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

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8   **Abstract**

9   Natural soil pipes are recognised as a common geomorphological feature in many peatlands, and they

10   can discharge large quantities of water and sediment. However, little is known about their

11   morphological characteristics in heavily degraded peat systems. This paper presents a survey of pipe

12   outlets in which the frequency and extent of natural soil pipes are measured across a heavily gullied

13   blanket peat catchment in the Peak District of northern England. Over a stream length of 7.71 km we

14   determined the occurrence and size of 346 pipe outlets, and found a mean frequency of 22.8 km^{-1}

15   gully bank. Topographic position was an important control on the size and depth of pipe outlets.

16   Aspect had a large influence on pipe outlet frequency, with southwest and west- facing gully banks

17   hosting more than 43% of identified pipe outlets. Pipe outlets on streambanks with signs of headward

18   retreat were significantly larger and closer to the peat surface compared to pipe outlets that issued

19   onto uniform streambank edges. We suggest that larger pipe frequencies are observed on gully banks

20   that are more susceptible to desiccation cracking, and propose that future peatland restoration works

21   could prioritise mitigating against pipe formation by revegetating and reprofiling south and west

22   facing gully banks.

23   **Keywords**: piping, peatland, geomorphology, desiccation, degradation

24 Highlights:

25   -   Pipe outlets mostly occur on streambank edges parallel to the stream

26   -   At gully head retreat points, pipe outlets are large and close to the surface

27   -   Aspect is a strong control on pipe outlet frequency in degraded blanket bog

28   -   Pipe outlet frequency is associated with desiccation on gully edges

29

30   1.   Introduction

31 Natural soil pipes have been recognised as common geomorphological and hydrological features of

32 many environments (Baillie, 1975; Bryan and Jones, 1997; Chappell and Sherlock, 2005; Diaz, 2007;

33 Verachtert et al., 2010). Soil pipes can sometimes transport large volumes of water, nutrients and

34 sediment through hillslopes (Holden et al., 2012b; Nieber and Warner, 1991; Sayer et al., 2006). When

35 pipes erode into large tunnels they can cause surface collapse and gullies can form along former pipe

36 drainage lines (Bernatek-Jakiel and Poesen, 2018; Bryan and Yair, 1982; Marzolff and Ries, 2011;

37 Valentin et al., 2005). Pipes have often been reported to occur at the head of gullies (Frankl et al.,

38 2012; Leopold, 1964) but pipe outlets can also be seen along streambanks (Jones and Cottrell, 2007).

39 In the temperate humid zone, one of the most susceptible soils to piping is blanket peat (Jones, 1990).

40 Peatlands are globally important carbon stores, holding up to one third to half of the world's soil

41 carbon (Yu, 2012). Most peatlands occur on very gentle gradient landscapes, but blanket peatlands

42 can occur on terrain with slopes up to 20° and mainly occur in hyperoceanic regions such as eastern

43 and western Canada, southern Alaska, southern New Zealand, Falkland Islands and the British Isles

44 (Gallego-Sala and Prentice, 2013). Their sloping nature, coupled with a plentiful rainfall supply, makes

45 blanket peatlands prone to rapid degradation and gully development if the surface vegetation is

46 damaged (Bower, 1961; Evans and Warburton, 2007).

47 Blanket peat covers 8% of the UK, mainly in the uplands, and is often found to depths of several

48 metres. However, a significant portion of this peat cover is deeply eroded with extensive gullying

49   similar to badland erosion (Tallis, 1997). Possible causes of erosion include cutting of drainage ditches,

50   overgrazing and prescribed rotational vegetation burning for the gun-sports industry (Parry et al.,

51   2014). However, in the southern Pennines of England, widespread peat erosion is most commonly

52   ascribed to atmospheric deposition of acidic pollutants which, since the Industrial Revolution, has

53   severely damaged peat forming mosses (Yeloff et al., 2006). The extent and severity of this erosion is

54   high compared to elsewhere in the UK uplands, represents the loss of a major carbon store (Evans et

55   al., 2006), and causes problems downstream including reservoir sedimentation (Labadz et al., 1991)

56   and enhanced water discolouration, increasing treatment costs for potable supplies (Chow et al.,

57   2003; Fearing et al., 2004; Wallage et al., 2006).

58

59   Due to concerns about habitat loss, downstream water quality and carbon loss, peatland restoration

60   agencies have been actively undertaking measures to stabilise the peat, reduce erosion and re-

61   establish vegetation (O'Brien et al., 2007; Parry et al., 2014; Shuttleworth et al., 2015). However, there

62   have been no adequate assessments of the role of piping in this context. In order to support peatland

63   restoration decision-making, a better understanding of the frequency and characteristics of peat pipes

64   in these severely degraded systems is required. Such information would be useful to peatland

65   protection organisations who are considering whether and how to locate and block pipe outlets as an

66   erosion control mechanism.

67

68   Ground penetrating radar surveys conducted by Holden (2005), in a range of blanket peat catchments

69   across the UK, suggested that the frequency of large pipes (>10cm diameter) was greater on flatter

70   areas near summits and hillslope toes compared to steeper midslopes sections. These differences

71   were attributed to the variability in the accumulation of peat across hillslopes, providing flatter

72   surfaces with more heterogenous peat which may promote wandering pipe development. Such a

73   pattern was unlike the distribution found in other piped environments where steeper slopes have

74   been associated with enhanced piping due to larger hydraulic gradients (Gutierrez et al., 1997; Jones,

75   1981). However, it is not clear which patterns are found in extensively eroded and gullied peatlands.

76   Holden (2005) found that pipe density was greater where ditch drainage occurred possibly due to

77   locally enhanced hydraulic gradients (Terzaghi, 1943) and exposure of ditch edges to desiccation

78   processes. Hence, it is thought that pipe density might be high in densely gullied blanket peat

79   catchments. Soil cracking as a result of desiccation during dry summer periods has been considered a

80   driver of pipe development (Gilman and Newson, 1980; Jones, 2004). Exposed blanket peat gully walls

81   can frequently become cracked and desiccated (Burt and Gardiner, 1984). Given that gully incision in

82   the south Pennines has been relatively recent, it may be possible to test for the desiccation effect by

83   establishing whether there is more piping on south or westerly facing gully banks compared to the

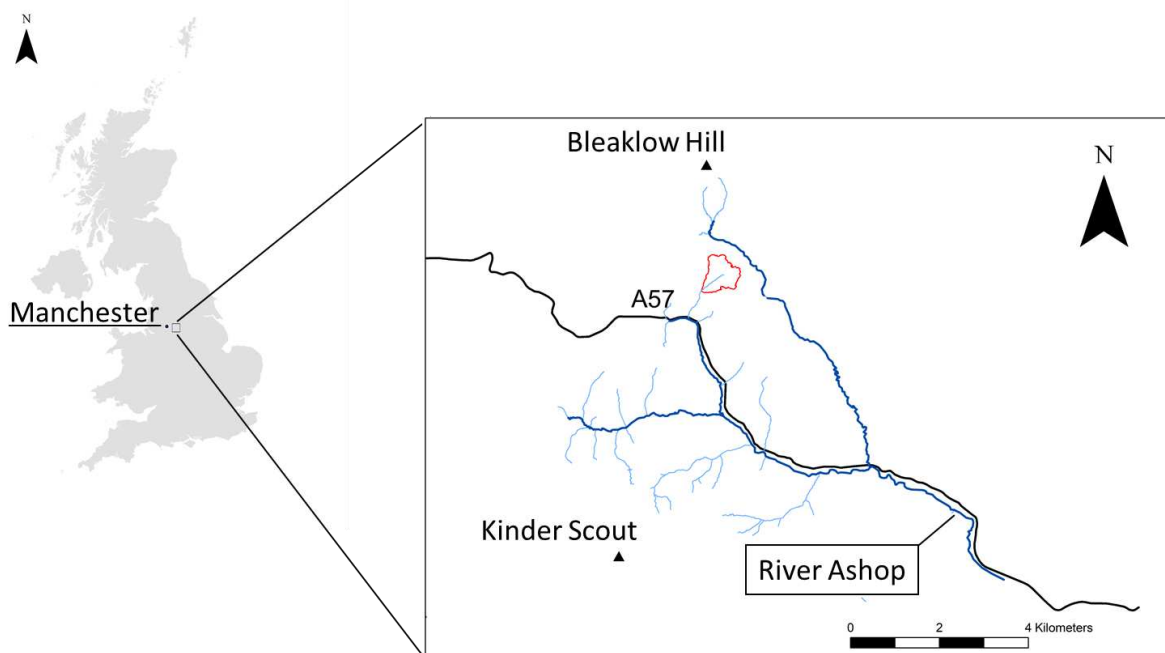84   opposite side of the gully walls that face north or east.

85

86   Soil pipes in blanket peatlands can occur at varying depths (Holden and Burt, 2002), where they can

87   form complex undulating networks connecting shallow and deep sources of water (Holden, 2004). In

88   peatland gully landscapes it is not yet known whether pipes are randomly distributed with peat depth,

89   whether more occur near the peat surface or whether more pipes occur near the base of the peat at

90   the interface between peat and the underlying substrate. Anderson and Burt (1982) reported the

91   existence of deep and shallow pipes in the eroded Shiny Brook catchment of the south Pennines, but

92   there was no systematic survey of pipes in the system. They also reported pipe diameters up to 50

93   cm, but it is not clear whether heavily gullied peat systems are dominated by a few large diameter

94   pipes, many smaller ones, or a mixture of both. Previous unpublished survey work on piping,

95   conducted in part of the Upper North Grain catchment, a small peatland headwater catchment in the

96   southern Pennines of England, identified pipes discharging water and dissolved organic carbon

97   actively to streams, but there was not a complete picture of piping activity in the whole catchment

98   (Goulsbra, 2010; Wallet, 2004). For peatland conservation practitioners such information would

99   support their planning process and help with decision-making about the feasibility of carrying out

100   targeted pipe blocking work as part of peatland restoration practice.

101 This paper reports on a survey of pipe outlets in a heavily degraded blanket peatland in the southern

102 Pennines of England. It aims to: (1) determine the extent and size of soil pipe outlets found along

103 gullies; (2) examine the relative roles of topographic position and stream bank aspect on pipe outlet

104 frequency and pipe outlet characteristics; (3) suggest process mechanisms associated with controls

105 on pipe outlet frequency that can be examined by further research; and (4) discuss the implications of

106 findings for peatland restoration management.

107 2. Methods

108 2.1 Study site

109 This research was conducted within the southern Pennines, on part of the National Trust High Peak

110 Estate in the Peak District National Park, in northern England. The study catchment, Upper North Grain

111 (UNG), is a small (0.49 km^2) headwater catchment of the River Ashop which drains the slopes of both

112 Bleaklow and Kinder Scout (Figure 1).

113

114 *Figure 1. Location of Upper North Grain catchment (red boundary) east of Manchester. The catchment drains into the river*

115 *Ashop, along which the A57 road runs.*

116 Upper North Grain has a mean annual rainfall of 1313 mm and a mean annual temperature of 6.9 °C

117 (Clay and Evans, 2017), which fits a sub-Arctic oceanic climate. Located at an altitudinal range of

118 between 467 and 540 m above mean sea level, with an overall south-southwest facing aspect, the

119 pedology of UNG is dominated by blanket peat, being 4 m thick in places. Slope angles within the

120 catchment vary between 0 and 15°, with the majority of the catchment (>80%) being between 0 and

121 7°. Catchment aspect is dominated by southeast to northwest facing slopes, with the main surface

122 water course flowing in a southwest direction. The vegetation is dominated by *Eriophorum vaginatum*,

123 *Eriophorum Augustifolium*, *Calluna vulgaris*, *Erica tetralix*, *Vaccinium myrtillus*, *Empetrum nigrum* and

124 patches of *Sphagnum spp.*. The peat overlies sandstones of the carboniferous age Millstone Grit Series

125 (Wolverson Cope, 1998). Separating the peat from the solid geology is a thin, discontinuous periglacial

126 head deposit. The Bleaklow and Kinder Scout upland plateaus are amongst the most severely eroded

127 peatland sites in the UK (Evans and Lindsay, 2010), and UNG is characterized by an extensive network

128 of deep gullies which, in the lower reaches, cuts into the underlying bedrock. Peat deposition records,

129 illustrating the growth behaviour of *Racomitrium lanuginosum* and *Sphagnum spp.* on both Holme

130 Moss and Over Wood Moss, blanket peat catchments neighbouring UNG, indicated that the initial

131 onset of erosion predates recent damage done by air pollution, land-use pressures and climate change

132 and the peat system in the southern Pennines was already set in an 'erosion mode' (Tallis, 1995). The

133 onset of peatland gully erosion in the southern Pennines correlates closely with climatic fluctuations

134 in the Early Medieval Warm Period, when *Racomitrium lanuginosum* and *Sphagnum spp.* deposits first

135 differed between uneroded and eroded sites (Tallis, 1995; Tallis, 1997).

136 2.2 Data collection

137 The primary goal of the survey was to assess the distribution of pipe outlets across the catchment and

138 to collect data to determine spatial distributions of pipe outlet characteristics. Surveyors walked in

139 pairs along the streambed of each gully in the upslope direction and identified pipe outlets by eye on

140 streambanks, and recorded the geographical location of each pipe outlet using a hand-held GPS (e.g.

141   Garmin Etrex10). Pipe outlets were recorded 1) in gullies, which had two clear banks (left- and right-

142   hand side), and 2) at exposed edges of the peat margin, that faced the main drainage stem of the

143   catchment (Figure 2 and 3). Both locations will hereafter be referred to as 'streambank'. At each

144   streambank the location of a pipe outlet was characterised as either occurring at: (1) the 'edge' where

145   the streambank was broadly linear, without perpendicular headward incisions or (2) the 'head' where

146   the streambank showed signs of headward retreat at the pipe outlet (Figure 2).

147   For each pipe outlet four main characteristics were recorded: 1) the pipe outlet dimensions, 2) the

148   distance from the roof of the pipe outlet to the top of the streambank, 3) the slope of the streambank

149   adjacent to the pipe outlet, and 4) the sloping length of the streambank. The latter was measured as

150   the distance along the slope of the streambank between the highest and the lowest point at the

151   streambank adjacent to the pipe outlet. Pipe outlet dimensions were defined by the vertical (H) and

152   horizontal (W) diameters, which were measured using a steel tape measure to the nearest 5 mm.

153   Macropores smaller than 5 mm were ignored following the method of Holden et al. (2012a). The

154   distance from pipe outlet roof to the top of the streambank was measured from the pipe roof to the

155   boundary between the visible peat surface of the gully edge and the vegetation line, and was recorded

156   to the nearest 5 mm. The slope of the streambank was measured by placing an inclinometer on its

157   surface, measuring in the perpendicular direction of the stream. To further determine the relative

158   position of each pipe outlet on the streambank, photographs were taken of each pipe outlet location

159   (Figure 2). Twelve pipe outlet surveys were carried out at UNG over a 22-month period between

160   December 2017 and September 2019. In order to sample different parts of the catchment, the survey

161   was conducted on different days during the year, which may have resulted in some inconsistencies in

162   the number of pipe outlets found in certain areas of the catchment due to daylight limitations,

163   flooding in streams, or adverse weather conditions.

164   2.3 Data processing

165   Table 1 describes the organization of the dataset used for analysis. Data preparation and processing

166   was performed in ESRI ArcGIS Software suite 10.6. High-resolution LiDAR data recorded at a ground

167   resolution of 0.5 m was used to produce a detailed digital terrain model (MFFP, 2014), which was used

168   to delineate hydrological functions and terrain characteristics, including slope, aspect, flow direction,

169   flow accumulation, stream raster, and the catchment boundary.

170   *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	Vector, polyline	Length of streambank
		Peat margin		
Pipe Outlet	GPS Location	Edge	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)
		Head		
	Shape	Circular	Vector, point feature	Count, vertical length (H), horizontal length (W), cross-sectional area
		Horizontally lenticular		
		Vertically lenticular		
	Surface cover	Bare	Vector, point feature	Count
		Non-bare ('Vegetated')		
	Aspect	Slope direction (Flat, N, NE, E, SE, S, SW, W, NW)	Vector, point feature	Count

171

172   To determine the actual depth of a pipe outlet at the gully bank, bank slope and the distance from the

173   pipe roof to the gully edge were converted into a parameter describing the depth to pipe roof relative

174   to the edge of the gully (Figure 3), which was derived as follows:

175
$$D_V = \sin\left(\frac{\alpha \cdot \pi}{180}\right) \cdot D_0 \qquad\qquad [2]$$

176   where α is the slope of the streambank in degrees, and D_0 represents the distance from pipe roof to

177   peat surface measured over the streambank. For pipe outlets on banks with a slope of 90°, D_0 was

178   used for D_V. To derive a value for streambank height, D_S, equation 2 was modified as followed:

179 $$D_S = \sin\left(\frac{\alpha \cdot \pi}{180}\right) \cdot SL \qquad [3]$$

180   where SL is the sloping length of the streambank in centimetres. To provide further insight about

181   where pipes issue onto streambanks, the relative position between the gully edge and gully floor was

182   determined for each pipe outlet by dividing D_V by D_S and subtracting this product from one. This

183   provided a value range between 0 and 1, where 0 represents the level of the bottom of the gully and

184   1 represents the level of the upper peat surface.

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

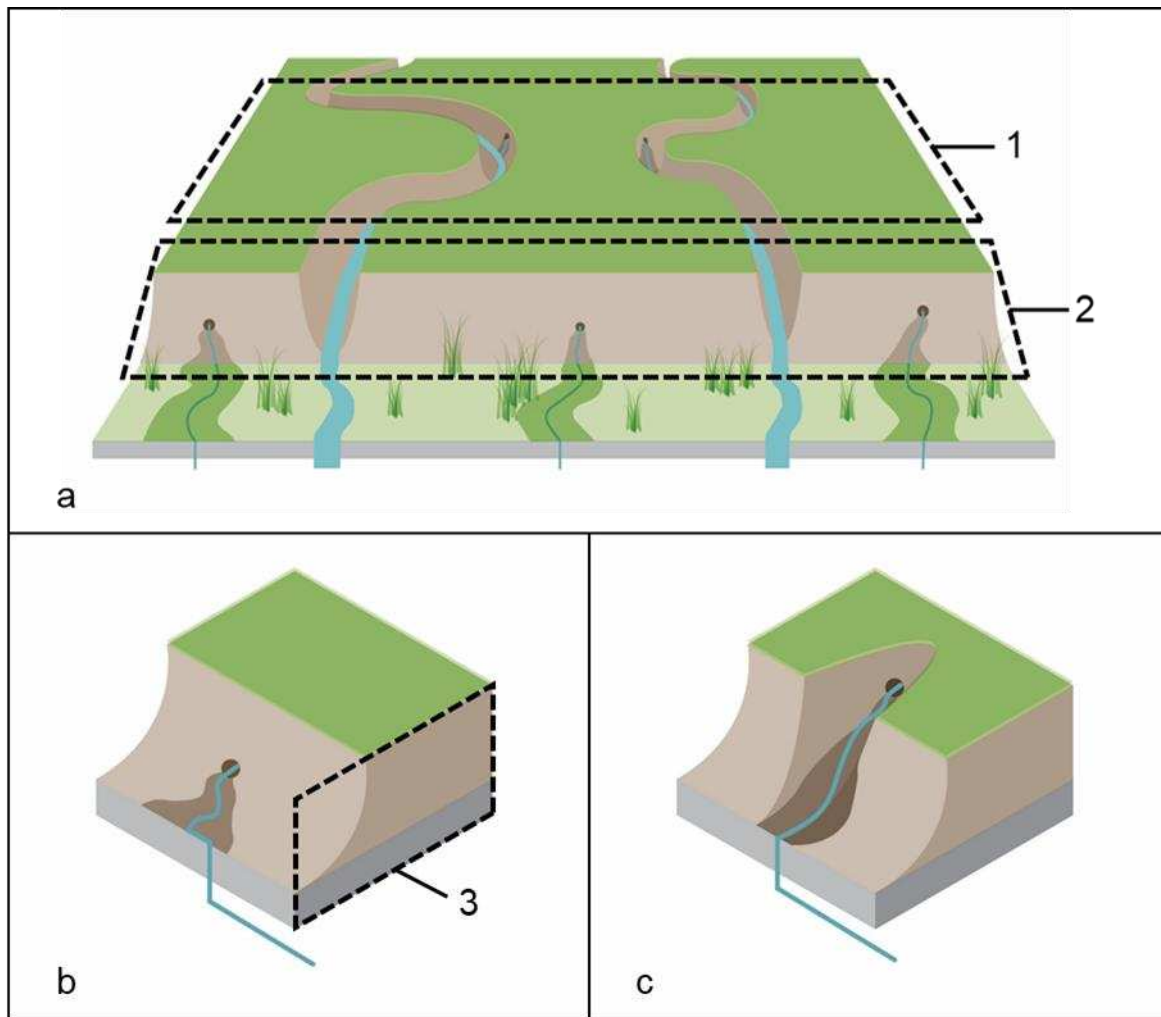186 $$cross\ sectional\ area\ =\ \pi \cdot H \cdot W \qquad [4]$$

187   where H is the vertical length of the pipe outlet (cm), and W is the horizontal length of the pipe outlet

188   (cm). The cross-sectional area of pipes along streambanks was calculated as the sum of the cross-

189   sectional area of all pipe outlets per surveyed streambank length. For each pipe outlet the topographic

190   upslope area that drained towards the pipe outlet was derived using the watershed tool in ArcGIS,

191   hereafter referred to as flow contribution area (FCA) measured in m^2. In this study, the cross-sections

192   of pipe outlets were divided into three shape types: horizontally-lenticular or vertically-lenticular if

193   one axis exceeded the other by more than 5 cm; and circular pipes if horizontal and vertical axes

194   differed by less than 5 cm. Surface cover was determined by identifying bare areas from pixel

195   classification of aerial photographs taken of UNG in June 2014 that were recorded at 8 cm pixel size

196   (MFFP, 2014). A colour signature representing the various colouring shades of bare peat surfaces in

197   the UNG catchment was used to produce a new raster at 10 cm cell size, detailing two feature classes:

198   bare peat surface (bare) and non-bare surface. Non-bare surfaces contained rock outcrop, water

199   bodies and vegetation. Projecting the layers of pipe outlet GPS location and cover information over

200   the aerial photographs, showed that most pipe outlets in non-bare areas actually occurred where

201   there was a vegetation cover, and hereafter non-bare surfaces will be referred to as 'vegetated'.

202   The length of surveyed streambanks in gullies was derived from the length of the stream raster in

203   ArcGIS. Since gullies had two streambanks on either side, the length of each gully was multiplied by

204   two to arrive at the total length of surveyed streambanks in gullies. Some of the observed pipe outlets

205   were located on the peat margin. The length of streambanks on the peat margin was extracted from

206   the length of polylines drawn upon the aerial photographs in ArcGIS. The latter streambanks were all

207   facing the main drainage stem of the catchment. The frequency of pipe outlets per total length of

208   streambank was calculated as follows:

209 $$pipe\ outlet\ frequency = n \cdot (2 \cdot Stream\ Raster + Polyline\ )^{-1} \qquad [5]$$

210   where n represents the total number of pipe outlets (dimensionless), stream raster and polyline are

211   in meters as the sum of the lengths for their respective streambank types. Pipe outlets were surveyed

212   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.
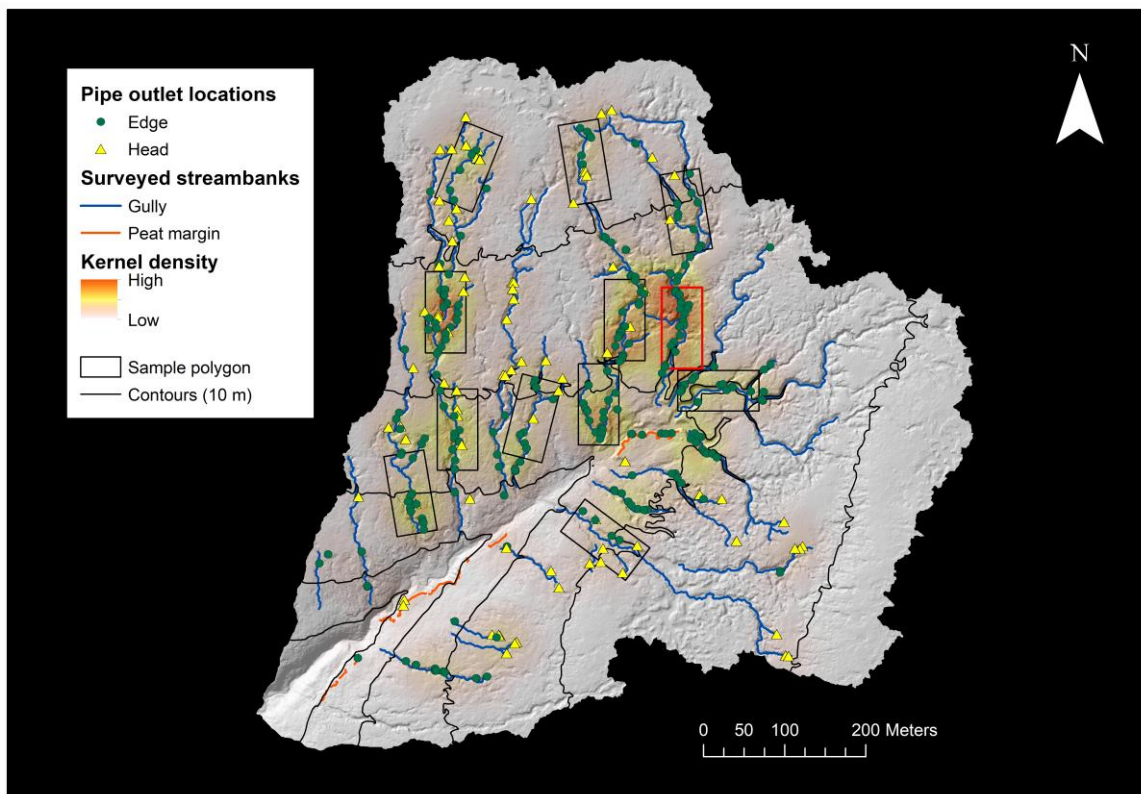
Normality tests were performed for all variables and showed non-normal distributions. Data transformation did not result in normal distributions and therefore non-parametric tests were

226   conducted using Mann-Whitney U tests, Spearman's Rank and Chi-squared in IBM SPSS Statistics

227   version 26.

228   3. Results

229   3.1 Frequency of piping

230   A total of 346 pipe outlets were identified, of which 336 pipe outlets occurred at streambanks in

231   gullies, while 10 pipe outlets occurred on the peat margin. A total of 88 pipe outlets were found at

232   head locations, and 258 pipe outlets were found at edge locations. The mean pipe outlet frequency

233   was 22.8 per km streambank. Sampling in areas with a high kernel density for pipe outlets resulted in

234   a maximum pipe outlet frequency of 91 per km streambank (Figure 3), located in the middle part of

235   the catchment in a wide and deeply eroded gully.
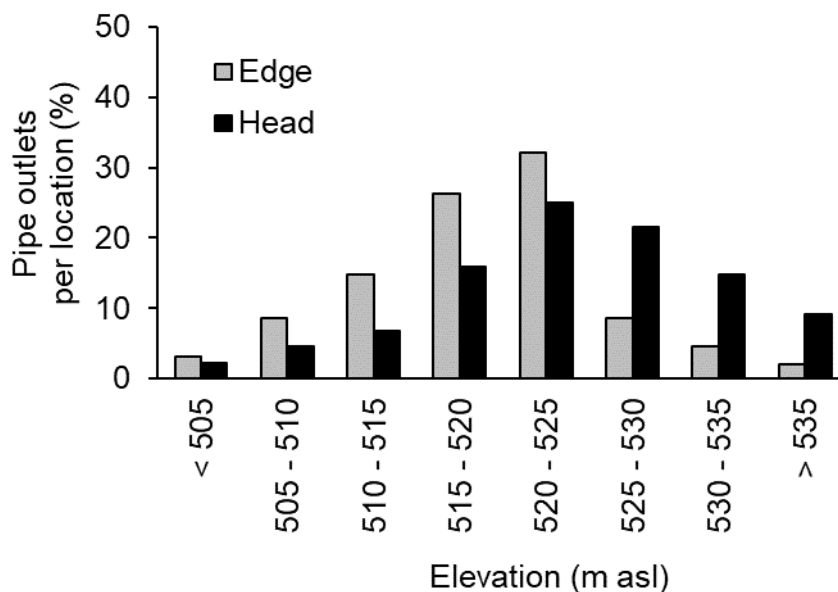

236

237   *Figure 3. Map showing surveyed streambanks with identified pipe outlets, superimposed on a hillshade map of the*

238   *catchment. A kernel density map was produced to indicate hotspots of pipe outlet frequency across the catchment, ranging*

239   *from low to high (indicative). Rectangular polygons indicate areas of interest to determine the maximum pipe outlet*

240 *frequency in the catchment. The polygon that is outlined in red indicates the location with the highest estimated pipe outlet*

241 *frequency. Contour lines run between 490 and 530 m, with 10 m interval. The highest point in the catchment is at 539.9 m*

242 *above mean sea level.*

243 3.2 Pipe outlet locations

244 More than half of the pipe outlets were identified at elevations between 515 m and 525 m (Figure 4),

245 which covers an area with wide and deep gullies (Figure 3). Edge and head locations were significantly

246 different across elevation (U = 15143.5, *p* < 0.001), with median elevation of 519.5 m (edge) and 523.6

247 m (head) respectively (Figure 4). The pipe outlets that were identified at streambanks on the peat

248 margin were mostly found at the interface of the organic layer and the mineral bedrock, whereas the

249 pipe outlets at streambanks in gullies were generally found in the peat profile (Figure 2 and 5).

250

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

252 Streambank slope was determined for 197 edge locations and 40 head locations. Slopes of

253 streambanks ranged from 3° to 87° with a median of 40°. Depth to pipe roof (D_V) ranged from 199 cm

254 to 0 cm, with a median of 44 cm. Pipe outlets on head locations were found significantly closer to the

255 surface (median D_V = 20 cm) compared to pipe outlets in gully edge areas (median D_V = 49 cm) (D_V

256 Mann-Whitney *U* = 1548, *p* < 0.001). Overall, depth to pipe roof had weak but significantly negative

257   relationships with vertical length (r_s(235) = -0.226, $p < 0.001$), horizontal length (r_s(235) = -0.174, $p =$

258   0.007), and cross-sectional area (r_s(235) = -0.217, $p = 0.001$).

259   The streambank height (D_S) was determined for 190 edge locations and 22 head locations. There was

260   no difference in streambank height between edge locations and head locations ($U= 1781.5$, $p = 0.257$)

261   but the relative position of pipe outlets was different across location ($U=3419$, $p < 0.001$), with a

262   median of 0.80 for edge locations compared to a median of 0.95 for head locations. A Spearman's

263   rank-order correlation showed that depth to pipe roof and streambank height had a positive

264   correlation at edge locations at $p < 0.001$ (r_s(188) = 0.350), whereas no significant correlation was

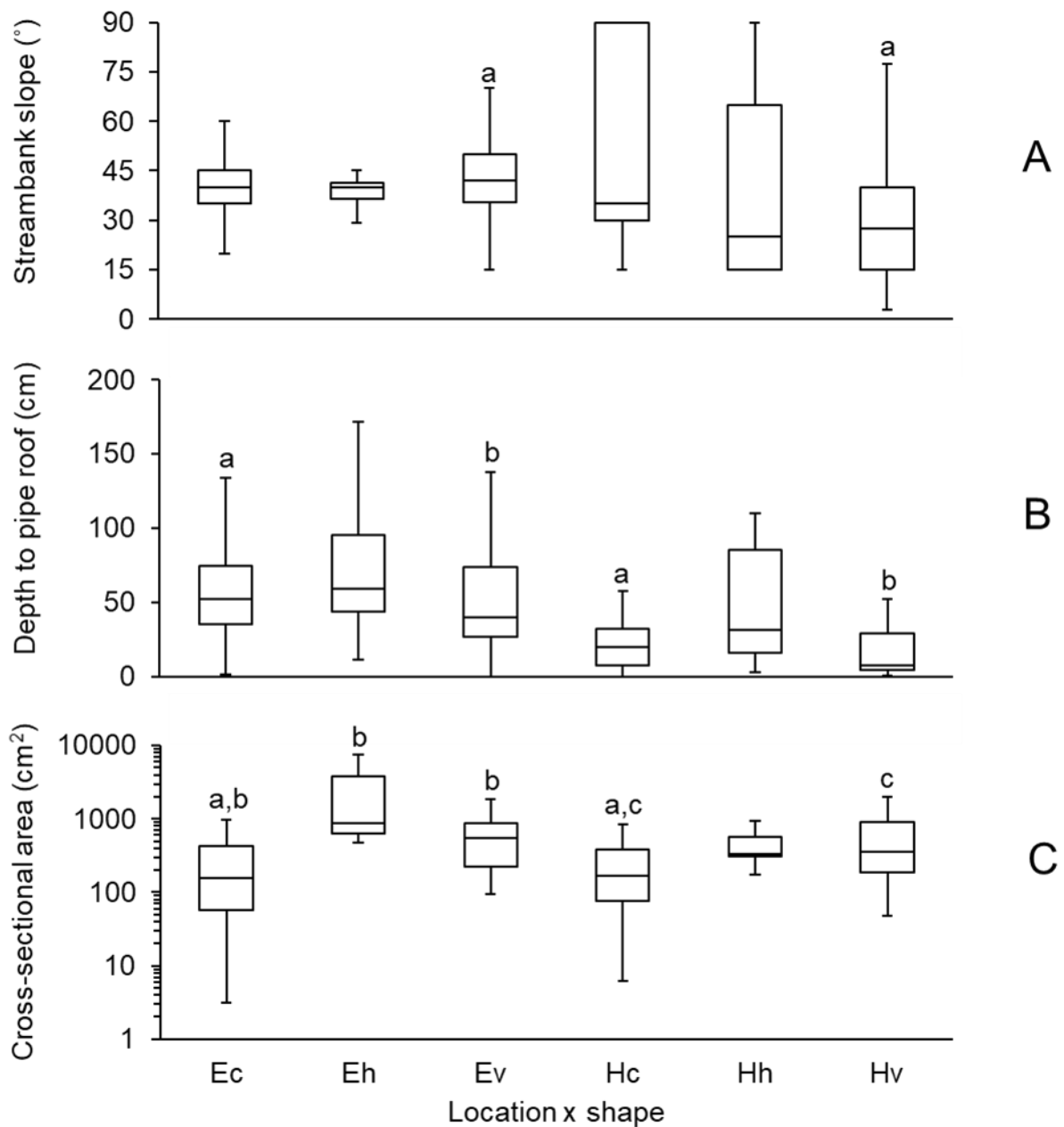265   found at head locations (r_s(20) = 0.307, $p = 0.165$) (Figure 5).

266

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

268

269   3.3 Pipe outlet shape and size

270   There were 227 circular pipe outlets (c) (185 edge, 42 head), 10 horizontally lenticular pipe outlets

271   (h)(5 at each location), 79 vertically lenticular pipe outlets (v)(52 edge, 27 head). Vertical length ranged

272   from 1 to 90 cm, with a median of 8 cm. The horizontal length ranged 1 to 60 cm and had a median of

273   5 cm. Cross-sectional area of pipe outlets ranged from 3 cm^2 to 7539 cm^2, with a median of 119 cm^2.

274   The total cross-sectional area of pipe outlets in the catchment was 110,477 cm^2, which translates to a

275   density of piping along streambanks of 0.73 m^2 km^{-1}. Figure 5 shows that pipe outlets at head locations

276   are particularly concentrated near the surface. Within head locations pipe outlets issuing at the head

277   of gullies occurred significantly closer to the surface compared to pipe outlets at head locations

278   elsewhere in the catchment, with medians of 5.1 cm and 22.9 cm respectively (Mann-Whitney U = 68,

279   *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 (cm²), 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.

287   Values for streambank slope and depth to pipe roof were determined for 175 circular pipe outlets

288   (154 edge, 21 head), 9 horizontally lenticular pipe outlets (4 edge, 5 head), and 53 vertically lenticular

289   pipe outlets (39 edge, 14 head). Figure 6a shows the distribution of streambank slope for pipe outlets

290   by location and shape type, with median values of streambank slope per shape type at edge locations

291   (Ec = 40 ˚, Eh = 40 ˚, and Ev = 42 ˚) and head locations (Hc = 35 ˚, Hh = 25 ˚, Hv = 27.5 ˚). Vertically

292   lenticular pipe outlets had significantly different distributions of streambank slope across categories

293   of location (U = 147.5, p = 0.011). Distributions of streambank slope for circular (U = 1532.5, p = 0.695)

294   and horizontally lenticular (U=8, p = 0.730) pipe outlets did not differ between locations. On edge

295   locations there was no difference in the distributions of streambank slope across shape types: Ec

296   versus Ev (U = 3494.5, p = 0.111), Ec versus Eh (U = 282.5, p = 0.775) and Eh versus Ev (U = 101, p =

297   0.361). At head locations the difference in streambank slope between Hc and Hv had a weak

298   significance at p < 0.1 (U = 97.5, p = 0.096), but streambank slopes did not differ between Hc and Hh

299   (U = 38, p = 0.374), and Hh and Hv (U = 29.5, p = 0.622) (Figure 6a).

300   Figure 6b shows the distribution of depth to pipe roof for pipe outlets by location and shape type, with

301   median values of depth to pipe roof per shape type at edge locations (Ec = 51.6 cm, Eh = 59.1 cm, and

302   Ev = 39.8 cm) and at head locations (Hc = 20.0 cm, Hh = 31.7 cm, Hv = 7.3 cm). The distribution of

303   depth to pipe roof of circular pipe outlets was significantly different across categories of location (U =

304   540.5, p < 0.001). The distribution of depth to pipe roof of vertically lenticular pipe outlets was

305   significantly different across categories of location (U = 108.5, p = 0.001) (Figure 6b). The distributions

306   of depth to pipe roof of horizontally lenticular pipe outlets did not differ across location (U = 8, p =

307   0.730) (Figure 6). At head locations there was no difference in the distributions of depth to pipe roof

308   across shape types: Hc versus Hv (U = 112.5, p = 0.249), Hc versus Hh (U = 67, p = 0.374) and Hh versus

309   Hv (U =20.5, p = 0.186) (Figure 6b). At edge locations the difference in depth to pipe roof between Ec

310   and Ev had a weak significance at p < 0.1 (U = 2408.5, p = 0.056). Depth to pipe roof did not differ

311   between Ec and Eh (U = 345.5, p = 0.678), and Eh and Ev (U = 60, p = 0.479) (Figure 6b).

312   The cross-sectional area of pipe outlets was determined for 227 circular pipe outlets (edge = 185,

313   head = 42), 10 horizontally lenticular pipe outlets (5 per location), and 79 vertically lenticular pipe

314   outlets (edge = 52, head = 27). The cross-sectional area of pipe outlets was significantly larger at head

315   locations with a median cross-sectional area of 292.2 cm^2 compared to pipe outlets at edge locations

316   which had a median cross-sectional area of 88.0 cm^2 (U = 12048.5, p < 0.001). Overall, circular pipe

317   outlets had significantly smaller cross-sectional areas with a median of 75.4 cm^2 compared to 351.9

318   cm^2 for vertically lenticular pipe outlets (U = 15028.5, p < 0.001) and 596.9 cm^2 for horizontally

319   lenticular pipe outlets (U = 2073, p < 0.001), whilst the latter two had similar distributions of cross-

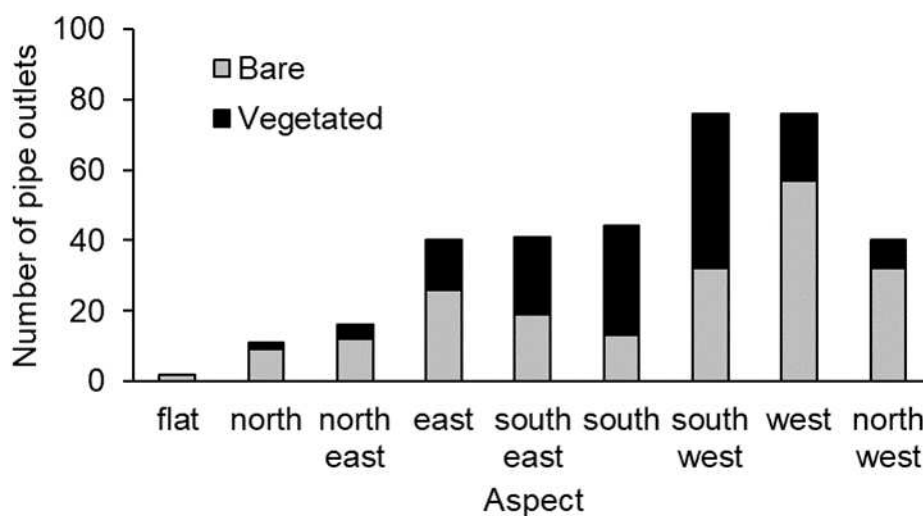320   sectional area (U = 258.5, p = 0.076).

321   Figure 6c shows the distribution of cross-sectional area of pipe outlets by location and shape type,

322   with median values per shape type at edge locations (Ec = 66.0 cm^2, Eh = 867.1 cm^2, and Ev = 340.9

323   cm^2) and head locations (Hc = 157.1 cm^2, Hh = 326.7 cm^2, Hv = 351.9 cm^2). The distribution of cross-

324   sectional area of circular pipe outlets was significantly different between categories of location (U =

325   5425, p < 0.001). No difference was found in distribution of cross-sectional area between locations for

326   horizontally lenticular (U = 5, p = 0.151) and vertically lenticular (U = 708, p = 0.951) pipe outlets. The

327   distribution of cross-sectional area of circular and vertically lenticular pipe outlets were significantly

328   different from each other at edge locations (U= 8395.5, p < 0.001) and at head locations (U=804.5, p

329   = 0.003). The distribution of cross-sectional area of circular and horizontally lenticular pipe outlets

330   were significantly different from each other at edge locations (U=895, p < 0.001), and at head

331   locations, but only at p < 0.1 (U=160, p = 0.058). The distribution of cross-sectional area of vertically

332   and horizontally lenticular pipe outlets was significantly different from each other at edge locations

333   (U=50.5, p = 0.021), but not at head locations (U=66, p = 0.960).

334   3.4 Relationship between pipe outlets and surface contributing area

335   The FCA was determined for 346 pipe outlet locations. The median FCA for pipe outlet locations was

336   1 m^2. There was no significant difference in FCA between head and edge locations (U = 10488, p =

337   0.283) and no significant relationship between the cross-sectional area of pipe outlets and FCA.

338   3.5 Relationship between pipe outlets and aspect

339   Aspect was determined for 346 pipe outlets. A *chi* square goodness of fit test showed that aspect was

340   a significant factor controlling the distribution of pipe outlets (χ^2(8) = 141.7, p < 0.001). For each of

341   eight aspect categories, 38.4 pipe outlets were expected, but the observed count was larger for

342   streambanks facing southwest (n = 76) and west (n = 76), which in total account for 43.9% of the pipe

343   outlets. The rest of the pipe outlets faced north (n = 11), northeast (n = 16), east (n = 40) and south

344   east (n = 41), south (n = 44), and northwest (n = 40). Two pipe outlets were found on flat surfaces

345   (Figure 7).

346

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

348   Post hoc pair wise *chi* square comparison showed that the number of pipe outlets was significantly

349   different for north versus south (χ^2(1)= 19.8, p < 0.001), north east versus south west (χ^2(1) = 39.1, p

350   < 0.001), and east versus west (χ^2(1) = 11.2, p = 0.001). The distribution of pipe outlets was assumed

351   to be the same between south east and north west facing streambanks (χ^2(1) = 0.012, p = 0.912).

352 *Table 2. Results of Mann-Whitney U independent sample tests on the distributions of depth to pipe roof (D_V) and cross-*

353 *sectional area across categories of location for classes of aspect. Fields marked with a dash indicate missing data in either*

354 *edge or head locations, hence comparisons were not performed.*

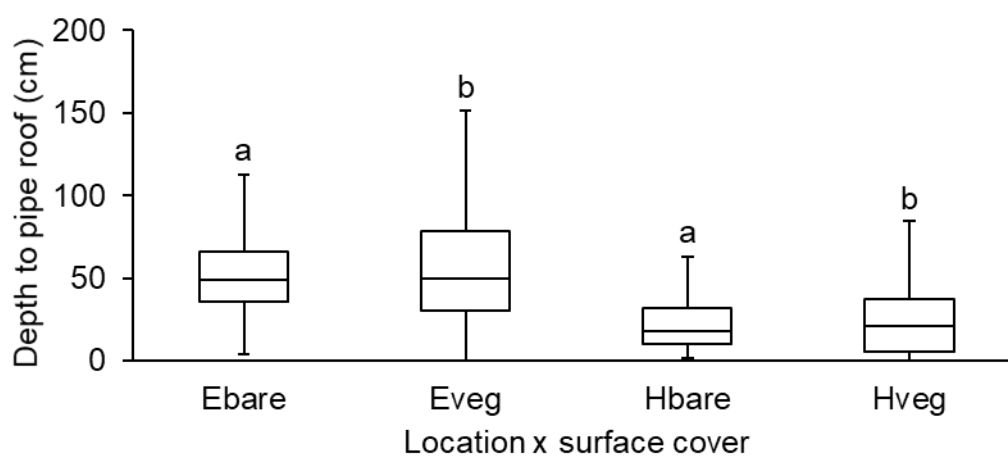|	Differences between edge and head locations					
	Depth to pipe roof (D_V)			**Cross-sectional area**		
aspect	MW-U	P - value	n	MW-U	P - value	n
flat	-			-		
north	-			-		
northeast	2.0	0.121	12	9.5	0.500	16
east	34.0	0.580	32	86.5	0.968	40
southeast	21.0	0.188	23	139.0	0.424	35
south	25.0	0.001	28	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

355

356 On streambanks with southerly, southwestly and westerly aspects, pipe outlets at edge locations were

357 found significantly deeper compared to pipe outlets at head locations with the same aspect, at *p* <

358 0.05 (Table 2). On streambanks facing south, southwest and west, the cross-sectional area of pipe

359 outlets at edge locations was significantly smaller compared to pipe outlets at head locations with the

360 same aspect, at *p* < 0.05 (Table 2).

361 3.6 Surface cover and pipe outlets

362 A total of 202 pipe outlets occurred where there was a bare surface (edge = 177, head = 25) with 144

363 pipe outlets where there was vegetation (edge = 81, head = 63). The distribution of depth to pipe roof

364   was the same across classes of surface cover in both edge locations (U = 3538.5, n = 197, p = 0.056)

365   and head locations (U = 126.5, n = 40, p = 0.159) (Figure 8).

366   On bare surfaces, the distribution of depth to pipe roof was significantly different across categories of

367   location (U = 433.0, n = 146, p = 0.003), with a median of 51.6 cm for edge locations and 22.9 cm for

368   head locations (Figure 8). On vegetated surfaces, the distribution of depth to pipe roof was

369   significantly different across categories of location (U = 330.5, n = 91, p < 0.001), with a median of 42.4

370   cm for edge locations and 10.0 cm for head locations (Figure 8).

371

372   *Figure 8. Box plots showing the distribution of depth to pipe roof (cm), grouped by location (E: edge; H: head) and surface*

373   *cover (bare; vegetated). The boxes show the interquartile range between Q1 and Q3, with the median indicated within the*

374   *boxes as a black horizontal line. The whiskers indicate the lowest and highest values that are still within the range: [Q1 - 1.5*

375   ** (Q3 - Q1)] and [Q3 + 1.5 * (Q3 - Q1)]. Different superscript letters indicate significant difference (p < 0.05) compared with*

376   *the other location and surface cover class combinations.*

377   The distribution of cross-sectional area across categories of surface cover type was assumed to be the

378   same in both edge locations (U = 7081.0, n = 248, p = 0.213) and head locations (U = 626, p = 0.523).

379   Cross-sectional area was significantly different across categories of location in both classes of surface

380   cover. In bare surface areas (U = 2374.5, n = 190, p = 0.030) edge pipes had a median cross-sectional

381   area of 88.0 cm^2 (edge) which was significantly smaller in size compared to pipe outlets in head

382   locations (219.9 cm^2). A similar pattern was observed for pipe outlets at vegetated surfaces (U =

383   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

384   locations.

385   A *Chi* square goodness of fit test indicated that the occurrence of pipe outlets was significantly

386   different across classes of aspect for areas with a bare surface (χ^2 (8) = 97.9, p < 0.001) and areas with

387   a vegetated surface (χ^2 (7) = 79.4, p < 0.001) (Figure 7). Bare surfaces that were facing west (n = 57)

388   had markedly more pipe outlets than bare surfaces at other aspects. Vegetated surfaces that were

389   facing south (n = 31) and southwest (n = 44) had markedly more pipe outlets than vegetated surfaces

390   at other aspects.

391   4. Discussion

392   4.1 Pipe outlet frequency

393   The pipe outlet frequency in UNG (22.8 km^{-1} streambank) was slightly larger in comparison to the

394   average pipe outlet frequency of 19.7 km^{-1} streambank across 160 blanket bog sites reported in

395   Holden (2005). Table 3 shows that UNG has a relatively high pipe outlet frequency when compared to

396   other blanket peat study catchments. One of the first surveys that looked specifically at the frequency

397   of pipes in streambanks was conducted on the streambanks of Burbage Brook in the Peak District

398   (podzol site) with 184 km^{-1} over 3 km of streambank in 1968 (Jones, 1975), and a resurvey in 2003

399   resulted in 134 km^{-1} over 500 m streambank (Jones and Cottrell, 2007). Other studies on piping

400   reported values from Welsh catchments of 36 km^{-1} and 56 km^{-1}, respectively, for Cerrig yr Wyn and

401   Nant Gerig (Gilman and Newson, 1980) and 80 km^{-1} for Afon Cerist (Jones, 1975). It should be noted

402   that pipe outlets found in UNG were not like those in the Welsh studies where pipes were commonly

403   disconnected from the stream and were found at breaks of slope on the hillside often coinciding with

404   changes in soil type. The Welsh pipe systems were also characterised by pipes found at the base of

405   the organic soil horizon. More recent examples in deep peat catchments in the north Pennines include

406   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}

407   (April 2010) at Cottage Hill Sike (Holden et al., 2012a). However, none of the above studies in Welsh

408   and North Pennine uplands mentioned the total length of their survey transects, nor the methods that

409   were used for calculating the pipe outlet frequency per length of streambank, and so a fair comparison

410   between studies is difficult to undertake.

411 *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		56		5	2200	472	10.3	9
(Gilman and Newson, 1980)							
Nant Gerrig, Cambria		36		10	2200	495	4.4	9
(Gilman and Newson, 1980)							
Burbage Brook, Peak District	humo-ferric	89	0.554	9	983.6[b]	150	2	10.2
(Jones, 1975)	podzols						

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

b: as presented in Jones and Cottrell (2007)

*: only observations included of survey in 2010

412

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

439 outlets predominantly on streambanks that face towards the sun and prevailing wind direction (west

440 southwest – (Clay and Evans, 2017)), and those pipe outlets occurred more at edge locations, which

441 sat deeper in the profile and were smaller than pipe outlets at head locations with the same aspect.

442 Moreover, edge locations in unvegetated (bare) areas hosted more and smaller pipe outlets than pipe

443 outlets on head locations in bare areas. Over the summer of 2018 prolonged drought caused peat to

444 crack open to depths of 40 cm at places across UNG. Cracks that were observed at south, southwest

445 and west-facing streambanks had not fully filled in by September 2019 as many of these cracks were

446 still visible. Desiccation-stress cracking can induce a form of piping called sapping (Parker and Jenne,

447 1967), which refers to the mass failure or slumping resulting from undercutting of an embankment by

448 seepage erosion (Fox and Wilson, 2010), followed by mass movement in the subsurface (subsidence)

449 (Baillie, 1975). This evidence supports the idea that the occurrence of soil piping at edge locations is

450 associated with the incidence of desiccation cracking as is observed on gully sides (Gilman and

451 Newson, 1980; Holden, 2006).

452 4.3 Size and shape of pipe outlets

453 Table 3 summarizes, for a number of selected studies, the cross-sectional area per length of

454 streambank. With 0.73 m^2 km^{-1} streambank UNG had a markedly greater surface occupied by pipe

455 outlets than the average of 0.556 m^2 km^{-1} observed across 160 UK blanket bog sites (Holden, 2005).

456 UNG ranks also higher than deep peat sites in the North Pennines, e.g. 0.026 m^2 km^{-1} at Little Dodgen

457 Pot Sike (Holden and Burt, 2002) and 0.35 m^2 km^{-1} at Cottage Sike Hill (Holden et al., 2012a), which

458 were both recorded in catchments that have naturally revegetated with slope-channel decoupling as

459 a result (Evans et al., 2006; Holden and Burt, 2002; Holden et al., 2012a). UNG is considered to be still

460 in an active eroding phase (Evans et al., 2006).

461 While pipe outlets in UNG were often found just downslope of surface depressions, most pipe outlets

462 on streambanks seem disconnected from upstream overland flow routes. The cross-sectional area of

463 pipe outlets was not related to topographic contribution area for each pipe outlet, corroborating

464   findings of other piping studies in blanket peatland that suggest surface topography is not a suitable

465   guide to pipe contributing area (e.g. Goulsbra (2010), Jones (2010), and Smart et al. (2013)).

466   Jones and Cottrell (2007) noted that vertically lenticular cross-sections suggest active downcutting,

467   whereas horizontally-lenticular outlets suggest that pipe floor erosion is being inhibited by a less

468   erodible soil horizon. We found only 3.2% of pipe outlets in UNG were horizontally-lenticular, which

469   were found throughout the depth profile, and 25% of pipe outlets were vertically-lenticular, which

470   were significantly closer to the surface than circular pipe outlets, suggesting that active downcutting

471   of pipe outlets is occurring. However, no evidence was found that horizontally and vertically lenticular

472   pipe outlets differ in cross-sectional area. The most common pipe outlet shape was circular (71.8%)

473   which tended to be significantly smaller than elongated pipe outlets, whereas Holden et al. (2012a)

474   found the opposite in the North Pennines. This suggests that pipe outlet shapes in UNG are distributed

475   differently compared to other peatland sites, but factors that cause this effect need further research.

476   4.4 Implications for peatland restoration

477   The survey presented here was carried out to assess the extent and occurrence of piping in UNG, to

478   provide evidence for peatland restoration practitioners who are interested in pipe blocking as an

479   erosion mitigation measure. We have shown that natural soil piping is a common phenomenon in

480   heavily degraded blanket peatland. While there are no tested guidelines for soil and water

481   conservation measures to target soil piping in peatland environments, some ideas have been put

482   forward in other environments (e.g. Frankl et al. (2016)) but have not yet been tested in the field. One

483   of the key challenges that our work has identified is that topography alone is a poor guide to likely

484   flow from pipe outlets as there was no relation between pipe size and upslope surface contributing

485   area, and the mean pipe contributing area was an unrealistic 1 m^2. Therefore, prioritising which pipe

486   outlets to target for blocking based on topographic maps will not be useful. In addition, it should be

487   noted that piping is found in most blanket peatlands (Holden, 2006). Therefore, the idea of blocking

488   all pipes in a catchment as part of restoration efforts may not be reasonable given that pipes are part

489   of a natural state. An alternative option for practitioners is the use of existing practices that may help

490   to prevent the initiation of new pipes on south and west facing edge locations. Such practices include

491   gully reprofiling and subsequent revegetation or protective covering of exposed peat (Parry et al.,

492   2014). Reprofiling of gullies aims to reduce the slope of gully sides, thereby eliminating factors that

493   promote sheet and rill erosion and potentially reducing strong hydraulic gradients that may encourage

494   pipe sapping. Revegetation of bare surfaces may lower overland flow velocities (Holden et al., 2008),

495   cool the peat surface (Brown et al., 2016) and help retain moisture in the peat reducing the risk of

496   desiccation. This revegetation and reprofiling may be particularly important on south to west facing

497   gully sides to reduce the risk of new pipe development.

498

499   5. Conclusions

500   This paper provided the first published survey of natural pipe outlets in a heavily eroded blanket

501   peatland. Pipes were common features of the landscape. The analysis showed that:

502   1) the location in the catchment is a strong control of the frequency, size, shape and depth of

503   pipes issuing onto streambanks, with significantly more pipes at edge locations than at head

504   locations,

505   2) topographic contribution area is not a suitable surrogate for actual pipe contributing area;

506   3) aspect of gully banks had a strong influence on pipe outlet frequency with 43% of the pipe

507   outlets observed on southwest and west facing streambanks, particularly in deeply eroded

508   gullies;

509   4) desiccation-cracking is identified as a possible control for pipe outlet frequency, which may

510   inform a different approach to piping in future peatland restoration plans.

511   Gully restoration in blanket peatlands is being applied on a large scale but the approach has not yet

512   included mitigation of pipe development as a key feature. Our results suggest that such an approach

513   warrants attention.

522   Data availability

523   Datasets related to this article can be found at https://doi.org/10.5518/839, hosted at the University

524   of Leeds data repository (Regensburg, 2020).

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