Article:

Regensburg, TH, Chapman, PJ, Pilkington, MG et al. (3 more authors) (2020) Controls on the spatial distribution of natural pipe outlets in heavily degraded blanket peat. Geomorphology, 367. 107322. ISSN 0169-555X

https://doi.org/10.1016/j.geomorph.2020.107322

Controls on the spatial distribution of natural pipe outlets in heavily degraded blanket peat

Regensburg, T.H.[1]*, Chapman, P.J.[1], Pilkington, M.[2], Chandler, D.[2], Evans, M.G.[3], Holden, J.[1]

[1]water@leeds, School of Geography, University of Leeds, Leeds, LS2 9JT, UK

[2]Moors for the Future Partnership, The Moorland Centre, Edale, S33 7ZA, UK

[3]School of Environment, Education, and Development, The University of Manchester, Oxford Road, Manchester, M13 9PL, UK

*Corresponding author: gytr@leeds.ac.uk

Abstract

Natural soil pipes are recognised as a common geomorphological feature in many peatlands, and they can discharge large quantities of water and sediment. However, little is known about their morphological characteristics in heavily degraded peat systems. This paper presents a survey of pipe outlets in which the frequency and extent of natural soil pipes are measured across a heavily gullied blanket peat catchment in the Peak District of northern England. Over a stream length of 7.71 km we determined the occurrence and size of 346 pipe outlets, and found a mean frequency of 22.8 km^{-1} gully bank. Topographic position was an important control on the size and depth of pipe outlets. Aspect had a large influence on pipe outlet frequency, with southwest and west- facing gully banks hosting more than 43% of identified pipe outlets. Pipe outlets on streambanks with signs of headward retreat were significantly larger and closer to the peat surface compared to pipe outlets that issued onto uniform streambank edges. We suggest that larger pipe frequencies are observed on gully banks that are more susceptible to desiccation cracking, and propose that future peatland restoration works could prioritise mitigating against pipe formation by revegetating and reprofiling south and west facing gully banks.

Keywords: piping, peatland, geomorphology, desiccation, degradation

Highlights:

- Pipe outlets mostly occur on streambank edges parallel to the stream
- At gully head retreat points, pipe outlets are large and close to the surface
- Aspect is a strong control on pipe outlet frequency in degraded blanket bog
- Pipe outlet frequency is associated with desiccation on gully edges

1. Introduction

Natural soil pipes have been recognised as common geomorphological and hydrological features of many environments (Baillie, 1975; Bryan and Jones, 1997; Chappell and Sherlock, 2005; Diaz, 2007; Verachtert et al., 2010). Soil pipes can sometimes transport large volumes of water, nutrients and sediment through hillslopes (Holden et al., 2012b; Nieber and Warner, 1991; Sayer et al., 2006). When pipes erode into large tunnels they can cause surface collapse and gullies can form along former pipe drainage lines (Bernatek-Jakiel and Poesen, 2018; Bryan and Yair, 1982; Marzolff and Ries, 2011; Valentin et al., 2005). Pipes have often been reported to occur at the head of gullies (Frankl et al., 2012; Leopold, 1964) but pipe outlets can also be seen along streambanks (Jones and Cottrell, 2007). In the temperate humid zone, one of the most susceptible soils to piping is blanket peat (Jones, 1990). Peatlands are globally important carbon stores, holding up to one third to half of the world's soil carbon (Yu, 2012). Most peatlands occur on very gentle gradient landscapes, but blanket peatlands can occur on terrain with slopes up to 20^{o} and mainly occur in hyperoceanic regions such as eastern and western Canada, southern Alaska, southern New Zealand, Falkland Islands and the British Isles (Gallego-Sala and Prentice, 2013). Their sloping nature, coupled with a plentiful rainfall supply, makes blanket peatlands prone to rapid degradation and gully development if the surface vegetation is damaged (Bower, 1961; Evans and Warburton, 2007).

Blanket peat covers 8% of the UK, mainly in the uplands, and is often found to depths of several metres. However, a significant portion of this peat cover is deeply eroded with extensive gullying similar to badland erosion (Tallis, 1997). Possible causes of erosion include cutting of drainage ditches, overgrazing and prescribed rotational vegetation burning for the gun-sports industry (Parry et al., 2014). However, in the southern Pennines of England, widespread peat erosion is most commonly ascribed to atmospheric deposition of acidic pollutants which, since the Industrial Revolution, has severely damaged peat forming mosses (Yeloff et al., 2006). The extent and severity of this erosion is high compared to elsewhere in the UK uplands, represents the loss of a major carbon store (Evans et al., 2006), and causes problems downstream including reservoir sedimentation (Labadz et al., 1991) and enhanced water discolouration, increasing treatment costs for potable supplies (Chow et al., 2003; Fearing et al., 2004; Wallage et al., 2006).

Due to concerns about habitat loss, downstream water quality and carbon loss, peatland restoration agencies have been actively undertaking measures to stabilise the peat, reduce erosion and re-establish vegetation (O'Brien et al., 2007; Parry et al., 2014; Shuttleworth et al., 2015). However, there have been no adequate assessments of the role of piping in this context. In order to support peatland restoration decision-making, a better understanding of the frequency and characteristics of peat pipes in these severely degraded systems is required. Such information would be useful to peatland protection organisations who are considering whether and how to locate and block pipe outlets as an erosion control mechanism.

Ground penetrating radar surveys conducted by Holden (2005), in a range of blanket peat catchments across the UK, suggested that the frequency of large pipes (>10cm diameter) was greater on flatter areas near summits and hillslope toes compared to steeper midslopes sections. These differences were attributed to the variability in the accumulation of peat across hillslopes, providing flatter surfaces with more heterogenous peat which may promote wandering pipe development. Such a pattern was unlike the distribution found in other piped environments where steeper slopes have been associated with enhanced piping due to larger hydraulic gradients (Gutierrez et al., 1997; Jones, 1981). However, it is not clear which patterns are found in extensively eroded and gullied peatlands. Holden (2005) found that pipe density was greater where ditch drainage occurred possibly due to locally enhanced hydraulic gradients (Terzaghi, 1943) and exposure of ditch edges to desiccation processes. Hence, it is thought that pipe density might be high in densely gullied blanket peat catchments. Soil cracking as a result of desiccation during dry summer periods has been considered a driver of pipe development (Gilman and Newson, 1980; Jones, 2004). Exposed blanket peat gully walls can frequently become cracked and desiccated (Burt and Gardiner, 1984). Given that gully incision in the south Pennines has been relatively recent, it may be possible to test for the desiccation effect by establishing whether there is more piping on south or westerly facing gully banks compared to the opposite side of the gully walls that face north or east.

Soil pipes in blanket peatlands can occur at varying depths (Holden and Burt, 2002), where they can form complex undulating networks connecting shallow and deep sources of water (Holden, 2004). In peatland gully landscapes it is not yet known whether pipes are randomly distributed with peat depth, whether more occur near the peat surface or whether more pipes occur near the base of the peat at the interface between peat and the underlying substrate. Anderson and Burt (1982) reported the existence of deep and shallow pipes in the eroded Shiny Brook catchment of the south Pennines, but there was no systematic survey of pipes in the system. They also reported pipe diameters up to 50 cm, but it is not clear whether heavily gullied peat systems are dominated by a few large diameter pipes, many smaller ones, or a mixture of both. Previous unpublished survey work on piping, conducted in part of the Upper North Grain catchment, a small peatland headwater catchment in the southern Pennines of England, identified pipes discharging water and dissolved organic carbon actively to streams, but there was not a complete picture of piping activity in the whole catchment (Goulsbra, 2010; Wallet, 2004). For peatland conservation practitioners such information would support their planning process and help with decision-making about the feasibility of carrying out targeted pipe blocking work as part of peatland restoration practice.

This paper reports on a survey of pipe outlets in a heavily degraded blanket peatland in the southern Pennines of England. It aims to: (1) determine the extent and size of soil pipe outlets found along gullies; (2) examine the relative roles of topographic position and stream bank aspect on pipe outlet frequency and pipe outlet characteristics; (3) suggest process mechanisms associated with controls on pipe outlet frequency that can be examined by further research; and (4) discuss the implications of findings for peatland restoration management.

2. Methods

2.1 Study site

This research was conducted within the southern Pennines, on part of the National Trust High Peak Estate in the Peak District National Park, in northern England. The study catchment, Upper North Grain (UNG), is a small (0.49 km^2) headwater catchment of the River Ashop which drains the slopes of both Bleaklow and Kinder Scout (Figure 1).

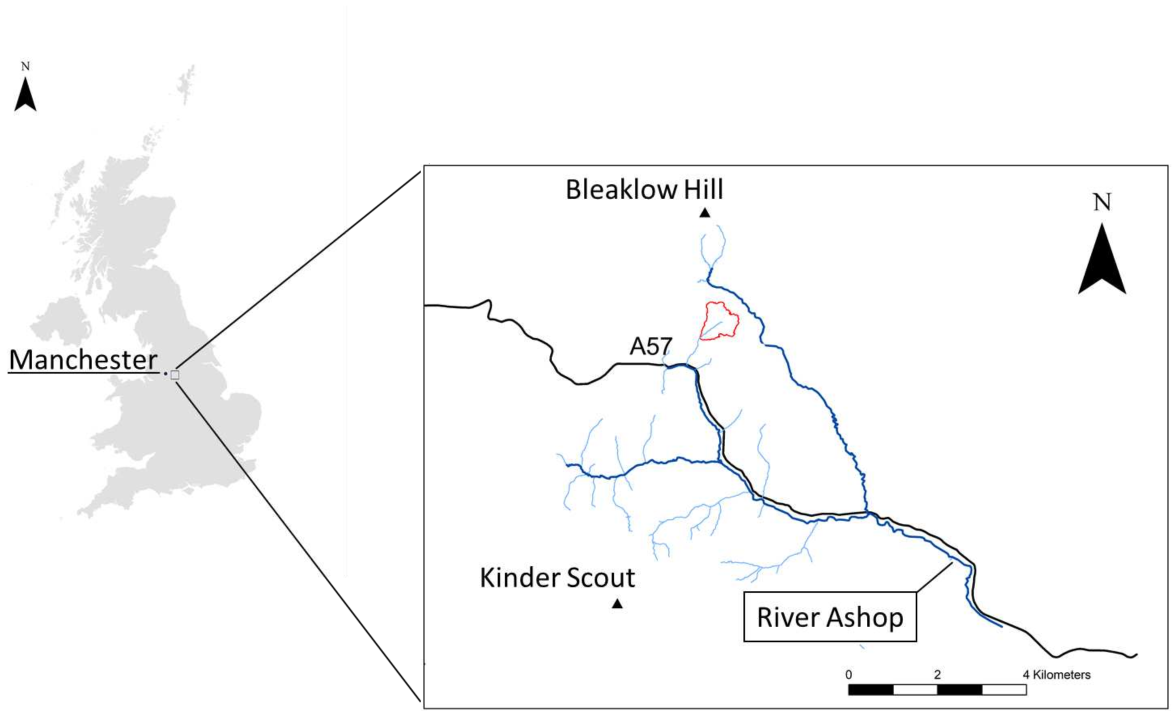

Figure 1. Location of Upper North Grain catchment (red boundary) east of Manchester. The catchment drains into the river Ashop, along which the A57 road runs.

Upper North Grain has a mean annual rainfall of 1313 mm and a mean annual temperature of 6.9 °C (Clay and Evans, 2017), which fits a sub-Arctic oceanic climate. Located at an altitudinal range of between 467 and 540 m above mean sea level, with an overall south-southwest facing aspect, the pedology of UNG is dominated by blanket peat, being 4 m thick in places. Slope angles within the catchment vary between 0 and 15°, with the majority of the catchment (>80%) being between 0 and 7°. Catchment aspect is dominated by southeast to northwest facing slopes, with the main surface water course flowing in a southwest direction. The vegetation is dominated by *Eriophorum vaginatum*, *Eriophorum Augustifolium*, *Calluna vulgaris*, *Erica tetralix*, *Vaccinium myrtillus*, *Empetrum nigrum* and patches of *Sphagnum spp*. The peat overlies sandstones of the carboniferous age Millstone Grit Series (Wolverson Cope, 1998). Separating the peat from the solid geology is a thin, discontinuous periglacial head deposit. The Bleaklow and Kinder Scout upland plateaus are amongst the most severely eroded peatland sites in the UK (Evans and Lindsay, 2010), and UNG is characterized by an extensive network of deep gullies which, in the lower reaches, cuts into the underlying bedrock. Peat deposition records, illustrating the growth behaviour of *Racomitrium lanuginosum* and *Sphagnum spp.* on both Holme Moss and Over Wood Moss, blanket peat catchments neighbouring UNG, indicated that the initial onset of erosion predates recent damage done by air pollution, land-use pressures and climate change and the peat system in the southern Pennines was already set in an 'erosion mode' (Tallis, 1995). The onset of peatland gully erosion in the southern Pennines correlates closely with climatic fluctuations in the Early Medieval Warm Period, when *Racomitrium lanuginosum* and *Sphagnum spp.* deposits first differed between uneroded and eroded sites (Tallis, 1995; Tallis, 1997).

2.2 Data collection

The primary goal of the survey was to assess the distribution of pipe outlets across the catchment and to collect data to determine spatial distributions of pipe outlet characteristics. Surveyors walked in pairs along the streambed of each gully in the upslope direction and identified pipe outlets by eye on streambanks, and recorded the geographical location of each pipe outlet using a hand-held GPS (e.g.

Garmin Etrex10). Pipe outlets were recorded 1) in gullies, which had two clear banks (left- and right-hand side), and 2) at exposed edges of the peat margin, that faced the main drainage stem of the catchment (Figure 2 and 3). Both locations will hereafter be referred to as 'streambank'. At each streambank the location of a pipe outlet was characterised as either occurring at: (1) the 'edge' where the streambank was broadly linear, without perpendicular headward incisions or (2) the 'head' where the streambank showed signs of headward retreat at the pipe outlet (Figure 2).

For each pipe outlet four main characteristics were recorded: 1) the pipe outlet dimensions, 2) the distance from the roof of the pipe outlet to the top of the streambank, 3) the slope of the streambank adjacent to the pipe outlet, and 4) the sloping length of the streambank. The latter was measured as the distance along the slope of the streambank between the highest and the lowest point at the streambank adjacent to the pipe outlet. Pipe outlet dimensions were defined by the vertical (H) and horizontal (W) diameters, which were measured using a steel tape measure to the nearest 5 mm. Macropores smaller than 5 mm were ignored following the method of Holden et al. (2012a). The distance from pipe outlet roof to the top of the streambank was measured from the pipe roof to the boundary between the visible peat surface of the gully edge and the vegetation line, and was recorded to the nearest 5 mm. The slope of the streambank was measured by placing an inclinometer on its surface, measuring in the perpendicular direction of the stream. To further determine the relative position of each pipe outlet on the streambank, photographs were taken of each pipe outlet location (Figure 2). Twelve pipe outlet surveys were carried out at UNG over a 22-month period between December 2017 and September 2019. In order to sample different parts of the catchment, the survey was conducted on different days during the year, which may have resulted in some inconsistencies in the number of pipe outlets found in certain areas of the catchment due to daylight limitations, flooding in streams, or adverse weather conditions.

2.3 Data processing

Table 1 describes the organization of the dataset used for analysis. Data preparation and processing was performed in ESRI ArcGIS Software suite 10.6. High-resolution LiDAR data recorded at a ground resolution of 0.5 m was used to produce a detailed digital terrain model (MFFP, 2014), which was used to delineate hydrological functions and terrain characteristics, including slope, aspect, flow direction, flow accumulation, stream raster, and the catchment boundary.

Table 1. Data frame showing selected parameters used in the analyses

Object	Feature	Feature class	File Type	Attributes
Catchment	Surface		Raster, 0.05 x 0.05 m	Elevation, slope, aspect, flow direction, flow accumulation, stream raster, watershed area
Streams	Streambank	Gully Peat margin	Vector, polyline	Length of streambank
Pipe Outlet	GPS Location	Edge Head	Vector, point feature	Count, GPS coordinates, streambank slope (α), depth to pipe roof (D_V), streambank height (D_S), relative position (RP), flow contribution area (FCA)
	Shape	Circular Horizontally lenticular Vertically lenticular	Vector, point feature	Count, vertical length (H), horizontal length (W), cross-sectional area
	Surface cover	Bare Non-bare ('Vegetated')	Vector, point feature	Count
	Aspect	Slope direction (Flat, N, NE, E, SE, S, SW, W, NW)	Vector, point feature	Count

To determine the actual depth of a pipe outlet at the gully bank, bank slope and the distance from the pipe roof to the gully edge were converted into a parameter describing the depth to pipe roof relative to the edge of the gully (Figure 3), which was derived as follows:

$$D_V = \sin\left(\frac{\alpha \cdot \pi}{180}\right) \cdot D_0 \qquad [2]$$

where α is the slope of the streambank in degrees, and D_0 represents the distance from pipe roof to peat surface measured over the streambank. For pipe outlets on banks with a slope of 90°, D_0 was used for D_V. To derive a value for streambank height, D_S, equation 2 was modified as followed:

$$D_S = \sin\left(\frac{\alpha \cdot \pi}{180}\right) \cdot SL \qquad [3]$$

where *SL* is the sloping length of the streambank in centimetres. To provide further insight about where pipes issue onto streambanks, the relative position between the gully edge and gully floor was determined for each pipe outlet by dividing D_V by D_S and subtracting this product from one. This provided a value range between 0 and 1, where 0 represents the level of the bottom of the gully and 1 represents the level of the upper peat surface.

The cross-sectional area of a pipe outlet was calculated using the surface area formula of an ellipsoid:

$$cross\ sectional\ area = \pi \cdot H \cdot W \qquad [4]$$

where H is the vertical length of the pipe outlet (cm), and W is the horizontal length of the pipe outlet (cm). The cross-sectional area of pipes along streambanks was calculated as the sum of the cross-sectional area of all pipe outlets per surveyed streambank length. For each pipe outlet the topographic upslope area that drained towards the pipe outlet was derived using the watershed tool in ArcGIS, hereafter referred to as flow contribution area (FCA) measured in m^2. In this study, the cross-sections of pipe outlets were divided into three shape types: horizontally-lenticular or vertically-lenticular if one axis exceeded the other by more than 5 cm; and circular pipes if horizontal and vertical axes differed by less than 5 cm. Surface cover was determined by identifying bare areas from pixel classification of aerial photographs taken of UNG in June 2014 that were recorded at 8 cm pixel size (MFFP, 2014). A colour signature representing the various colouring shades of bare peat surfaces in the UNG catchment was used to produce a new raster at 10 cm cell size, detailing two feature classes: bare peat surface (bare) and non-bare surface. Non-bare surfaces contained rock outcrop, water bodies and vegetation. Projecting the layers of pipe outlet GPS location and cover information over the aerial photographs, showed that most pipe outlets in non-bare areas actually occurred where there was a vegetation cover, and hereafter non-bare surfaces will be referred to as ‘vegetated’.

The length of surveyed streambanks in gullies was derived from the length of the stream raster in ArcGIS. Since gullies had two streambanks on either side, the length of each gully was multiplied by two to arrive at the total length of surveyed streambanks in gullies. Some of the observed pipe outlets were located on the peat margin. The length of streambanks on the peat margin was extracted from the length of polylines drawn upon the aerial photographs in ArcGIS. The latter streambanks were all facing the main drainage stem of the catchment. The frequency of pipe outlets per total length of streambank was calculated as follows:

$$pipe\ outlet\ frequency = n \cdot (2 \cdot Stream\ Raster + Polyline)^{-1} \qquad [5]$$

where *n* represents the total number of pipe outlets (dimensionless), stream raster and polyline are in meters as the sum of the lengths for their respective streambank types. Pipe outlets were surveyed along a total of 15.16 km streambank.

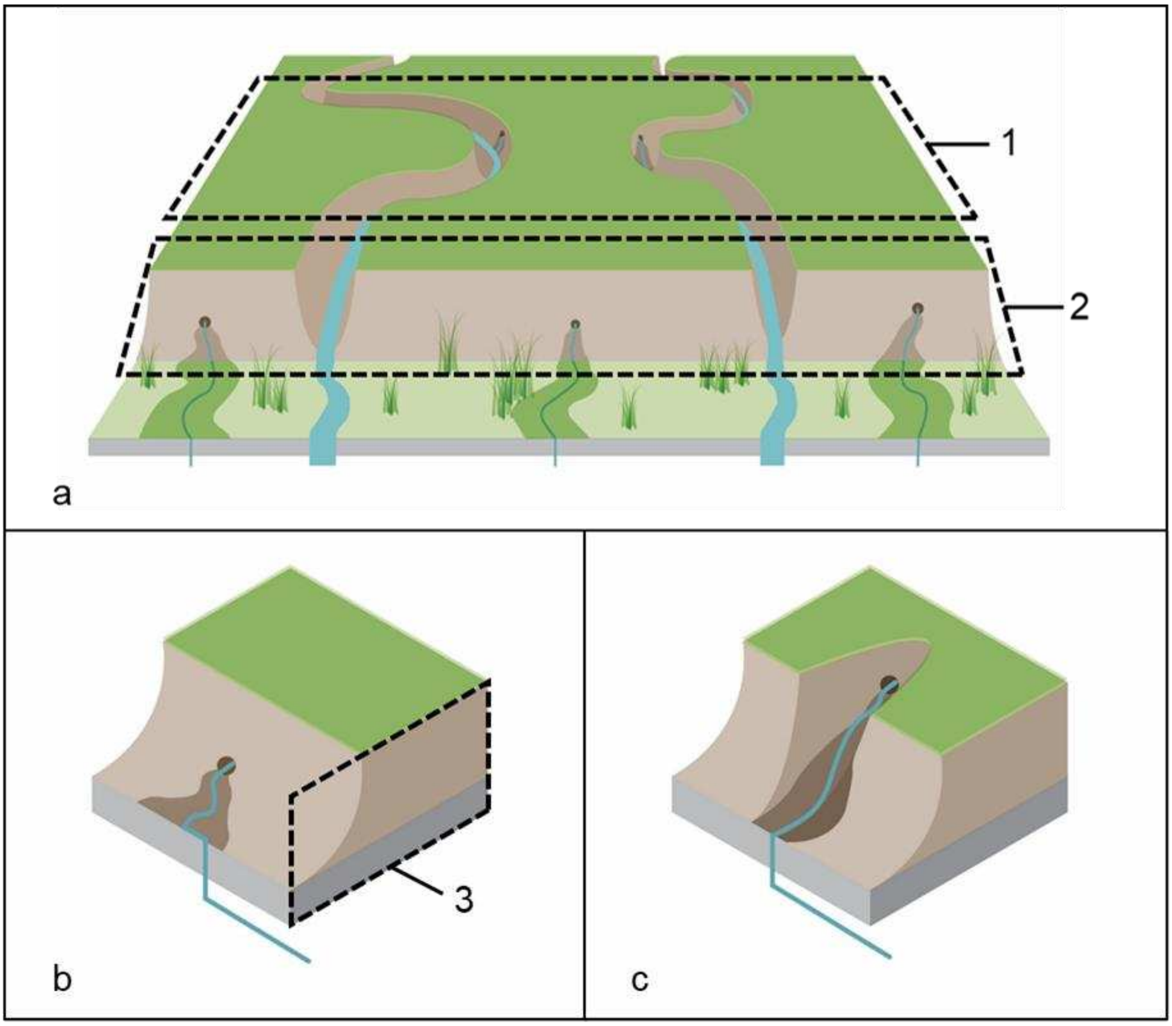

Figure 2. Diagram showing schematic representation of survey locations and pipe outlet locations: a. locations at which pipe outlets have been surveyed; in gullies (1) and along the peat margin (2); b. edge locations and c. head locations. Streambanks were defined as the area covering one gully wall and its adjacent peat surface (3).

To determine where hotspots of pipe outlets occurred in the catchment, a kernel density map was constructed using the pipe outlet locations as input data. Areas with high kernel density were further analysed by sampling the sum of pipe outlets over a length of streambank inside sample polygons of 100 m x 50 m. In this way, for each polygon the pipe outlet frequency was calculated per km streambank. In Figure 3 the sample polygon with the highest value of pipe outlet frequency is indicated with a red line. This area depicts the maximum pipe outlet frequency in the catchment recorded over at least 200 m of streambank, denoted as pipe outlets per km streambank.

Normality tests were performed for all variables and showed non-normal distributions. Data transformation did not result in normal distributions and therefore non-parametric tests were conducted using Mann-Whitney U tests, Spearman's Rank and Chi-squared in IBM SPSS Statistics version 26.

3. Results

3.1 Frequency of piping

A total of 346 pipe outlets were identified, of which 336 pipe outlets occurred at streambanks in gullies, while 10 pipe outlets occurred on the peat margin. A total of 88 pipe outlets were found at head locations, and 258 pipe outlets were found at edge locations. The mean pipe outlet frequency was 22.8 per km streambank. Sampling in areas with a high kernel density for pipe outlets resulted in a maximum pipe outlet frequency of 91 per km streambank (Figure 3), located in the middle part of the catchment in a wide and deeply eroded gully.

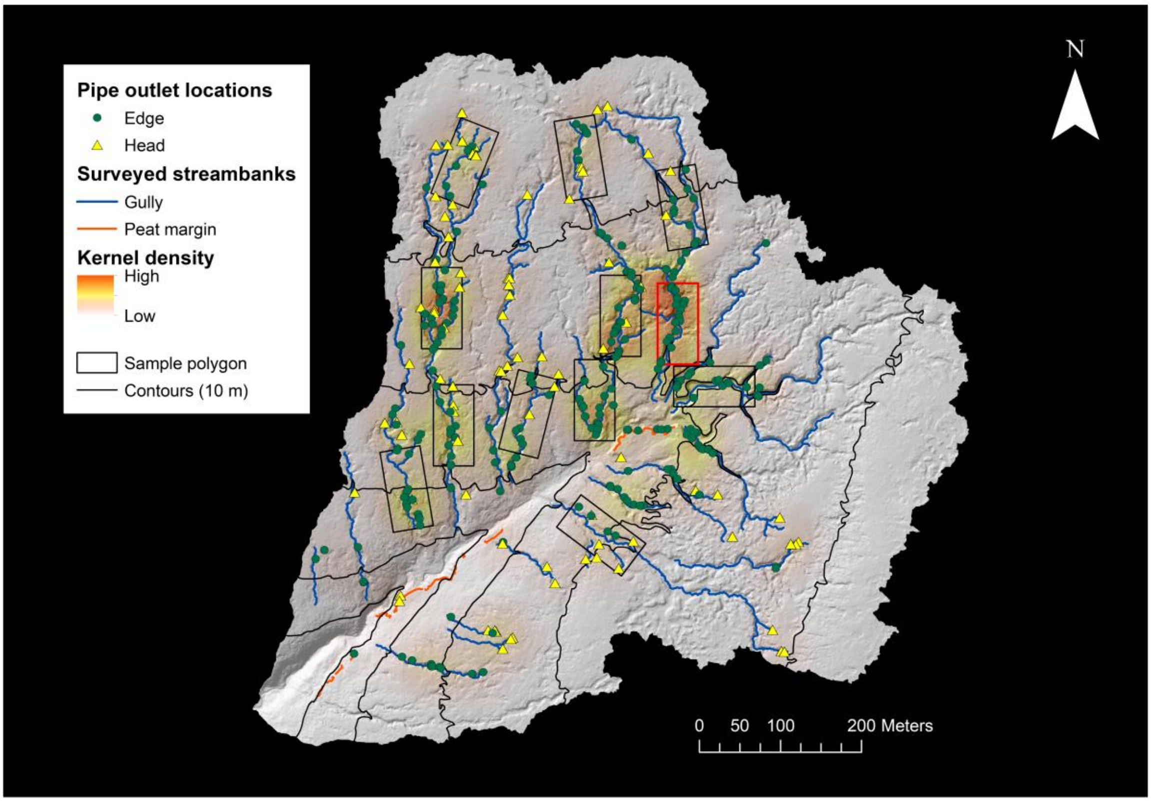

Figure 3. Map showing surveyed streambanks with identified pipe outlets, superimposed on a hillshade map of the catchment. A kernel density map was produced to indicate hotspots of pipe outlet frequency across the catchment, ranging from low to high (indicative). Rectangular polygons indicate areas of interest to determine the maximum pipe outlet

frequency in the catchment. The polygon that is outlined in red indicates the location with the highest estimated pipe outlet frequency. Contour lines run between 490 and 530 m, with 10 m interval. The highest point in the catchment is at 539.9 m above mean sea level.

3.2 Pipe outlet locations

More than half of the pipe outlets were identified at elevations between 515 m and 525 m (Figure 4), which covers an area with wide and deep gullies (Figure 3). Edge and head locations were significantly different across elevation ($U = 15143.5$, $p < 0.001$), with median elevation of 519.5 m (edge) and 523.6 m (head) respectively (Figure 4). The pipe outlets that were identified at streambanks on the peat margin were mostly found at the interface of the organic layer and the mineral bedrock, whereas the pipe outlets at streambanks in gullies were generally found in the peat profile (Figure 2 and 5).

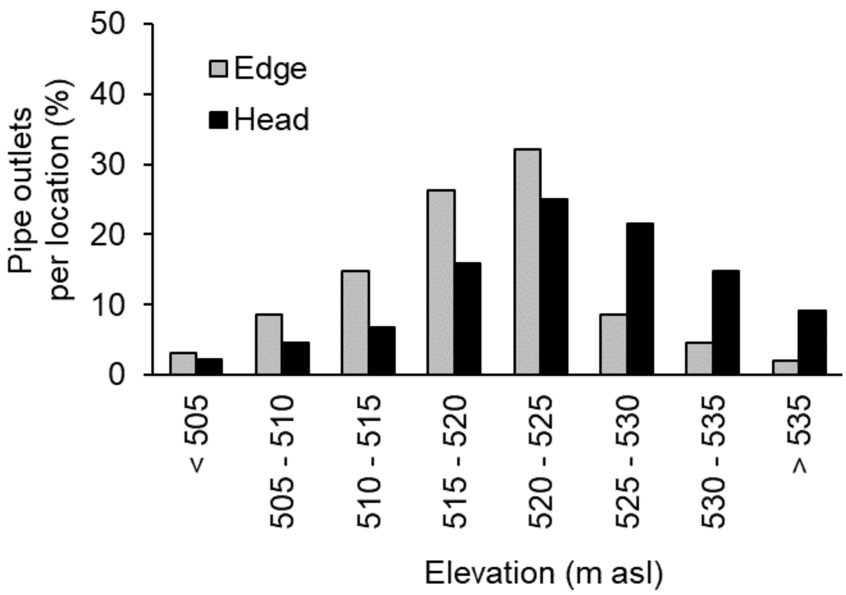

Figure 4. Bar diagram showing the distribution of pipe outlets by elevation in the catchment.

Streambank slope was determined for 197 edge locations and 40 head locations. Slopes of streambanks ranged from 3° to 87° with a median of 40°. Depth to pipe roof (D_V) ranged from 199 cm to 0 cm, with a median of 44 cm. Pipe outlets on head locations were found significantly closer to the surface (median D_V = 20 cm) compared to pipe outlets in gully edge areas (median D_V = 49 cm) (D_V Mann-Whitney $U = 1548$, $p < 0.001$). Overall, depth to pipe roof had weak but significantly negative relationships with vertical length ($r_s(235) = -0.226$, $p < 0.001$), horizontal length ($r_s(235) = -0.174$, $p = 0.007$), and cross-sectional area ($r_s(235) = -0.217$, $p = 0.001$).

The streambank height (D_S) was determined for 190 edge locations and 22 head locations. There was no difference in streambank height between edge locations and head locations ($U = 1781.5$, $p = 0.257$) but the relative position of pipe outlets was different across location (U=3419, p < 0.001), with a median of 0.80 for edge locations compared to a median of 0.95 for head locations. A Spearman's rank-order correlation showed that depth to pipe roof and streambank height had a positive correlation at edge locations at $p < 0.001$ ($r_s(188) = 0.350$), whereas no significant correlation was found at head locations ($r_s(20) = 0.307$, $p = 0.165$) (Figure 5).

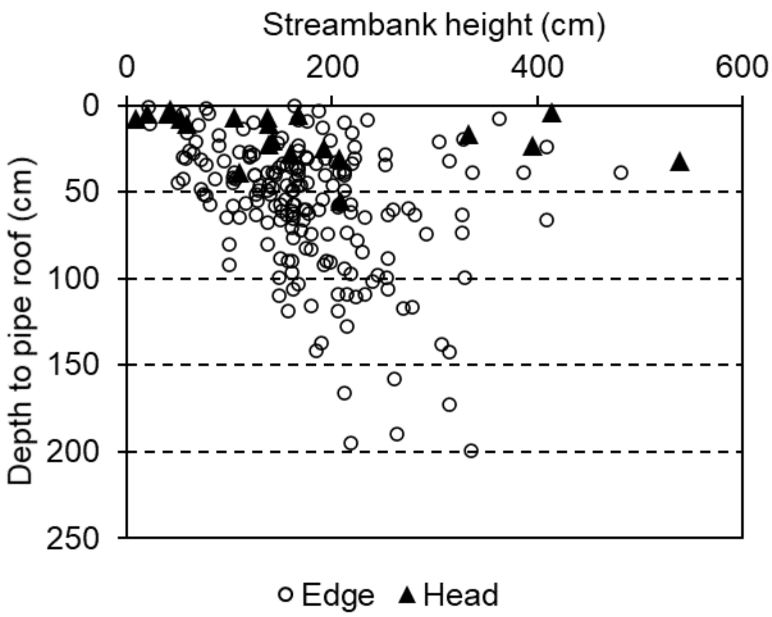

Figure 5. Scatter plot showing depth to pipe roof against streambank height for pipe outlets at edge and head locations.

3.3 Pipe outlet shape and size

There were 227 circular pipe outlets (c) (185 edge, 42 head), 10 horizontally lenticular pipe outlets (h)(5 at each location), 79 vertically lenticular pipe outlets (v)(52 edge, 27 head). Vertical length ranged from 1 to 90 cm, with a median of 8 cm. The horizontal length ranged 1 to 60 cm and had a median of 5 cm. Cross-sectional area of pipe outlets ranged from 3 cm^2 to 7539 cm^2, with a median of 119 cm^2. The total cross-sectional area of pipe outlets in the catchment was 110,477 cm^2, which translates to a density of piping along streambanks of 0.73 $m^2\ km^{-1}$. Figure 5 shows that pipe outlets at head locations are particularly concentrated near the surface. Within head locations pipe outlets issuing at the head of gullies occurred significantly closer to the surface compared to pipe outlets at head locations elsewhere in the catchment, with medians of 5.1 cm and 22.9 cm respectively (Mann-Whitney $U = 68$, $p = 0.020$). Such differences were not found for cross-sectional area.

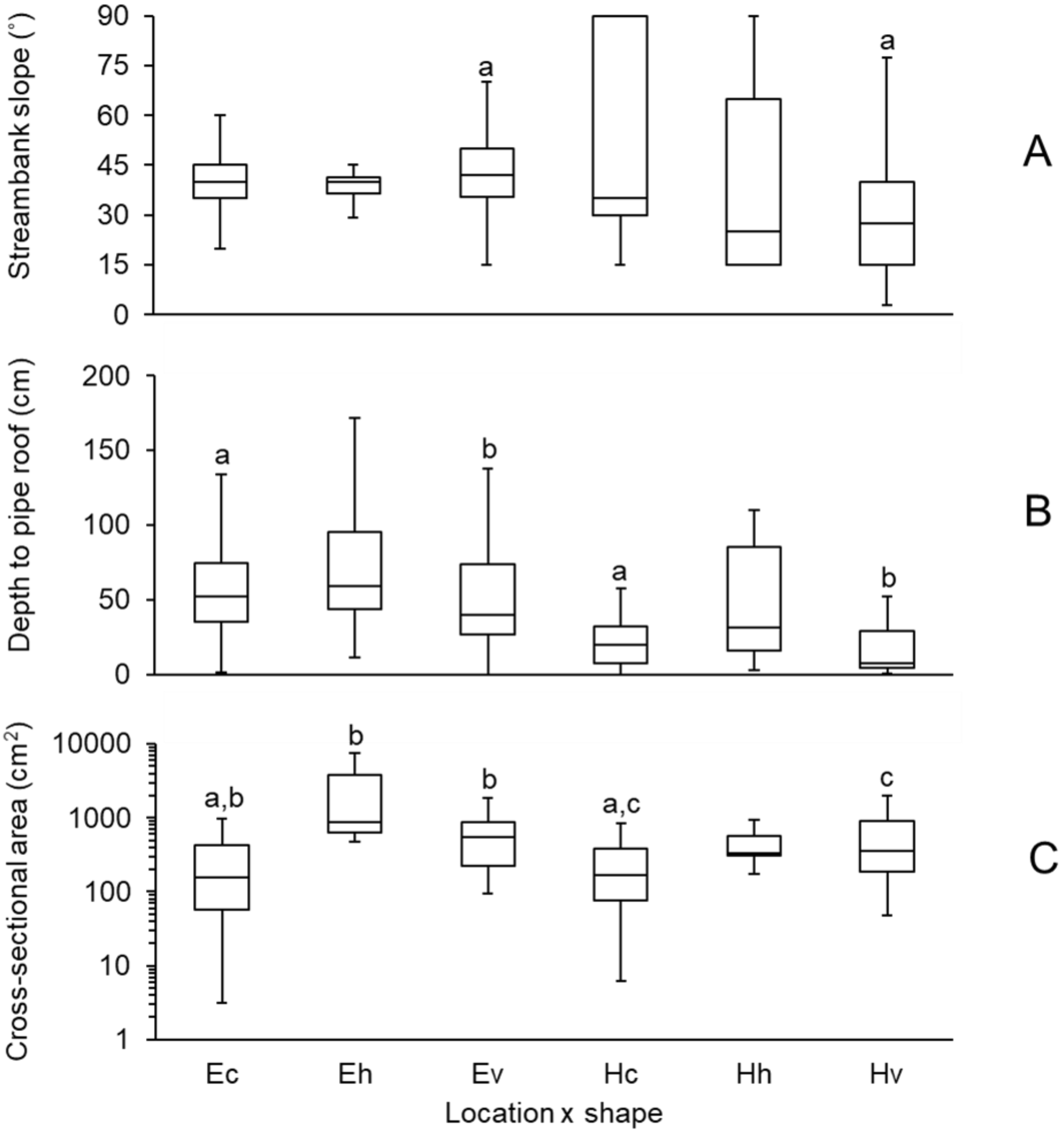

*Figure 6. Box plots showing the effects of location in the gully on: A) bank slope (degrees), B) depth to pipe roof (cm) and C) cross-sectional area of pipe outlets (cm^2), for location (E: edge; H: head) and shape type (c: circular; h: horizontally lenticular; v: vertically lenticular). The boxes show the interquartile range between Q1 and Q3, with the median indicated within the boxes as a black horizontal line. The whiskers indicate the lowest and highest values that are still within the range: [Q1 - 1.5 * (Q3 - Q1)] and [Q3 + 1.5 * (Q3 - Q1)]. Different superscript letters indicate significant difference ($p < 0.05$) compared with the other location and shape combinations.*

Values for streambank slope and depth to pipe roof were determined for 175 circular pipe outlets (154 edge, 21 head), 9 horizontally lenticular pipe outlets (4 edge, 5 head), and 53 vertically lenticular pipe outlets (39 edge, 14 head). Figure 6a shows the distribution of streambank slope for pipe outlets by location and shape type, with median values of streambank slope per shape type at edge locations (Ec = 40 ˚, Eh = 40 ˚, and Ev = 42 ˚) and head locations (Hc = 35 ˚, Hh = 25 ˚, Hv = 27.5 ˚). Vertically lenticular pipe outlets had significantly different distributions of streambank slope across categories of location (U = 147.5, p = 0.011). Distributions of streambank slope for circular (U = 1532.5, p = 0.695) and horizontally lenticular (U=8, p = 0.730) pipe outlets did not differ between locations. On edge locations there was no difference in the distributions of streambank slope across shape types: Ec versus Ev (U = 3494.5, p = 0.111), Ec versus Eh (U = 282.5, p = 0.775) and Eh versus Ev (U = 101, p = 0.361). At head locations the difference in streambank slope between Hc and Hv had a weak significance at $p < 0.1$ (U = 97.5, p = 0.096), but streambank slopes did not differ between Hc and Hh (U = 38, p = 0.374), and Hh and Hv (U = 29.5, p = 0.622) (Figure 6a).

Figure 6b shows the distribution of depth to pipe roof for pipe outlets by location and shape type, with median values of depth to pipe roof per shape type at edge locations (Ec = 51.6 cm, Eh = 59.1 cm, and Ev = 39.8 cm) and at head locations (Hc = 20.0 cm, Hh = 31.7 cm, Hv = 7.3 cm). The distribution of depth to pipe roof of circular pipe outlets was significantly different across categories of location (U = 540.5, $p < 0.001$). The distribution of depth to pipe roof of vertically lenticular pipe outlets was significantly different across categories of location (U = 108.5, p = 0.001) (Figure 6b). The distributions of depth to pipe roof of horizontally lenticular pipe outlets did not differ across location (U = 8, p = 0.730) (Figure 6). At head locations there was no difference in the distributions of depth to pipe roof across shape types: Hc versus Hv (U = 112.5, p = 0.249), Hc versus Hh (U = 67, p = 0.374) and Hh versus Hv (U =20.5, p = 0.186) (Figure 6b). At edge locations the difference in depth to pipe roof between Ec and Ev had a weak significance at $p < 0.1$ (U = 2408.5, p = 0.056). Depth to pipe roof did not differ between Ec and Eh (U = 345.5, p = 0.678), and Eh and Ev (U = 60, p = 0.479) (Figure 6b).

The cross-sectional area of pipe outlets was determined for 227 circular pipe outlets (edge = 185, head = 42), 10 horizontally lenticular pipe outlets (5 per location), and 79 vertically lenticular pipe outlets (edge = 52, head = 27). The cross-sectional area of pipe outlets was significantly larger at head locations with a median cross-sectional area of 292.2 cm^2 compared to pipe outlets at edge locations which had a median cross-sectional area of 88.0 cm^2 ($U = 12048.5$, $p < 0.001$). Overall, circular pipe outlets had significantly smaller cross-sectional areas with a median of 75.4 cm^2 compared to 351.9 cm^2 for vertically lenticular pipe outlets ($U = 15028.5$, $p < 0.001$) and 596.9 cm^2 for horizontally lenticular pipe outlets ($U = 2073$, $p < 0.001$), whilst the latter two had similar distributions of cross-sectional area ($U = 258.5$, $p = 0.076$).

Figure 6c shows the distribution of cross-sectional area of pipe outlets by location and shape type, with median values per shape type at edge locations (Ec = 66.0 cm^2, Eh = 867.1 cm^2, and Ev = 340.9 cm^2) and head locations (Hc = 157.1 cm^2, Hh = 326.7 cm^2, Hv = 351.9 cm^2). The distribution of cross-sectional area of circular pipe outlets was significantly different between categories of location ($U = 5425$, $p < 0.001$). No difference was found in distribution of cross-sectional area between locations for horizontally lenticular ($U = 5$, $p = 0.151$) and vertically lenticular ($U = 708$, $p = 0.951$) pipe outlets. The distribution of cross-sectional area of circular and vertically lenticular pipe outlets were significantly different from each other at edge locations ($U = 8395.5$, $p < 0.001$) and at head locations ($U=804.5$, $p = 0.003$). The distribution of cross-sectional area of circular and horizontally lenticular pipe outlets were significantly different from each other at edge locations ($U=895$, $p < 0.001$), and at head locations, but only at $p < 0.1$ ($U=160$, $p = 0.058$). The distribution of cross-sectional area of vertically and horizontally lenticular pipe outlets was significantly different from each other at edge locations ($U=50.5$, $p = 0.021$), but not at head locations ($U=66$, $p = 0.960$).

3.4 Relationship between pipe outlets and surface contributing area

The FCA was determined for 346 pipe outlet locations. The median FCA for pipe outlet locations was 1 m^2. There was no significant difference in FCA between head and edge locations (U = 10488, p = 0.283) and no significant relationship between the cross-sectional area of pipe outlets and FCA.

3.5 Relationship between pipe outlets and aspect

Aspect was determined for 346 pipe outlets. A *chi* square goodness of fit test showed that aspect was a significant factor controlling the distribution of pipe outlets ($\chi^2(8) = 141.7$, $p < 0.001$). For each of eight aspect categories, 38.4 pipe outlets were expected, but the observed count was larger for streambanks facing southwest (n = 76) and west (n = 76), which in total account for 43.9% of the pipe outlets. The rest of the pipe outlets faced north (n = 11), northeast (n = 16), east (n = 40) and south east (n = 41), south (n = 44), and northwest (n = 40). Two pipe outlets were found on flat surfaces (Figure 7).

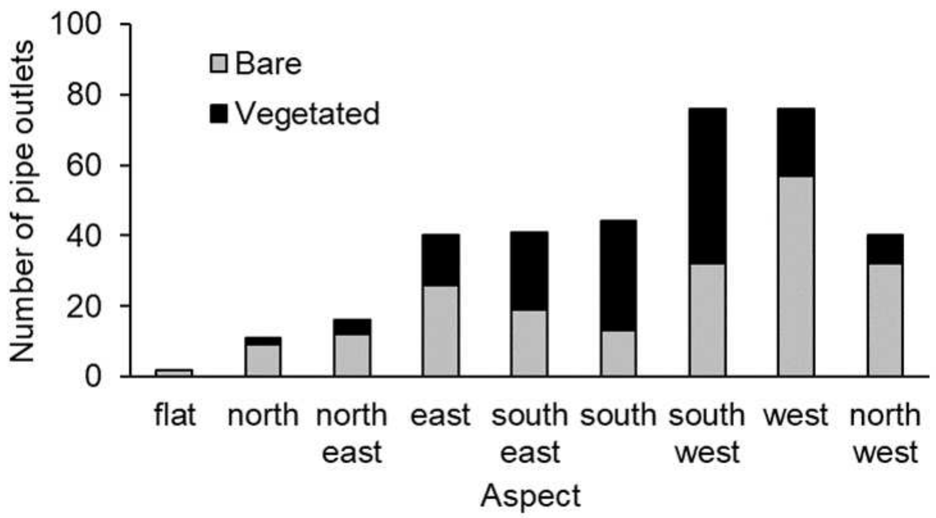

Figure 7. Stacked bar chart showing number of pipe outlets against aspect, stacked by cover type.

Post hoc pair wise *chi* square comparison showed that the number of pipe outlets was significantly different for north versus south ($\chi^2(1)= 19.8$, $p < 0.001$), north east versus south west ($\chi^2(1) = 39.1$, $p < 0.001$), and east versus west ($\chi^2(1) = 11.2$, $p = 0.001$). The distribution of pipe outlets was assumed to be the same between south east and north west facing streambanks ($\chi^2(1) = 0.012$, $p = 0.912$).

Table 2. Results of Mann-Whitney U independent sample tests on the distributions of depth to pipe roof (D_V) and cross-sectional area across categories of location for classes of aspect. Fields marked with a dash indicate missing data in either edge or head locations, hence comparisons were not performed.

Differences between edge and head locations						
	Depth to pipe roof (D_V)			**Cross-sectional area**		
aspect	MW-U	P - value	n	MW-U	P - value	n
flat	-			-		
north	-			-		
northeast	2.0	0.121	12	9.5	0.500	16
east	34.0	0.580	32	86.5	0.968	40
southeast	21.0	0.188	23	139.0	0.424	35
south	25.0	0.001	28	272.0	0.019	39
southwest	58.5	< 0.001	50	734.0	< 0.001	66
west	67.5	0.041	52	564.0	0.008	72
northwest	24.0	0.126	28	106.0	0.428	35

On streambanks with southerly, southwestly and westerly aspects, pipe outlets at edge locations were found significantly deeper compared to pipe outlets at head locations with the same aspect, at $p < 0.05$ (Table 2). On streambanks facing south, southwest and west, the cross-sectional area of pipe outlets at edge locations was significantly smaller compared to pipe outlets at head locations with the same aspect, at $p < 0.05$ (Table 2).

3.6 Surface cover and pipe outlets

A total of 202 pipe outlets occurred where there was a bare surface (edge = 177, head = 25) with 144 pipe outlets where there was vegetation (edge = 81, head = 63). The distribution of depth to pipe roof was the same across classes of surface cover in both edge locations (U = 3538.5, n = 197, p = 0.056) and head locations (U = 126.5, n = 40, p = 0.159) (Figure 8).

On bare surfaces, the distribution of depth to pipe roof was significantly different across categories of location (U = 433.0, n = 146, p = 0.003), with a median of 51.6 cm for edge locations and 22.9 cm for head locations (Figure 8). On vegetated surfaces, the distribution of depth to pipe roof was significantly different across categories of location (U = 330.5, n = 91, p < 0.001), with a median of 42.4 cm for edge locations and 10.0 cm for head locations (Figure 8).

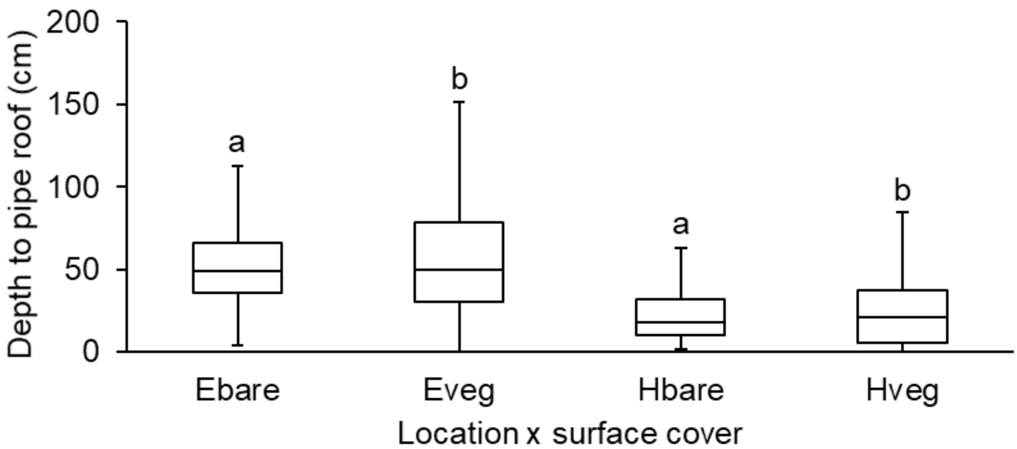

*Figure 8. Box plots showing the distribution of depth to pipe roof (cm), grouped by location (E: edge; H: head) and surface cover (bare; vegetated). The boxes show the interquartile range between Q1 and Q3, with the median indicated within the boxes as a black horizontal line. The whiskers indicate the lowest and highest values that are still within the range: [Q1 - 1.5 * (Q3 - Q1)] and [Q3 + 1.5 * (Q3 - Q1)]. Different superscript letters indicate significant difference (p < 0.05) compared with the other location and surface cover class combinations.*

The distribution of cross-sectional area across categories of surface cover type was assumed to be the same in both edge locations (U = 7081.0, n = 248, p = 0.213) and head locations (U = 626, p = 0.523). Cross-sectional area was significantly different across categories of location in both classes of surface cover. In bare surface areas (U = 2374.5, n = 190, p = 0.030) edge pipes had a median cross-sectional area of 88.0 cm^2 (edge) which was significantly smaller in size compared to pipe outlets in head locations (219.9 cm^2). A similar pattern was observed for pipe outlets at vegetated surfaces (U =

2570.0, n = 126, $p = 0.001$), with median values of 94.2 cm^2 for edge locations and 304.7 cm^2 for head locations.

A *Chi* square goodness of fit test indicated that the occurrence of pipe outlets was significantly different across classes of aspect for areas with a bare surface (χ^2 (8) = 97.9, $p < 0.001$) and areas with a vegetated surface (χ^2 (7) = 79.4, $p < 0.001$) (Figure 7). Bare surfaces that were facing west (n = 57) had markedly more pipe outlets than bare surfaces at other aspects. Vegetated surfaces that were facing south (n = 31) and southwest (n = 44) had markedly more pipe outlets than vegetated surfaces at other aspects.

4. Discussion

4.1 Pipe outlet frequency

The pipe outlet frequency in UNG (22.8 km^{-1} streambank) was slightly larger in comparison to the average pipe outlet frequency of 19.7 km^{-1} streambank across 160 blanket bog sites reported in Holden (2005). Table 3 shows that UNG has a relatively high pipe outlet frequency when compared to other blanket peat study catchments. One of the first surveys that looked specifically at the frequency of pipes in streambanks was conducted on the streambanks of Burbage Brook in the Peak District (podzol site) with 184 km^{-1} over 3 km of streambank in 1968 (Jones, 1975), and a resurvey in 2003 resulted in 134 km^{-1} over 500 m streambank (Jones and Cottrell, 2007). Other studies on piping reported values from Welsh catchments of 36 km^{-1} and 56 km^{-1}, respectively, for Cerrig yr Wyn and Nant Gerig (Gilman and Newson, 1980) and 80 km^{-1} for Afon Cerist (Jones, 1975). It should be noted that pipe outlets found in UNG were not like those in the Welsh studies where pipes were commonly disconnected from the stream and were found at breaks of slope on the hillside often coinciding with changes in soil type. The Welsh pipe systems were also characterised by pipes found at the base of the organic soil horizon. More recent examples in deep peat catchments in the north Pennines include 9.5 km^{-1} at Little Dodgen Pot Sike (Holden and Burt, 2002), and 36.6 km^{-1} (August 2007) and 31.7 km^{-1} (April 2010) at Cottage Hill Sike (Holden et al., 2012a). However, none of the above studies in Welsh and North Pennine uplands mentioned the total length of their survey transects, nor the methods that were used for calculating the pipe outlet frequency per length of streambank, and so a fair comparison between studies is difficult to undertake.

Table 3. Identified frequency of piping in UNG compared to other selected piped sites (after Holden and Burt (2002) - calculated using source data from papers and topographic maps).

Catchment	Soil type	Pipe frequency (km^{-1} stream bank)	Cross-sectional area of pipes (m^{-2} km^{-1} Streambank)	Mean diameter of pipes (cm)	Mean annual ppt (mm)	Mean altitude (m)	Mean main stream slope (*)	Mean valley side slope (*)
UNG	blanket peat	22.8	0.73	10.5	1314	521	9.06	7.22
Cottage Hill Sike, North Pennines (Holden et al., 2012a) *	blanket peat	31.69	0.308			563		5
160 blanket bog sites across UK (Holden, 2005)	blanket peat	19.7	0.556					
Burbage Brook, Peak District (Jones and Cottrell, 2007)	humo-ferric podzols	168	1.037	7.1	1019.4[b]	330		
Little Dodgen Pot Sike, North Pennines (Holden and Burt, 2002)	blanket peat	9.5	0.026	19	2000	540	2.2	3
Maesnant, Cambria	histic podzols	14.5	0.656	10[a]	2200	541	8.1	9.5

(Jones and Crane, 1984)								
Cerrig yr Wyn, Cambria **(Gilman and Newson, 1980)**		56		5	2200	472	10.3	9
Nant Gerrig, Cambria **(Gilman and Newson, 1980)**		36		10	2200	495	4.4	9
Burbage Brook, Peak District **(Jones, 1975)**	humo-ferric podzols	89	0.554	9	983.6[b]	150	2	10.2

a: 10 cm (ephemeral), 24 cm (perennial)

b: as presented in Jones and Cottrell (2007)

*: only observations included of survey in 2010

4.2 Location of pipe outlets

This study showed that pipe outlets were mostly concentrated in mid- and footslope areas of UNG while Holden (2005) found topslopes had greater pipe frequencies than footslopes which in turn had more pipes than midslopes. However, Holden's (2005) work was conducted using hillslope GPR grid surveys rather than observational surveys of pipe outlets on gully and streambanks which was the focus of the UNG work reported here, so the two surveys are not directly comparable. The occurrence of pipe outlets in UNG differed greatly between edge and head locations. Figure 3 showed that pipe outlets at head locations were, unsurprisingly, mainly found near the top of the catchment, and pipe outlets at edge locations occurred more frequently at lower elevations in UNG. Topslope segments in UNG consist of shallow channels that run within the peat profile, whilst sections at lower elevation are more characterized by deep gullies that have shallow tributaries. Bower (1961) suggested gullies in blanket peatlands mature from shallow, narrow channels within the peat to form wider, and deeply eroded, channel forms, by slumping of gully sides and collapse of pipe roofs. Heede (1976) proposed that pipes disconnect from the surface at a young age, but resurface when they have grown old, as they may be too large to sustain the full support of their roof, with roof collapse as a result. Height measurements of streambanks in the mid- and footslope sections of UNG suggest those peat profiles to be of considerable age, but this study demonstrated that the majority of pipe outlets occurred in the upper half of the streambank profiles (Figure 5). Here, the absence of pipe outlets near the bottom of streambanks suggests piping to be a secondary eroding agent at streambanks. Sample polygons that covered areas with a high kernel density were mainly populated by pipe outlets at edge locations (Figure 3). Daniels et al. (2008) showed that water table levels in UNG drop to larger depths and more frequently at gully sides than in intact bog further away from the gully. Where water tables are lowered in consecutive years permanent cracks may form in the peat, that provide new routes for bypass flow, thus leading to pipeflow and piping (Holden, 2006). Examples from drylands suggest that when gullies incise deeper than the pipe outlet, increases of the hydraulic gradient can occur, which then promotes the development of more soil pipes upslope (Swanson et al., 1989). We found pipe outlets predominantly on streambanks that face towards the sun and prevailing wind direction (west southwest – (Clay and Evans, 2017)), and those pipe outlets occurred more at edge locations, which sat deeper in the profile and were smaller than pipe outlets at head locations with the same aspect. Moreover, edge locations in unvegetated (bare) areas hosted more and smaller pipe outlets than pipe outlets on head locations in bare areas. Over the summer of 2018 prolonged drought caused peat to crack open to depths of 40 cm at places across UNG. Cracks that were observed at south, southwest and west-facing streambanks had not fully filled in by September 2019 as many of these cracks were still visible. Desiccation-stress cracking can induce a form of piping called sapping (Parker and Jenne, 1967), which refers to the mass failure or slumping resulting from undercutting of an embankment by seepage erosion (Fox and Wilson, 2010), followed by mass movement in the subsurface (subsidence) (Baillie, 1975). This evidence supports the idea that the occurrence of soil piping at edge locations is associated with the incidence of desiccation cracking as is observed on gully sides (Gilman and Newson, 1980; Holden, 2006).

4.3 Size and shape of pipe outlets

Table 3 summarizes, for a number of selected studies, the cross-sectional area per length of streambank. With 0.73 m^2 km^{-1} streambank UNG had a markedly greater surface occupied by pipe outlets than the average of 0.556 m^2 km^{-1} observed across 160 UK blanket bog sites (Holden, 2005). UNG ranks also higher than deep peat sites in the North Pennines, e.g. 0.026 m^2 km^{-1} at Little Dodgen Pot Sike (Holden and Burt, 2002) and 0.35 m^2 km^{-1} at Cottage Sike Hill (Holden et al., 2012a), which were both recorded in catchments that have naturally revegetated with slope-channel decoupling as a result (Evans et al., 2006; Holden and Burt, 2002; Holden et al., 2012a). UNG is considered to be still in an active eroding phase (Evans et al., 2006).

While pipe outlets in UNG were often found just downslope of surface depressions, most pipe outlets on streambanks seem disconnected from upstream overland flow routes. The cross-sectional area of pipe outlets was not related to topographic contribution area for each pipe outlet, corroborating findings of other piping studies in blanket peatland that suggest surface topography is not a suitable guide to pipe contributing area (e.g. Goulsbra (2010), Jones (2010), and Smart et al. (2013)).

Jones and Cottrell (2007) noted that vertically lenticular cross-sections suggest active downcutting, whereas horizontally-lenticular outlets suggest that pipe floor erosion is being inhibited by a less erodible soil horizon. We found only 3.2% of pipe outlets in UNG were horizontally-lenticular, which were found throughout the depth profile, and 25% of pipe outlets were vertically-lenticular, which were significantly closer to the surface than circular pipe outlets, suggesting that active downcutting of pipe outlets is occurring. However, no evidence was found that horizontally and vertically lenticular pipe outlets differ in cross-sectional area. The most common pipe outlet shape was circular (71.8%) which tended to be significantly smaller than elongated pipe outlets, whereas Holden et al. (2012a) found the opposite in the North Pennines. This suggests that pipe outlet shapes in UNG are distributed differently compared to other peatland sites, but factors that cause this effect need further research.

4.4 Implications for peatland restoration

The survey presented here was carried out to assess the extent and occurrence of piping in UNG, to provide evidence for peatland restoration practitioners who are interested in pipe blocking as an erosion mitigation measure. We have shown that natural soil piping is a common phenomenon in heavily degraded blanket peatland. While there are no tested guidelines for soil and water conservation measures to target soil piping in peatland environments, some ideas have been put forward in other environments (e.g. Frankl et al. (2016)) but have not yet been tested in the field. One of the key challenges that our work has identified is that topography alone is a poor guide to likely flow from pipe outlets as there was no relation between pipe size and upslope surface contributing area, and the mean pipe contributing area was an unrealistic 1 m^2. Therefore, prioritising which pipe outlets to target for blocking based on topographic maps will not be useful. In addition, it should be noted that piping is found in most blanket peatlands (Holden, 2006). Therefore, the idea of blocking all pipes in a catchment as part of restoration efforts may not be reasonable given that pipes are part of a natural state. An alternative option for practitioners is the use of existing practices that may help to prevent the initiation of new pipes on south and west facing edge locations. Such practices include gully reprofiling and subsequent revegetation or protective covering of exposed peat (Parry et al., 2014). Reprofiling of gullies aims to reduce the slope of gully sides, thereby eliminating factors that promote sheet and rill erosion and potentially reducing strong hydraulic gradients that may encourage pipe sapping. Revegetation of bare surfaces may lower overland flow velocities (Holden et al., 2008), cool the peat surface (Brown et al., 2016) and help retain moisture in the peat reducing the risk of desiccation. This revegetation and reprofiling may be particularly important on south to west facing gully sides to reduce the risk of new pipe development.

5. Conclusions

This paper provided the first published survey of natural pipe outlets in a heavily eroded blanket peatland. Pipes were common features of the landscape. The analysis showed that:

1) the location in the catchment is a strong control of the frequency, size, shape and depth of pipes issuing onto streambanks, with significantly more pipes at edge locations than at head locations,
2) topographic contribution area is not a suitable surrogate for actual pipe contributing area;
3) aspect of gully banks had a strong influence on pipe outlet frequency with 43% of the pipe outlets observed on southwest and west facing streambanks, particularly in deeply eroded gullies;
4) desiccation-cracking is identified as a possible control for pipe outlet frequency, which may inform a different approach to piping in future peatland restoration plans.

Gully restoration in blanket peatlands is being applied on a large scale but the approach has not yet included mitigation of pipe development as a key feature. Our results suggest that such an approach warrants attention.

Acknowledgements

The research was jointly funded by EU MOORLIFE2020-D3 awarded to Moors for the Future Partnership and by the School of Geography, University of Leeds. We are grateful to the Peak District National Park Authority for supporting the project and to The National Trust and Natural England for granting site access and permissions. We gratefully acknowledge the support of all volunteers that helped undertake the pipe survey and the advice given by two anonymous reviewers providing insightful comments on an earlier draft of the manuscript.

Data availability

Datasets related to this article can be found at https://doi.org/10.5518/839, hosted at the University of Leeds data repository (Regensburg, 2020).

References

Anderson, M., Burt, T.P., 1982. Throughflow and pipe monitoring in the humid temperate environment. In: R. Bryan, A. Yair (Eds.), Badland geomorphology and piping. Geo Books, Norwich, pp. 337-353.

Baillie, I.C., 1975. Piping as an erosion process in the uplands of Sarawak. Journal of Tropical Geography, 41, 9-15

Bernatek-Jakiel, A., Poesen, J., 2018. Subsurface erosion by soil piping: significance and research needs. Earth-Science Reviews, 185, 1107-1128. https://doi.org/10.1016/j.earscirev.2018.08.006.

Bower, M.M., 1961. The Distribution of Erosion in Blanket Peat Bogs in the Pennines. Transactions and Papers (Institute of British Geographers), 29, 17-30. https://doi.org/10.2307/621241.

Bryan, R., Yair, A., 1982. Badland geomorphology and piping. Geo Books, Norwich, England.

Bryan, R.B., Jones, J.A.A., 1997. The significance of soil piping processes: inventory and prospect. Geomorphology, 20(3), 209-218. https://doi.org/10.1016/S0169-555X(97)00024-X.

Burt, T.P., Gardiner, A.T., 1984. Runoff and sediment production in a small peat-covered catchment: some preliminary results. In: T.P. Burt, D.E. Walling (Eds.), Catchment experiments in fluvial geomorphology. Geobooks, Norwich, pp. 133-152.

Chappell, N.A., Sherlock, M.D., 2005. Contrasting flow pathways within tropical forest slopes of Ultisol soils. Earth Surface Processes and Landforms, 30(6), 735-753. http://dx.doi.org/10.1002/esp.1173.

Chow, A.T., Tanji, K.K., Gao, S., 2003. Production of dissolved organic carbon (DOC) and trihalomethane (THM) precursor from peat soils. Water Research, 37(18), 4475-4485. http://dx.doi.org/10.1016/S0043-1354(03)00437-8.

Clay, G.D., Evans, M.G., 2017. Ten-year meteorological record for an upland research catchment near the summit of Snake Pass in the Peak District, UK. Weather, 72(8), 242-249. http://dx.doi.org/10.1002/wea.2824.

Daniels, S.M., Agnew, C.T., Allott, T.E.H., Evans, M.G., 2008. Water table variability and runoff generation in an eroded peatland, South Pennines, UK. Journal of Hydrology, 361(1), 214-226. http://dx.doi.org/10.1016/j.jhydrol.2008.07.042.

Diaz, A.R.S., P.M.; Soriano, A.S.; Serrato, F.B.; Faulkner, H., 2007. The causes of piping in a set of abandoned agricultural terraces in southeast Spain. CATENA, 69, 282-293. https://dx.doi.org/10.1016/j.catena.2006.07.008.

Evans, M., Lindsay, J., 2010. Impact of gully erosion on carbon sequestration in blanket peatlands. Climate Research, 45, 31-41. https://dx.doi.org/10.3354/cr00887.

Evans, M., Warburton, J., 2007. Geomorphology of upland peat : erosion, form and landscape change. Blackwell, Oxford.

Evans, M., Warburton, J., Yang, J., 2006. Eroding blanket peat catchments: Global and local implications of upland organic sediment budgets. Geomorphology, 79(1), 45-57. https://doi.org/10.1016/j.geomorph.2005.09.015.

Fearing, D.A., Banks, J., Guyetand, S., Monfort Eroles, C., Jefferson, B., Wilson, D., Hillis, P., Campbell, A.T., Parsons, S.A., 2004. Combination of ferric and MIEX® for the treatment of a humic rich water. Water Research, 38(10), 2551-2558. http://dx.doi.org/10.1016/j.watres.2004.02.020.

Fox, G.A., Wilson, G.V., 2010. The Role of Subsurface Flow in Hillslope and Stream Bank Erosion: A Review. Soil Science Society of America Journal, 74(3), 717-733. http://dx.doi.org/10.2136/sssaj2009.0319.

Frankl, A., Deckers, J., Moulaert, L., Van Damme, A., Haile, M., Poesen, J., Nyssen, J., 2016. Integrated Solutions for Combating Gully Erosion in Areas Prone to Soil Piping: Innovations from the Drylands of Northern Ethiopia. Land Degradation & Development, 27(8), 1797-1804. http://dx.doi.org/10.1002/ldr.2301.

Frankl, A., Poesen, J., Deckers, J., Haile, M., Nyssen, J., 2012. Gully head retreat rates in the semi-arid highlands of Northern Ethiopia. Geomorphology, 173-174, 185-195. https://doi.org/10.1016/j.geomorph.2012.06.011.

Gallego-Sala, A.V., Prentice, C.I., 2013. Blanket peat biome endangered by climate change. Nature Clim. Change, 3(2), 152-155. http://dx.doi.org/10.1038/nclimate1672.

Gilman, K., Newson, M., 1980. Soil pipes and pipeflow : a hydrological study in upland Wales. Research monograph series. Geo Abstracts, Norwich, England.

Goulsbra, C.S., 2010. Monitoring the connectivity of hydrological pathways in a peatland headwater catchment. PhD thesis, University of Manchester, 243 pp.

Gutierrez, M., Sancho, C., Benito, G., Sirvent, J., Desir, G., 1997. Quantitative study of piping processes in badland areas of Ebro basin, NE Spain. Geomorphology, 20, 121-134

Heede, B.H., 1976. Gully development and control: the status of our knowledge. RM-169, USDA Forest Service, Fort Collins.

Holden, J., 2004. Hydrological connectivity of soil pipes determined by ground-penetrating radar tracer detection. Earth Surface Processes and Landforms, 29(4), 437-442. http://dx.doi.org/10.1002/esp.1039.

Holden, J., 2005. Controls of soil pipe frequency in upland blanket peat. Journal of Geophysical Research-Earth Surface, 110, Artn F01002. http://dx.doi.org/10.1029/2004fj000143.

Holden, J., 2006. Sediment and particulate carbon removal by pipe erosion increase over time in blanket peatlands as a consequence of land drainage. Journal of Geophysical Research-Earth Surface, 111, Artn F02010. http://dx.doi.org/10.1029/2005jf000386.

Holden, J., Burt, T.P., 2002. Piping and pipeflow in a deep peat catchment. CATENA, 48(3), 163-199. http://dx.doi.org/10.1016/S0341-8162(01)00189-8.

Holden, J., Kirkby, M.J., Lane, S.N., Milledge, D.G., Brookes, C.J., Holden, V., McDonald, A.T., 2008. Overland flow velocity and roughness properties in peatlands. Water Resources Research, 44(6), Artn WR006052. http://dx.doi.org/10.1029/2007WR006052.

Holden, J., Smart, R.P., Dinsmore, K.J., Baird, A.J., Billett, M.F., Chapman, P.J., 2012a. Morphological change of natural pipe outlets in blanket peat. Earth Surface Processes and Landforms, 37(1), 109-118. http://dx.doi.org/10.1002/esp.2239.

Holden, J., Smart, R.P., Dinsmore, K.J., Baird, A.J., Billett, M.F., Chapman, P.J., 2012b. Natural pipes in blanket peatlands: major point sources for the release of carbon to the aquatic system. Global Change Biology, 18, 3568-3580

Jones, J.A.A., 1975. Soil piping and subsurface initiation of stream channel networks. PhD thesis, University of Cambridge.

Jones, J.A.A., 1981. The nature of soil piping: a review of research. British Geomorphological Research Group Monograph Series, 3. Geo Books, Norwich.

Jones, J.A.A., 1990. Piping effects in humid lands. In: C.G. Higgins, D.R. Coates (Eds.), Groundwater geomorphology; the role of subsurface water in Earth-surface processes and landforms. Geological Society of America Special Papers. Geological Society of America, pp. 111-137.

Jones, J.A.A., 2004. Implications of natural soil piping for basin management in upland Britain. Land Degradation & Development, 15(3), 325-349. http://dx.doi.org/10.1002/ldr.618.

Jones, J.A.A., 2010. Soil piping and catchment response. Hydrological Processes, 24(12), 1548-1566. http://dx.doi.org/10.1002/hyp.7634.

Jones, J.A.A., Cottrell, C.I., 2007. Long-term changes in stream bank soil pipes and the effects of afforestation. Journal of Geophysical Research-Earth Surface, 112(F1), Artn F01010. http://dx.doi.org/10.1029/2006jf000509.

Jones, J.A.A., Crane, F.G., 1984. Pipeflow and pipe erosion in the Maesnant experimental catchment. In: T.P. Butt, D.E. Walling (Eds.), Catchment experiments in fluvial geomorphology. GeoBooks, Norwich,, pp. 55-72.

Labadz, J.C., Burt, T.P., Potter, A.W.R., 1991. Sediment yield and delivery in the blanket peat moorlands of the southern Pennines. Earth Surface Processes and Landforms, 16(3), 255-271. http://dx.doi.org/10.1002/esp.3290160306.
Leopold, L.B. (Ed.), 1964. Fluvial processes in geomorphology. Series of Books in Geology. W.H. Freeman.
Marzolff, I., Ries, J., 2011. Piping as a process of gully erosion in small-format aerial photography. A short note. Cuadernos de investigación histórica, 37, 115-120. http://dx.doi.org/10.18172/cig.1249.
MFFP, 2014. LiDAR (0.5 m x 0.5 m) and aerial imagery with 0.1 m ground resolution - dataset produced by BlueSky. Moors for the Future Partnership. v1.
Nieber, J.L., Warner, G.S., 1991. Soil Pipe Contribution to Steady Subsurface Stormflow. Hydrological Processes, 5(4), 329-344
O'Brien, H., Labadz, J.C., Butcher, D.P., 2007. Technical report to DEFRA: Review of Blanket Bog Management and Restoration, Nottingham Trent University, Brackenhurst, Southwell.
Parker, G.G., Jenne, E.A., 1967. Structural Failure of Western U.S. highways caused by piping, U.S. Geological Survey Water Resources Division.
Parry, L.E., Holden, J., Chapman, P.J., 2014. Restoration of blanket peatlands. J Environ Manage, 133, 193-205. http://dx.doi.org/10.1016/j.jenvman.2013.11.033.
Regensburg, T.H., 2020. Controls on the spatial distribution of natural pipe outlets in heavily degraded blanket peat - dataset. http://dx.doi.org/10.5518/839
Sayer, A.M., Walsh, R.P.D., Bidin, K., 2006. Pipeflow suspended sediment dynamics and their contribution to stream sediment budgets in small rainforest catchments, Sabah, Malaysia. Forest Ecology and Management, 224(1-2), 119-130
Shuttleworth, E.L., Evans, M.G., Hutchinson, S.M., Rothwell, J.J., 2015. Peatland restoration: controls on sediment production and reductions in carbon and pollutant export. Earth Surface Processes and Landforms, 40(4), 459-472. http://dx.doi.org/10.1002/esp.3645.
Smart, R.P., Holden, J., Dinsmore, K.J., Baird, A.J., Billett, M.F., Chapman, P.J., Grayson, R., 2013. The dynamics of natural pipe hydrological behaviour in blanket peat. Hydrological Processes, 27(11), 1523-1534. http://dx.doi.org/10.1002/hyp.9242.
Swanson, M.L., Kondolf, G.M., Boison, P.J., 1989. An example of rapid gully initiation and extension by subsurface erosion: Coastal San Mateo County, California. Geomorphology, 2(4), 393-403. https://doi.org/10.1016/0169-555X(89)90023-8.
Tallis, J.H., 1995. Climate and Erosion Signals in British Blanket Peats: The Significance of Racomitrium Lanuginosum Remains. Journal of Ecology, 83(6), 1021-1030. http://dx.doi.org/10.2307/2261183.
Tallis, J.H., 1997. The southern Pennine experience: an overview of blanket mire degradation. In: J.H. Tallis, R. Meade, P.D. Hulme (Eds.), Blanket mire degradation: Causes, consequences and challenges. Mucaulay Land Use Research Institute, Aberdeen, pp. 7–16.
Terzaghi, K., 1943. Theoretical soil mechanics. John Wiley, Hoboken, N. J.
Valentin, C., Poesen, J., Li, Y., 2005. Gully erosion: Impacts, factors and control. CATENA, 63(2), 132-153. http://dx.doi.org/10.1016/j.catena.2005.06.001.
Verachtert, E., Van Den Eeckhaut, M., Poesen, J., Deckers, J., 2010. Factors controlling the spatial distribution of soil piping erosion on loess-derived soils: A case study from central Belgium. Geomorphology, 118(3), 339-348. https://doi.org/10.1016/j.geomorph.2010.02.001.
Wallage, Z.E., Holden, J., McDonald, A.T., 2006. Drain blocking: An effective treatment for reducing dissolved organic carbon loss and water discolouration in a drained peatland. Science of The Total Environment, 367(2–3), 811-821. https://doi.org/10.1016/j.scitotenv.2006.02.010.
Wallet, C.V., 2004. The Importance of Pipeflow to the Flux of Carbon from an Upland Peat. Master Thesis, University of Manchester, 56 pp.
Wolverson Cope, F., 1998. Geology Explained in the Peak District. Scarthin Books, Derbyshire.

Yeloff, D.E., Labadz, J.C., Hunt, C.O., 2006. Causes of degradation and erosion of a blanket mire in the southern Pennines, UK. Mires and Peat, 1(Artn. 4), 1-18

Yu, Z.C., 2012. Northern peatland carbon stocks and dynamics: a review. Biogeosciences, 9(10), 4071-4085. http://dx.doi.org/10.5194/bg-9-4071-2012.