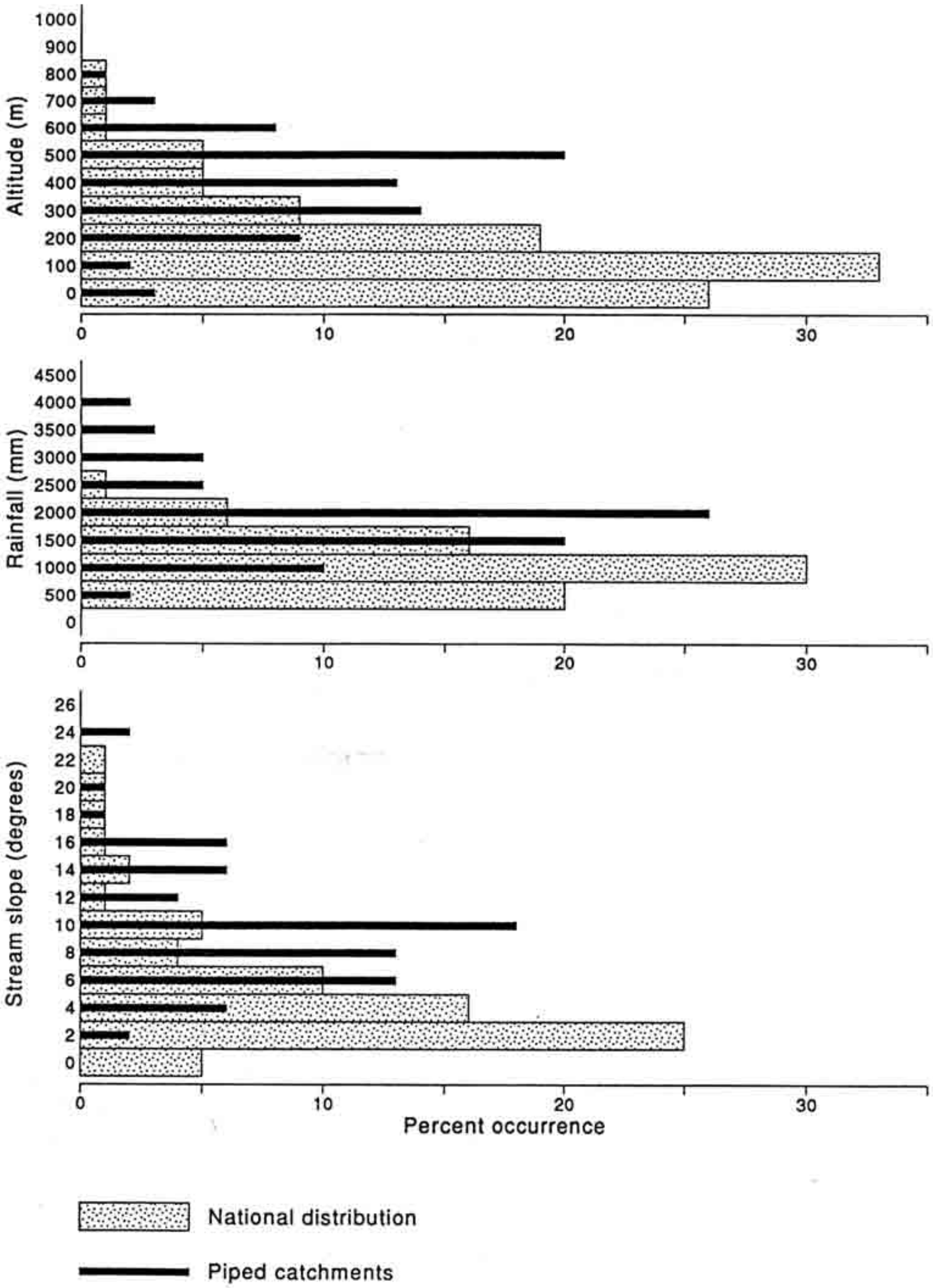

Fig. 4. The topographic and climatic distribution of piping in Britain compared with national distributions of catchment parameters derived from the UK Flood Studies Report (NERC, 1975) by Richardson (1992).

Figure 3 shows one reason why this is so. The average size of pipes in semiarid regions is nearly an order of magnitude greater than in midlatitude temperate marine climates. Size in Figure 3 is almost the reverse of frequency in Figure 2. These are also only average sizes; pipes a number of metres across can be found in semiarid regions (Parker & Higgins, 1990). Their development is related especially to occasional, very high intensity rainfall, to erodible soils with low organic content, poor structure and often dispersible clays, and to greater thicknesses of soils, palaeosols and weak sediments accumulated in these areas.

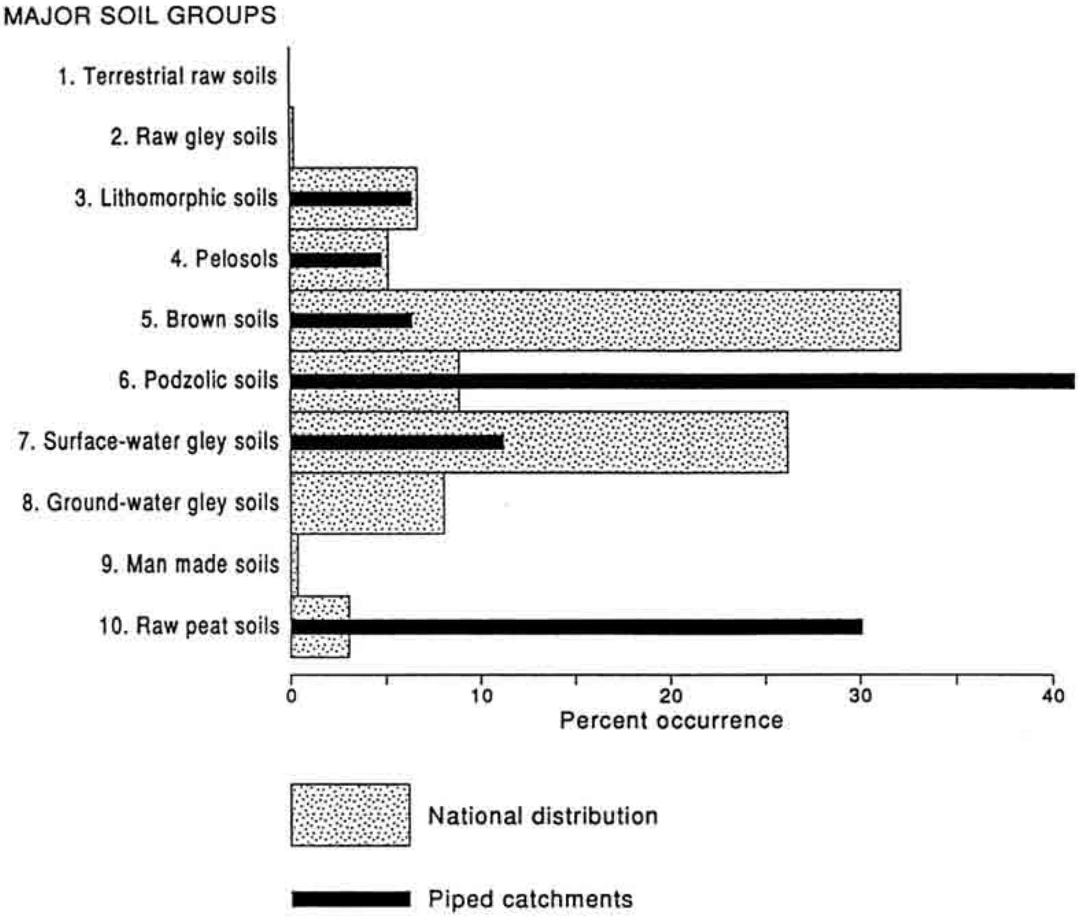

Fig. 5. Distribution of piping in major soil groups in Britain compared with the national distribution of soils according to Avery (1980).

Interbasin distribution in Britain: The distribution of piping in Britain illustrates the important factors behind pipe development in a humid temperate climate. Comparing the 74 piped basins recorded by Richardson (1992) with the basins used to represent average national characteristics in the UK Flood Studies Report (NERC, 1975) shows that they are higher, wetter and steeper than the average basin (Figure 4). The typical piped catchment is five times higher and steeper than the average British basin and receives twice the annual rainfall. The rainfall and the gradient provide the erosive power, but they are also associated with mountain soils that are conducive to pipe development. Figure 5 shows that three-quarters of the piping occurs in just two Major Soil Groups, podzolic and raw peat soils (spodosols and histosols), which between them account for only one-eighth of the national distribution. A further 12% occurs in surface water gley soils that are closely associated with the other two groups. This constitutes a very marked preferential clustering of piping features in a limited number of soils. The clustering persists at the sub-group level of soil classification (Figure 6) with just two out of five sub-groups of podzols, the typic brown podzolics and the ferric stagnopodzols, and one peat sub-group, the raw oligo-fibrous peats, dominating. These soils are typified to varying degrees by impermeable subsoils, including iron pans and eluvial clay layers, or strong cracking potential in histic peaty surface horizons.

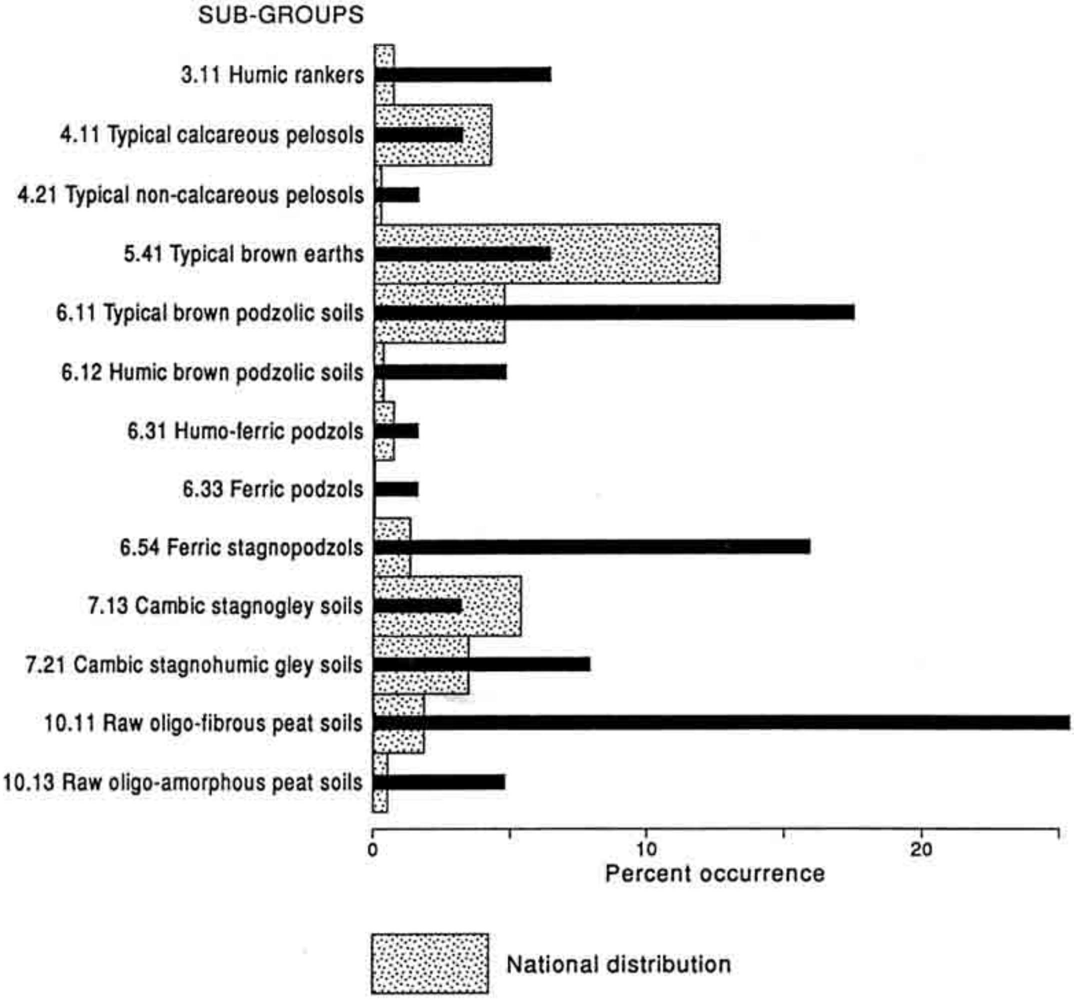

Fig. 6. Sub-groups of British soils that exhibit piping, showing the frequency of these sub-groups in the piping survey compared with the national frequency.

As the results of research accrue from around the world, so the role of cracking seems to stand out increasingly as one of the most important and widespread. Yair et al. (1980) observed this in the Negev Desert; so did De Ploey (1974) in semiarid Tunisia. Figure 7 shows the marked preference for piping in Britain to concentrate in south-facing catchments. This corroborates the observations of Hughes (1972) who found a preference for north-facing slopes in a similar midlatitude marine climate in New Zealand.

Intrabasin distributions: Close study of the distribution of piping within a catchment also reveals the importance of soil factors that modify the effect of the expected topographic controls on drainage patterns. Figure 8 plots piping patterns against the a/s index. Carson & Kirkby (1972) introduced the a/s index as means of quantifying the concentration of drainage waters within a basin: 'a' is the area drained per metre of contour length and 's' is the topographic slope. A high a/s indicates a relatively large area providing drainage to a point and a relatively low slope, which should cause wetter soils and more saturation overland flow.

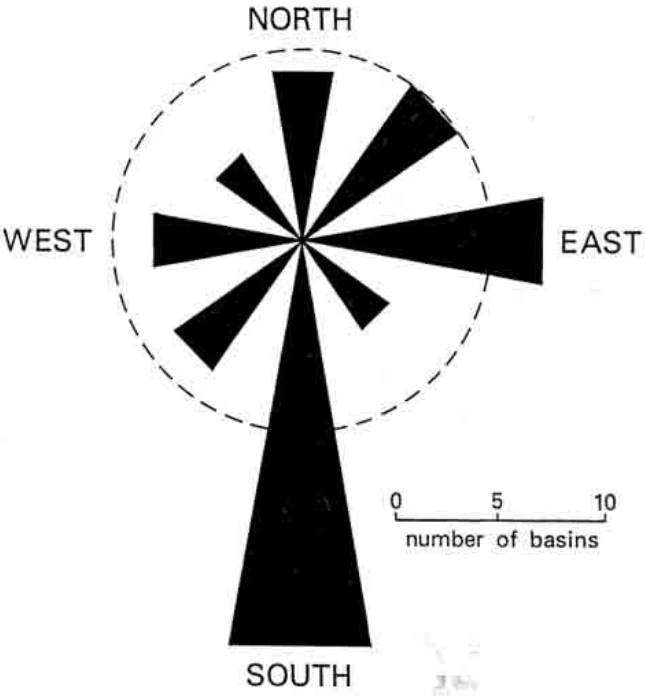

Fig.7. Catchment orientation and piping frequency in Britain. Ring indicates the null hypothesis of equal distribution over all orientations.

However, the pipes in Figure 8 show only a very broad correspondence with the index. In detail, the distributions diverge. In some locations piping begins with an a/s of just 0.5, roughly equivalent to a contributing area 500 m by 1 m, whereas in others 2.0 is needed. The discrepancy is explained by differences in soil types, thicknesses and exposure to desiccation cracking. The piping on the upper southern slopes of the basin with the lower a/s index is associated with thinner podzolic soils where desiccation cracking rather than water supply is clearly the main cause of initiation.

The long ephemerally-flowing pipe that extends upslope from this group of pipes also illustrates an important aspect, namely, that pipes can rewrite the drainage rules. They create their own subsurface catchments that may be different from those suggested by surface topography. In this case, the long pipe diverts considerably more water to the heads of this group of pipes than surface topography would do. It performs this function only in about one in every three storms, so that it does not inhibit desiccation by maintaining soil moisture levels, rather it provides added erosive power during heavy storms.

3. Geomorphic functions

Channel extension: The role of piping in channel extension has been noted on many occasions, although it has rarely been quantified and it is still generally ignored in quantitative theories (Jones, 1971). De Ploey (1974) observed that 'frontal' gully networks advance by pipe collapse. Multiple cycles of transformation between rilling, piping and gully development were reported by Aghassy (1973) in Israeli badlands. Rates of channel extension due to pipe collapse can be spectacular: from 315 m in one storm in Uganda reported by Bishop (1962) to an average of 5 m per annum over a 20 year period in Arizona (N.O. Jones, 1968). Parker & Higgins (1990) and Dardis & Beckedahl (1988) all regard piping

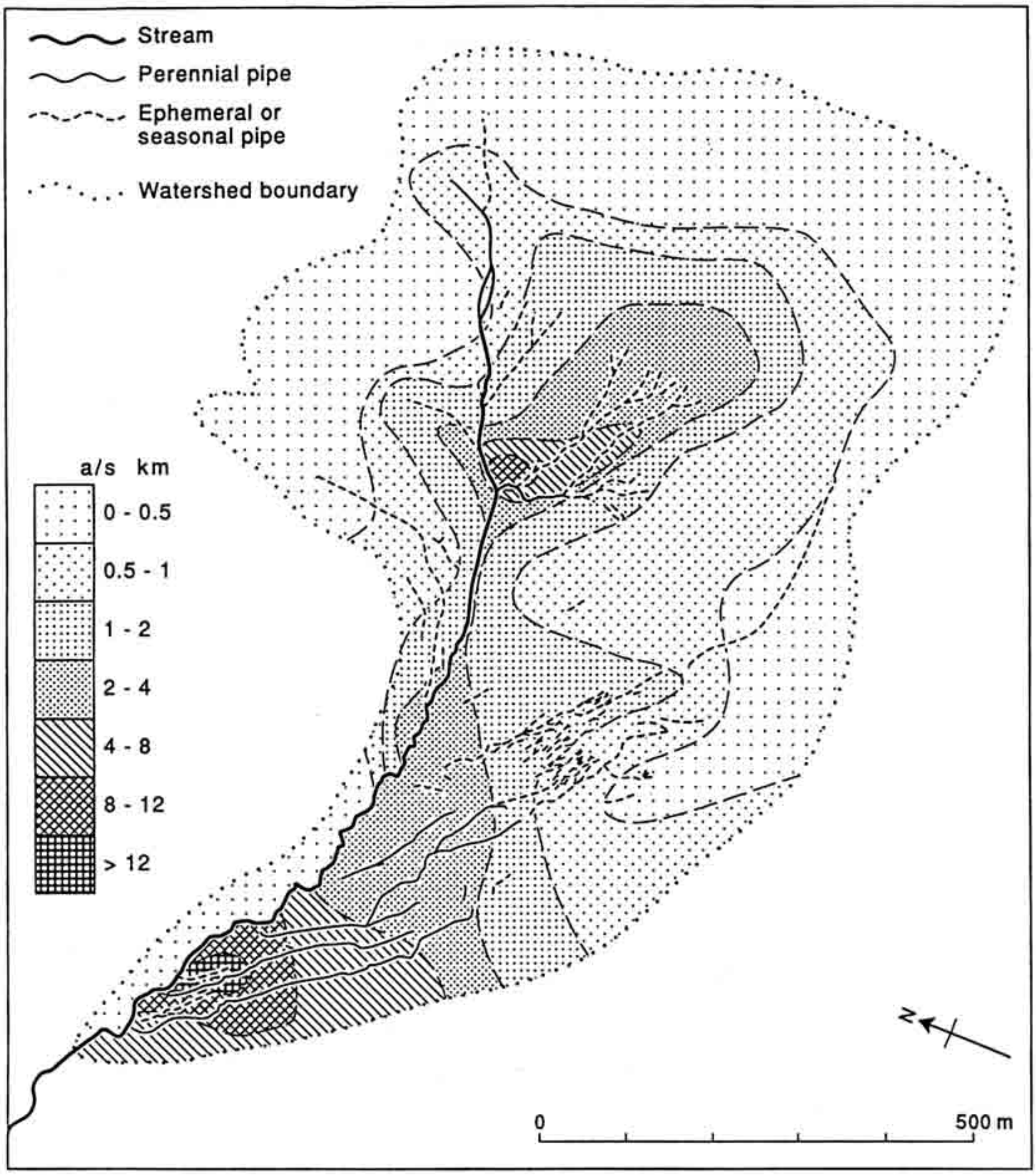

Fig. 8. Piping in relation to the a/s index in the Maesnant Experimental Basin, based on 4 m contour resolution 1:7500 photogrammetric map.

as a major casue of gullying in the drylands. Higgins (1990) regarded piping as a source of 'many, if not most' gullies in the Mediterranean climate of the Sacromento Valley, California.

Rates of channel extension are typically much slower in humid climates, except in highly erodible soils such loessial or 'slope loams'. Galarowski (1976) reported a 15 m extension in pipe collapses over 2 years in East Carpathian slope loams, but one pipe extended 150 m in 6 months. Figure 9 illustrates a common situation in the Welsh mountains, where pipehead channels are the norm and classic headcuts caused by overland flow the exception. At present, these systems appear to be very stable, and it may take decades to observe any reportable extension.

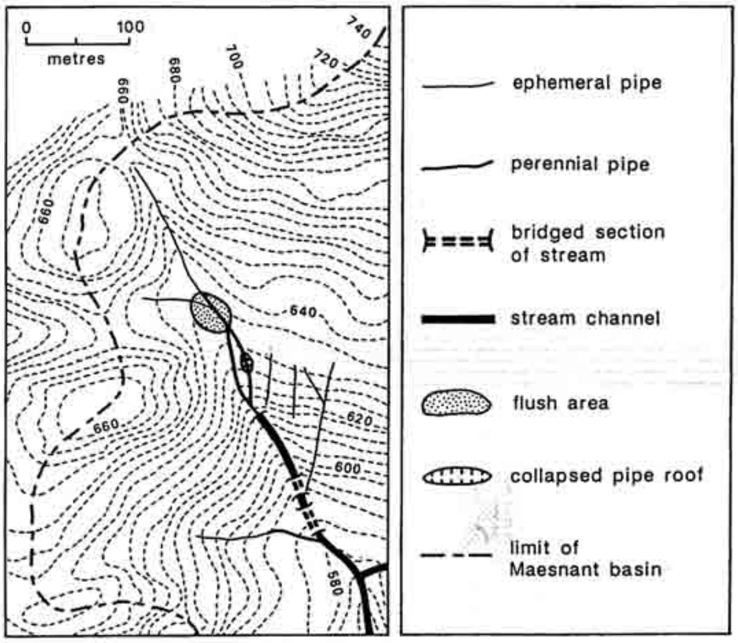

Fig. 9. The 'pipeflow streamhead' on the north branch of Maesnant.

Undoubtedly, many channel heads owe their origin to a mixture of overland and subsurface erosion, as illustrated by Stocking (1978). It can be extremely difficult to estimate the relative importance of the two processes in these situations, especially since the resulting landforms are so similar (Jones, 1994). There is no question that single process models of channel head migration based on overland flow, such as that developed by Calver (1978), are only a partial solution. But we still do not seem to have a more general model. Such a model would have to combine both surface and subsurface abrasion with cantilever collapse, along the lines of Osman & Thorne's (1988) models for bank erosion.

Piping and the drainage net: Even if piping is not actively extending the channel network, however, in itself piping does constitute an extension of the drainage network, as illustrated in Figure 10. Upslope segments of piping are often not directly connected to the stream channel and even piping on the footslopes can end on the floodplain or a terrace before reaching the stream. This may limit the speed of discharge of stormwater to varying extents, but this might not reduce its geomorphic significance very much. As pipes issue water onto the slope, they initiate linear elements of overland flow that may be much more effective as erosional agents than the dispersed overland flow that would otherwise have occurred. In trying to use the a/s index to predict patterns of sheetwash erosion McCaig (1984) noted that surface erosion was significantly lower than suggested by the index above a pipe outfall and significantly higher below. On many hillslopes there is a complex exchange of water between overland flow and pipeflow, which may eventually result in a integrated network of pipe and rill sections formed by both upslope and downslope extension of channelways.

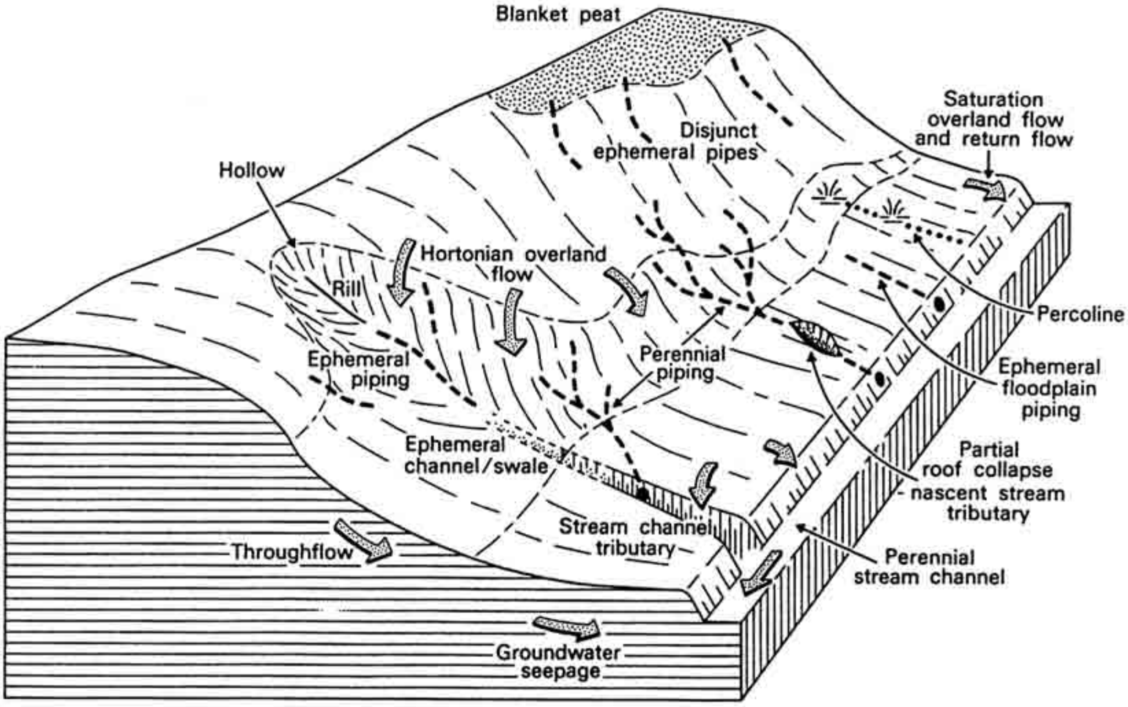

Fig. 10. Generalised view of piping within the hillslope and channel drainage system.

Figure 11 shows rills in loessial soils at the Leuven Laboratory for Experimental Geomorphology's Huldenberg field site, which are developing by pipe collapse. Workers at the laboratory now realise that this classic form of piping contribution needs to be incorporated into models of rill development (Govers, pers. comm.). This is in addition to the more subtle form of 'diffuse piping' originally described by Terzaghi (1931), in which individual soil particles are winnowed away by water seeping out of the rill walls, that was seen as a contributor to rill development by Savat & De Ploey (1982).

A number of reports refer to interesting 'symbiotic' sequences whereby cycles of piping and gullying succeed each other within the same network, e.g. linking discontinuous gullies (Heede, 1976; Higgins, 1990), and even within the same channels, causing cyclical lowering of the beds (Aghassy, 1973; Hamilton, 1970). Pipe-gully erosion typically proceeds by stepwise slumping of steep headwalls or the collapse of gullyhead tunnels.

Piping in landslides and bank failures: Piping has also been widely associated with landslides and bank failures. Again, Karl Terzaghi, the 'father' of soil mechanics, described one form of this, the flushing out of broad layers of sandy material in the banks of the Mississippi. Hagerty and his colleagues have surveyed and modelled many varieties of bank failure due to piping in the American midwest (Ullrich et al., 1986; Hagerty & Hamel 1989; Hagerty, 1991 a and b, 1992). However, one significant feature in the contribution of piping to streambank failure, pointed out by Jones (1989), is that it introduces a process for which the main controlling factors may originate well away from the free face of the bank. This may call into question the traditional engineering approach of estimating the risk of piping failure solely by analysing the mechanical properties of the bank materials themselves.

Bryan & Price (1980) observed the importance of piping in causing landslip failures in cliffs along the shore of Lake Ontario outside Toronto, while Tsukamoto et al. (1982) found that landslip failures in forested hills in Japan were concentrated at locations where pipeflow and throughflow produce upward pressure on the soil mass and lubricate its movement.

However, there are numerous cases in which the direction of causality is less clear. Piping can follow landsliding, utilising the cracks and weaknesses created by the mass movement or stimulated by the increased hydraulic gradient resulting from the newly created free face above the slip. But, since most geomorphic observations occur after the event, it can prove impossible to reconstruct the sequence of events and decide whether the piping is the cause or the effect (cp Jackson, 1966; Jenkins et al., 1988). Piping may even be neither. It can stabilise slopes by releasing excessive pore water pressures, as civil engineers who construct 'weep holes' in embankments well know (Jones, 1981).

Fig. 11. Partially collapsed ephemeral piping creating rills on loessial soil at an experimental plot of the University of Leuven, Laboratory for Experimental Geomorphology at Huldenberg, Belgium.

Piping in badlands and land degradation: There is now a considerable body of literature on the development and role of piping in badlands (e.g. Bryan & Yair, 1982; Imeson et al., 1982; Harvey, 1982; Bryan & Campbell, 1986; Parker & Higgins, 1990; López-Bermúdez & Torcal, 1986; Gutiérrez & Rodriguez, 1984; Gutiérrez et al., 1988; Benito et al., 1993; Gutiérrez et al., 1994). Most studies have concentrated on the factors that control piping in badlands (e.g. Gutiérrez et al., 1994). Dynamic studies, like those undertaken by Bryan and colleagues in Canada, are complicated by the three-dimensional nature of the pipe networks and the infrequency but often catastrophic form of erosional events (cp Bryan & Campbell, 1986). Badland piping is commonly found at a number of levels within badland slopes, corresponding to impermeable layers, with varying amounts of interconnecting vertical pipe sections penetrating these layers at weak points. Figure 12 illustrates a very simple example of piping and rilling in a small 'haystack' hillock. In common with badlands in general, this 'popcorn' surface is being eroded by rainwash as well as being undermined by piping.

Another area of study that is rapidly accumulating a sizeable literature is the degradation of agricultural land by piping erosion. Despite the claim by Hudson (1971) that piping is usually confined to badlands of little agricultural value, Masannat (1980) estimated that almost 50% of agricultural land has been destroyed or seriously affected by piping in the San Pedro Valley, Arizona. Considerable areas of agricultural land were lost in Australia and New Zealand in the 1930s and 1940s through a combination of surface erosion and piping. The losses led to the establishment of Soil Conservation Services (Cumberland, 1944; McCaskill, 1973; Boucher, 1990) and some long-term research programmes aimed at devising methods of control and rehabilitation (Newman & Phillips, 1957; Floyd, 1974). Barrón et al. (1994) report renewed extension of piping systems in the Ebro basin, N Spain, following Spain's entry into the European Community and changes in the type of crops from wheat to barley and from soft wheat to hard wheat.

Fig. 12. Piping in a small 'haystack' in badlands near Huesca, Ebro basin.

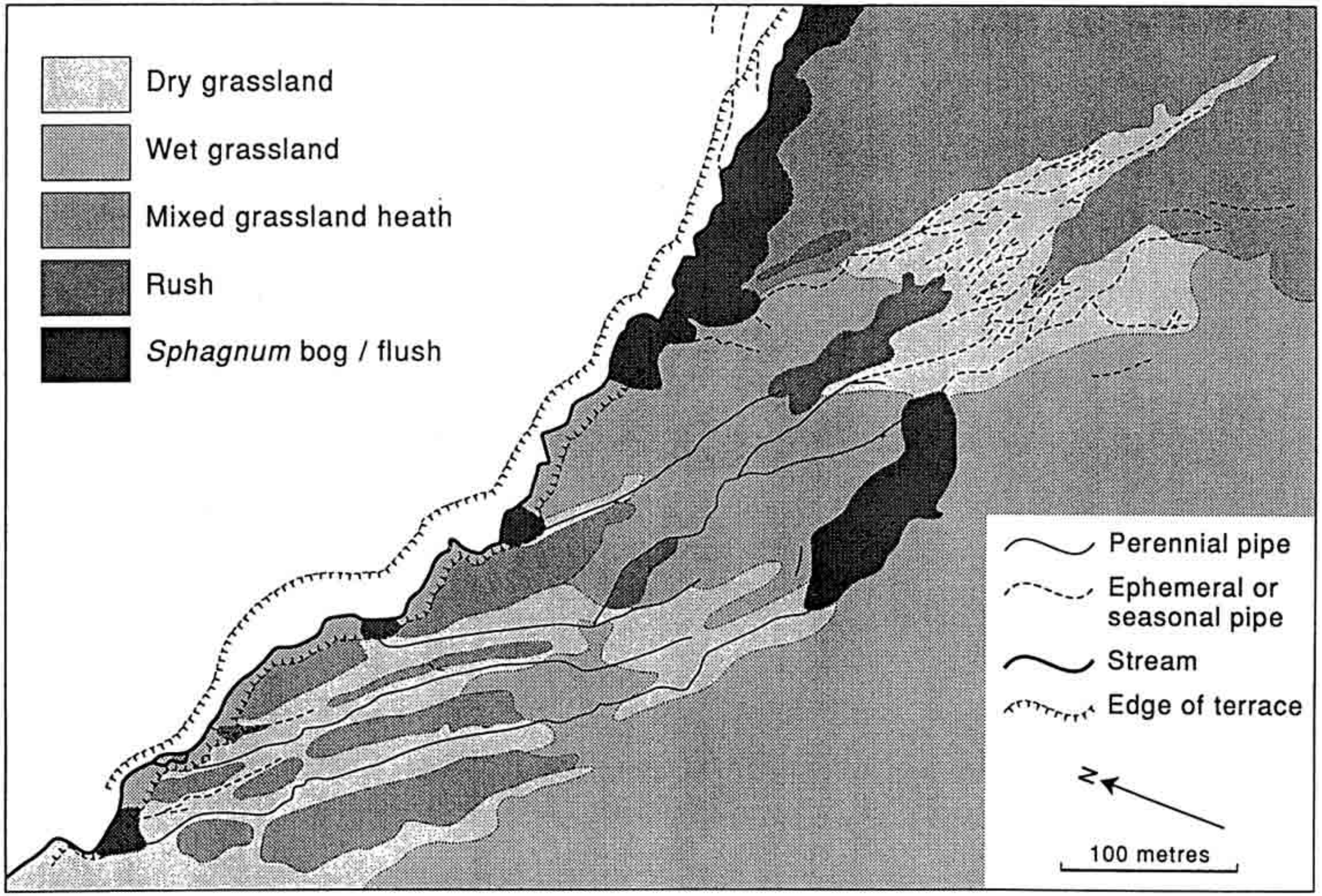

Fig. 13. The distribution of major plant associations around piping on the lower Maesnant.

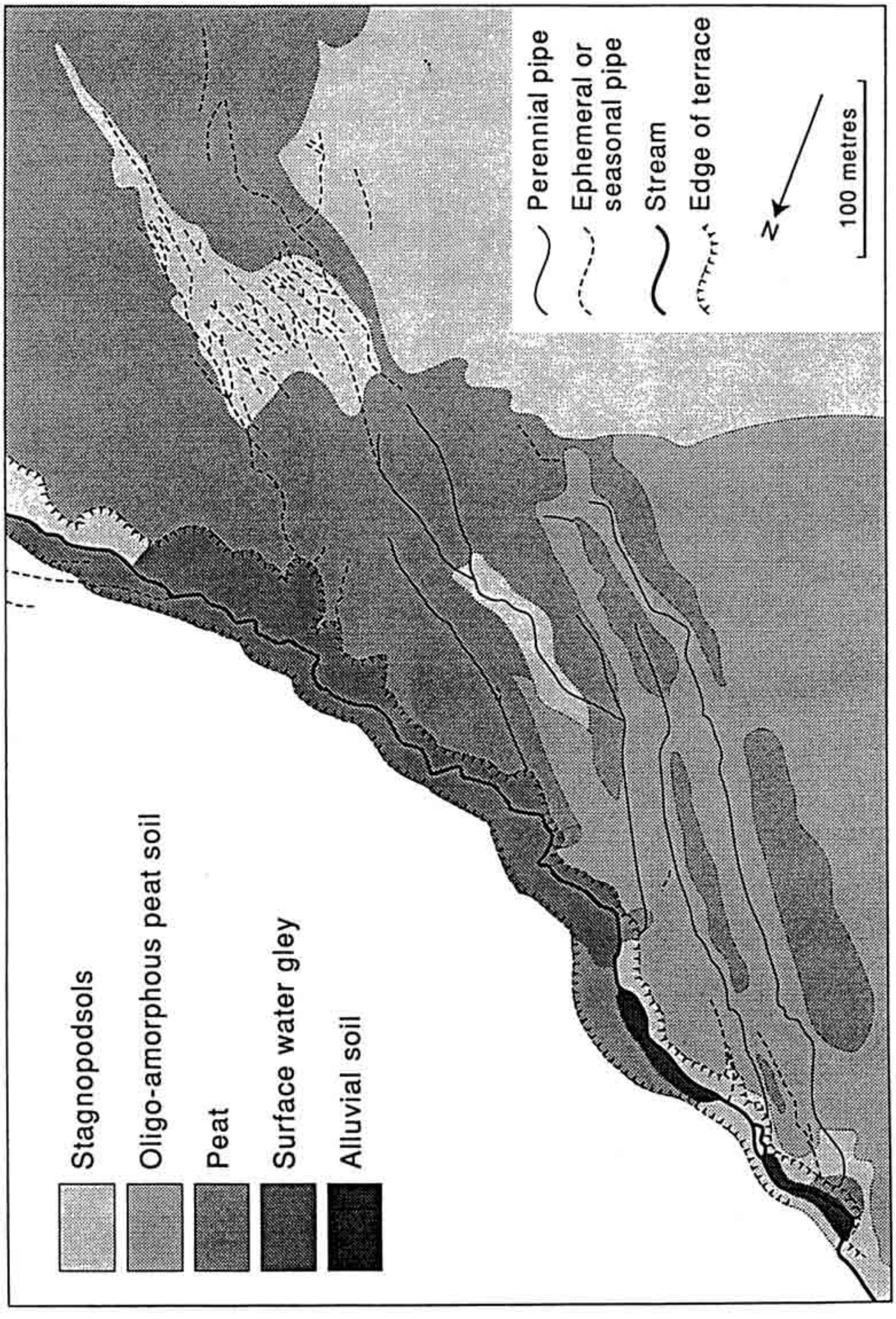

Fig. 14. The distribution of soil groups around piping on the lower Maesnant.

Fortunately, despite another claim by Hudson (1971) that there are no effective control measures for piping erosion, the Soil Conservation Service of New South Wales and others have had reasonable success in containing the problem. These measures have included (1) infilling gully systems, contour ploughing and terracing to reduce local hydraulic gradients, (2) planting deep-rooting trees to increase evapotranspiration and reduce the volume of throughflow, (3) improving the soil structure with soil conditioners in order to reduce erodibility, and (4) ripping and deep ploughing to destroy pipes, ploughpans and other impermeble horizons. These remedial measures clearly need to be applied with caution and due respect for local conditions: Fletcher & Carroll (1948) actually blamed deep-rooted plants and over-zealous ploughing for encouraging rapid percolation and eluviation leading to pipe initiation.

Some of this piping has been initiated by over-irrigation. Fletcher & Carroll (1948) first reported this in Arizona. Recent work in Spain by García-Ruíz et al. (1986) and García-Ruíz et al. (1994) and in California (Higgins & Schoner, in press) has highlighted this problem again. The work confirms the role of deep-rooted crops, especially in fields planted with alfalfa for more than 3 years just as Fletcher & Carroll had observed. It also shows that terracing is not always a sure anti-erosion measure, since piping tends to begin on the terrace edges, where hydraulic gradients are greatest.

Fig. 15. Hang-glider aerial photograph of vegetation patterns associated with piping on the lower Maesnant.

Impacts on pedogenesis and moorland habitats: In contrast, the piping on moorland grazing land in Wales studied by Jones et al. (1991) is very stable and does not present an agricultural problem. It does, however, have a marked impact on soil development and vegetation cover. Ironically, this may improve grazing by providing better drainage on the slopes and encouraging colonisation by grasses and a reduction in the area of coarse heath vegetation comprising ling (Calluna vulgaris) and bilberry (Vaccinium myrtillus). Figures 13 and 14 show the close correspondance between vegetation patterns, soil type and the location of pipes, in which the pattern of development amongst the deep, perennial pipes, which run 0.5 m below the surface, is clearly responsible for creating the lines of better drained and oxidised soils (Jones, 1994). Figure 15 is an aerial photograph of part of this area taken by hang-glider, which shows the grassy 'lanes' that follow the lines of piping. Figure 16 confirms the clear association between piping and grassland habitats.

Whilst the perennially-flowing pipes seem to control soil development and have diameters of c. 0.3 m, the smaller ephemerally-flowing pipes at the top right of Figure 12 seem to be largely controlled by existing soil properties. These are typically about 0.09 m in diameter and run at a depth of just 0.15 m. The pipes are clearly developed from the dense pattern of desiccation cracks in the thin peaty surface horizon and run over the impermeable iron pans of the stagnopodzols. The adjacent area of stagnopodzols probably lacks piping mainly because it is on the catchment divide and therefore has little water flow.

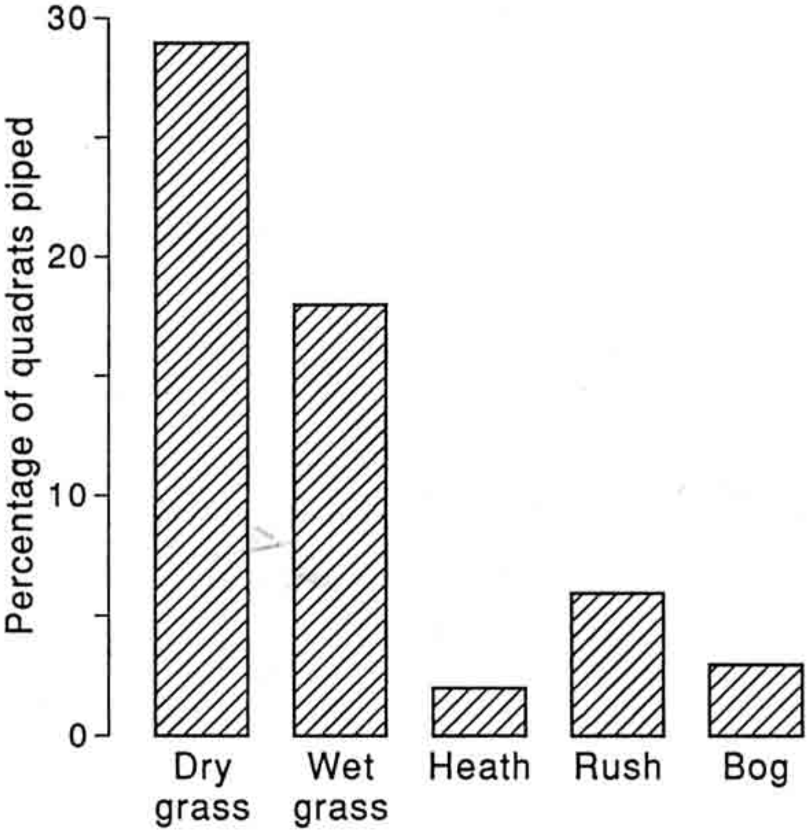

Fig. 16. The frequency of piping in the major plant associations on Maesnant.

We have a clear gradation here between the rudimentary piping which is dependent on pre-existing soil properties and the fully mature piping which is able to sculpt a more integrated network and to influence pedogenic processes. The ephemeral pipes flow in only about one-third of the storms which generate stormflow in the perennial pipes, and calculations of Manning's n suggest that this flow is normally laminar, whereas flow in the perennial pipes is typically more turbulent and erosive (Jones, 1990).

Figure 17 places the perennial and ephemeral pipes within a framework of environmental properties and vegetation types. The axes of the graph are the result of a botanical principal components analysis. The plotted pipe sites tend to eschew the very wet and the very dry environments and to concentrate in the moderately wet areas where there is enough soil moisture to support pipeflow but also perhaps some tendency to develop desiccation cracks during the summer. Similarly, pipes tend not to occur in the more nutrient deficient areas, largely perhaps because pipes form a channelway for nutrients and certainly on the lower slopes areas of nutrient enrichment can be found alongside the pipes. Details of the analysis can be found in Jones et al. (1991) and Richardson (1992).

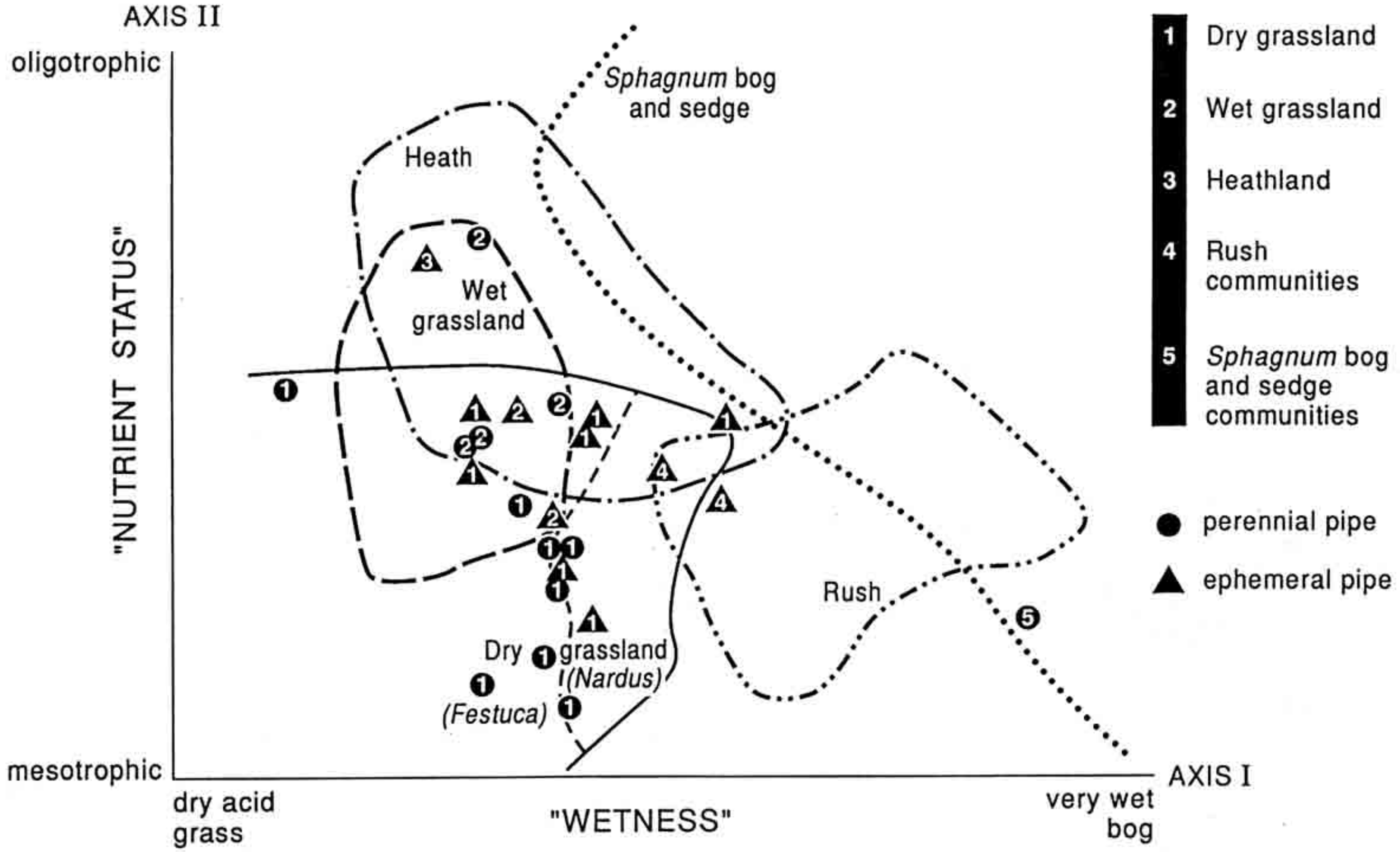

Fig.17. Quadrat ordination showing the distribution of piped quadrats in relation to major vegetation associations.

4. Hydrological functions

Surface water acidification: Pipes move not only plant nutrients but also acid rain and the toxic monomeric aluminium that is released from the soil in acidities of pH 3 and below. Work in the same catchment has shown how aluminium concentrations tend to increase down the perennial pipes to above the toxic threshold for fish (Figure 18), and how acid flushes after heavy rainfall tend to cause a pulse of aluminium-rich water to issue from these pipes (Jones & Hyett, 1987; Hyett, 1990).

The pipes are the main source of aluminium in the stream because they modify drainage pathways in three critical respects. First, they speed up drainage, which reduces the time available for chemical neutralisation of the acid rain. Secondly, they cause a more rapid build up to peak flow, which carries the acid flush. Thirdly, they direct infiltrating water through the upper, organic layers (which are also acidic and release sulphates and weak organic acids) and reduce contact between throughflow and deeper horizons where weathering minerals might provide base cations that would help to neutralise the acid waters (Jones & Hyett, 1987; Gee & Stoner, 1989).

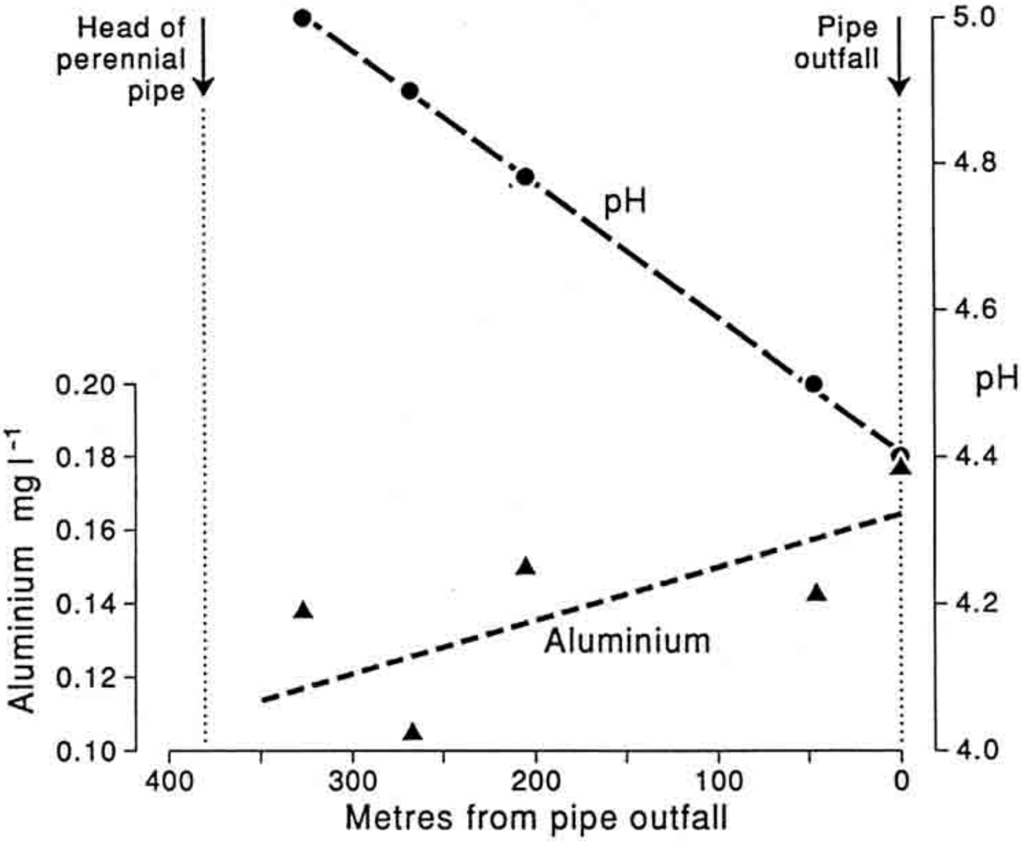

Fig. 18. Changes in pH and aluminium concentrations down the largest perennial pipe on Maesnant.

The sources of streamflow and the sources of pipeflow are therefore important to water quality in the Welsh mountains, and there is growing evidence to suggest that pipes play an important role in the acidification of surface waters in other parts of the northern hemisphere, notably in Canada and Norway (Roberge & Plamondon, 1987; Jacks & Norrström, 1993). The hydrology of contributing areas for pipe stormflow therefore has relevance for managing areas with low acid-neutralising capacity (ANC) and subject to acid precipitation. These pipeflow contributing areas should be designated 'no go' areas for coniferous afforestation, which would tend to exacerbate the acidification (Jones, 1994; Edwards et al., 1990). Particularly problematic pipes might even be 'turned out', i.e. diverted, destroyed or dammed to reduce their contribution during storm runoff.

Pipeflow as a contributor to direct runoff: There has been very little hydrological monitoring of pipeflow, but most of the evidence available from Europe and North America suggests that pipeflow can be a significant, and in some cases very important, contributor to streamflow, especially during storms (Jones, 1990). Unfortunately, most of this evidence is restricted to a few catchments in Wales (Jones, 1978; Gilman & Newson, 1980; Wilson & Smart, 1984) and only one catchment, the Maesnant, has been monitored in more than a handfull of storms. Nevertheless, the results of monitoring at Maesnant throughout much of the 1980s confirm that pipeflow can actually be the dominant contributor to streamflow in certain circumstances (Jones, 1982, 1987b, 1988; Jones & Crane, 1984; Connolly, 1993). Figure 19 shows a peak percentage contribution to streamflow in a moderately wet catchment and moderate rainstorms. Total pipeflow continues to rise in wetter situations, but its relative importance dwindles as other sources, like saturation overland flow, begin to operate and increase.

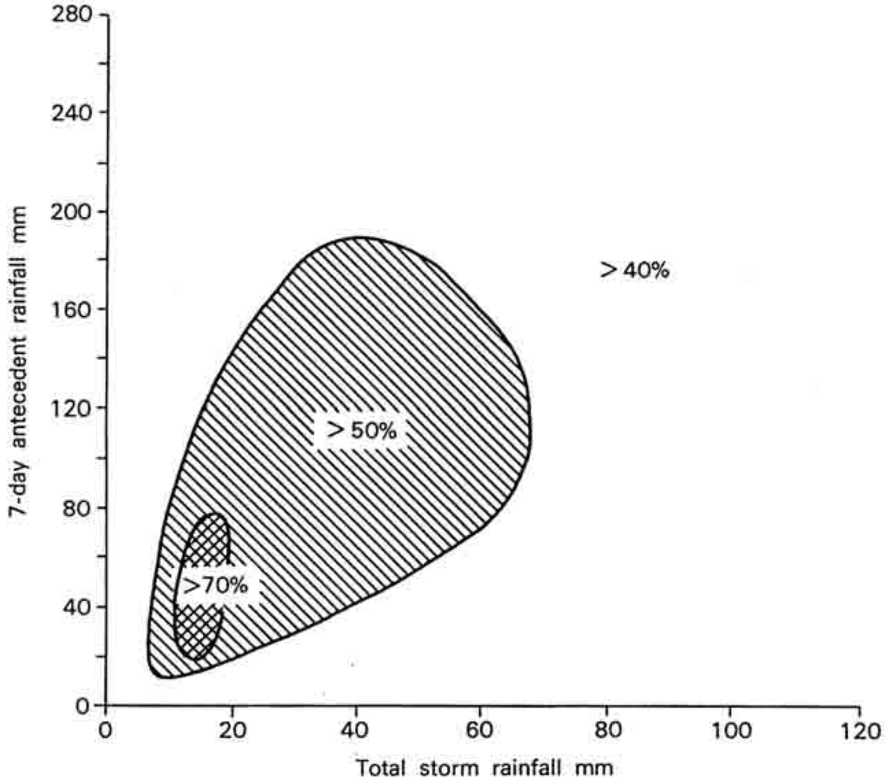

Fig. 19. Percentage contributions of pipeflow to stormflow in the Maesnant stream.

The Maesnant experiments reveal an amazing complexity of interchange between surface and subsurface water on the hillslope (Figure 20). They also show the area and extent of the area that can contribute to stormflow. On average, the piping adds 6 ha to the contributing area, doubling its size and allowing it to extend in 'fingers' up to 0.75 km from the stream channel. If this pipeflow did not exist, the average stormflow contributing area would extend for less than 40 m from the streambank. Even in the almost unlikely circumstances where all of the pipeflow were converted to overland flow, the contributing area would only extend some 70 m from the streambank. Piping would still be responsible for a tenfold extension of the contributing area in localised 'fingers'.

This could have important consequences for tracing sources of pollution or for planning land management strategies that have minimal environmental impact upon runoff regimes or water quality. Strategies for cost-effective liming of catchments to reduce acidification that restrict liming to

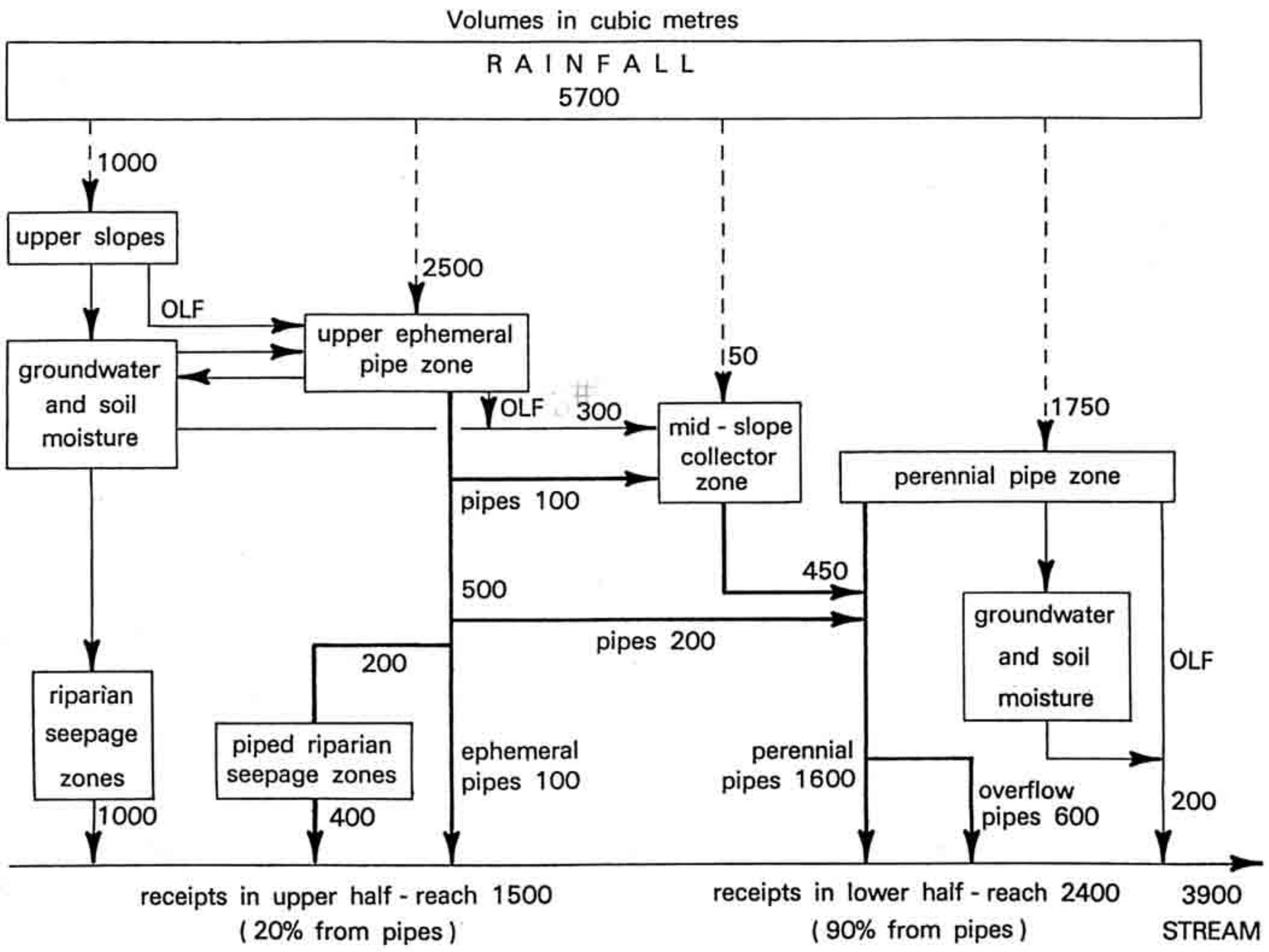

Fig. 20. A flowchart of hillslope drainage processes in the Maesnant Experimental Basin.

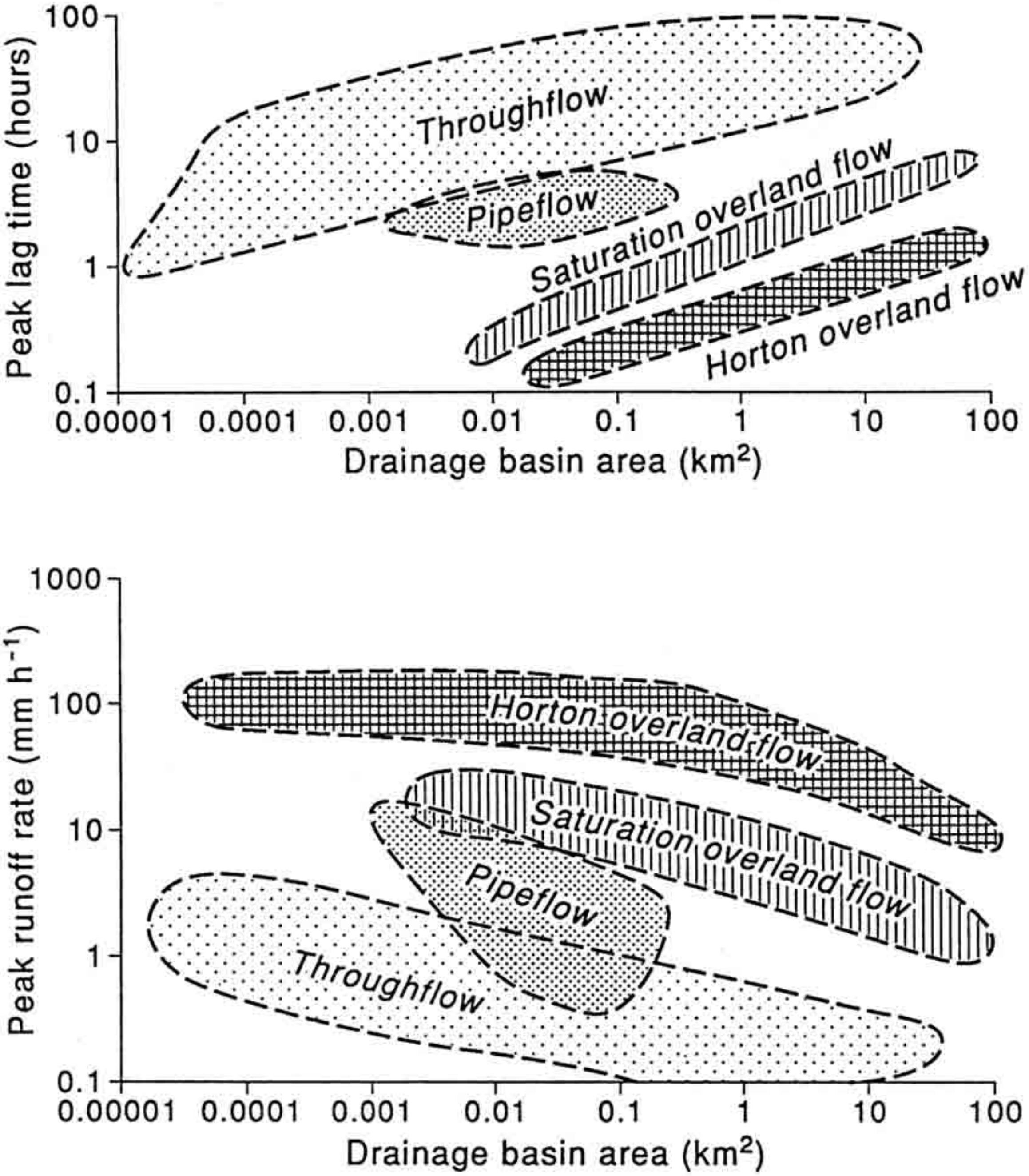

Fig. 21. Peak lag times and runoff rates for hillslope processes, including pipeflow. Based on collations by Dunne (1978), Anderson and Burt (1990), and the author.

contributing areas have so far only used traditional methods to identify those areas (Gee & Stoner, 1989; Edwards et al., 1990). Typically, this has used the a/s index, but as Figure 8 shows pipes do not necessarily obey the same rules. Hence, contributing areas are not delineated by a specific a/s value.

Recent work by the author has endeavoured to compare the efficiency of pipeflow with other hillslope drainage processes in terms of runoff rates, peak flow lag times and yields per unit length of streambank in relation to basin size. The stimulus for this comes from the work of Dunne (1978) and Anderson & Burt (1990), who collated and plotted data from a variety of catchments, especially from USDA experiments in America. The difficulty lies in determining the 'basin size' for pipe networks.

The solution adopted has been to take the maximum contributing area for each gauged section of pipe calculated from the rainfall and pipeflow records on Maesnant as absolute maximum. Since over 200 storms have been recorded, this seems a reasonable assumption. The main drawback is that only the data from the Maesnant basin is at all amenable to this type of analysis. Even so, the plots in Figure 21 show that pipeflow falls, very logically, in between overland flow and throughflow in terms of its responses. Calculations of contributions per metre of streambank also show the superiority of pipes, especially the larger perennial pipes, as discharge contributors compared with measurements of diffuse throughflow in riverside seepage areas (Figure 22).

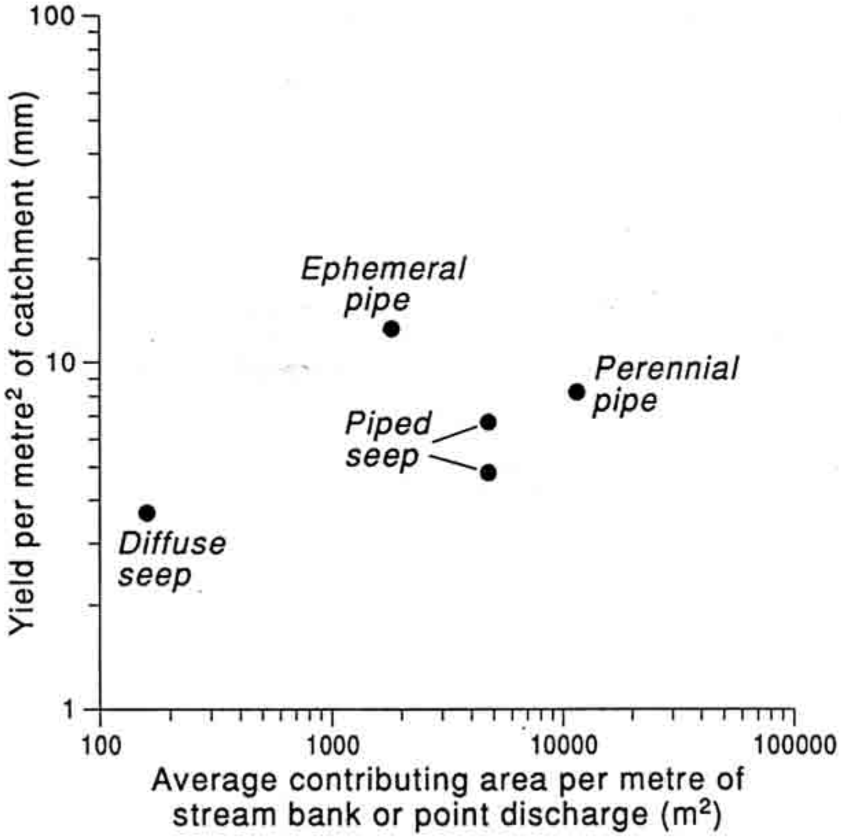

Fig. 22. The efficiency of drainage collection and yield for a variety of subsurface processes on Maesnant.

5. Conclusions.

Evidence is accruing, albeit slowly but relatively surely, to indicate that piping can have significant effects on a variety of geomorphic and hydrological processes. It is a major cause of channel head extension, rilling and gullying in landscapes as diverse as mediterranean California, temperate Wales, and semi-arid climates from Arizona to East Africa. It provides an effective alternative to Hortonian overland flow both in erosional terms and in contributions to streamflow. Whether erosional development is active or not, piping provides an extension to the drainage net which alters both streamflow and hillslope properties, and can be an important element in the river basin system. Even in this static role, piping can affect acidification processes and play an important part in generating storm runoff.

Both hydrologically and geomorphologically, piping blurs the distinction between hillslope processes and channel processes. Moreover, published reports from around the world clearly indicate that it not only exists in a wide variety of climatic and geomorphic environments, but that it is common and important in a good many of them. It plainly deserves more attention from both a theoretical and a practical point of view.

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