

Article (refereed) - postprint

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

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1 **Morphological change of natural pipe outlets in blanket peat**

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6

7 **Earth Surface Processes and Landforms**

8

9 **Abstract**

10 Peatlands are important carbon stores and many have natural pipes (tunnels) that transport
11 water and carbon. Pipes are often viewed as passive and slowly changing features of peatland
12 landscapes, particularly for sites that are relatively undisturbed by land management.
13 However, there is a lack of data on pipe morphology change over time. This paper presents
14 the first survey of natural pipe outlets in a peatland in which morphological changes in pipe
15 outlets through time were measured. Three surveys of natural pipe outlets between 2007-
16 2010 were conducted in a 17.4 hectare, relatively undisturbed, blanket-peat-covered
17 catchment in northern England. 27 of the 91 pipe outlets mapped in the first survey had
18 perennial discharge and these outlets were significantly larger and shallower than those from
19 ephemerally-flowing pipes. The cross-sectional area of 85 % of pipe outlets changed
20 (increased or decreased) during the study, with 20 % of pipe outlet areas changing by more
21 than 50 cm² (equivalent to a median 207 % change in area for this upper fifth of pipes) up to a
22 maximum of 312 cm² for one pipe outlet. During the study, 18 pipe outlets completely
23 infilled, while four new ones appeared. Mean pipe outlet area increased between August 2007

24 and July 2009 but decreased from July 2009 to April 2010. The largest changes in pipe
25 morphology occurred between July 2009 and April 2010, which spanned the coldest winter
26 for 31 years in the UK. During this period there was a significant increase in the proportion of
27 vertically-elongated pipes and a decrease in the proportion of circular pipes. Pipe outlet
28 morphology in blanket peat catchments is shown to be dynamic and may respond relatively
29 quickly to changes in flow or extreme events, linked to short-term changes in weather and
30 hence potentially to longer-term changes in climate or land management.

31

32 **Keywords**

33 Peatland, piping, macropores, tunnel erosion, carbon, geomorphology, sediment,

34 Environmental Change Network

35

36 **Introduction**

37 Peatlands contain over one third of the world's soil carbon pool (e.g. Gorham, 1991). It is

38 therefore important to understand the processes that transfer carbon within and from

39 peatlands. Recent carbon cycle research within peatlands has focussed on relationships

40 between water-table position, temperature, plants, microbes, carbon sequestration and

41 greenhouse gas release (Billett et al., 2006; Cole et al., 2002; Dinsmore et al., 2009; McNeil

42 and Waddington, 2003; Strack et al., 2008; Worrall et al., 2006). There is very little work

43 examining the role that water movement through peatlands plays in the retention and release

44 of carbon. However, where measurements have been undertaken, fluvial fluxes of carbon in

45 peatlands appear to account for losses of carbon equivalent to 30 to 40 % of net annual

46 carbon uptake by the peatland through gaseous exchange with the atmosphere (Dinsmore et

47 al., 2010; Nilsson et al., 2008; Roulet et al., 2007). Most aquatic carbon measurements in

48 peatland systems have focussed on dissolved organic carbon, yet the release of particulate
49 carbon may also be very important (Evans *et al.*, 2006; Pawson *et al.*, 2008), even in well-
50 vegetated peatlands (Evans and Warburton, 2007).

51

52 It is known that macropores play a significant role in transporting water in peatlands (Baird,
53 1997; Holden, 2009a; Holden, 2009b; Holden *et al.*, 2001). Natural soil pipes are large
54 macropores that typically consist of conduits, often many centimetres in diameter, via which
55 water, sediment, solutes and dissolved gases may move through the soil. Natural piping is
56 sometimes referred to as 'tunnel erosion' (Crouch *et al.*, 1986; Zhu, 1997; Zhu, 2003). The
57 pipes or tunnels can often be several hundred metres in length and typically form branching
58 networks. Natural soil pipes have been reported in a broad range of environments, but most
59 commonly in tropical forest soils (Baillie, 1975; Chappell and Sherlock, 2005; Sayer *et al.*,
60 2006), collapsible loess soils (Zhu, 2003), boreal forests (Roberge and Plamondon, 1987),
61 subarctic hillslopes (Carey and Woo, 2000), steep, temperate, humid hillslopes (Terajima *et al.*
62 *et al.*, 2000; Uchida *et al.*, 1999; Uchida *et al.*, 2005), dispersive semi-arid soils, where severe
63 gully erosion has often resulted from pipe development (Bryan and Jones, 1997; Crouch *et al.*
64 *et al.*, 1986; Gutierrez *et al.*, 1997), and the peatlands of Europe, New Zealand, Tasmania,
65 Indonesia, Canada and Siberia (e.g. Gunn, 2000; Holden, 2005; Holden and Burt, 2002;
66 Holden *et al.*, 2004; Jones, 1981; Jones *et al.*, 1997; Markov and Khoroshev, 1988; Norrstrom
67 and Jacks, 1996; Price, 1992; Rapson *et al.*, 2006; Thorp and Glanville, 2003). It is thought
68 that peatlands are conducive to piping because of the combined effect of a plentiful supply of
69 water, their capacity to retain water, and the sharp transitions in hydraulic conductivity that
70 occur both laterally and vertically within the peat profile (Holden and Burt, 2003a; Rosa and
71 Larocque, 2008). While pipe formation instigated by faunal burrows (e.g. small mammals,
72 earthworms, and crustaceans) is common in many environments (e.g. Onda and Itakura,

73 1997; Wilson and Smart, 1984), pipes have been reported in peatlands where the
74 environmental conditions are generally too harsh for such fauna to exist. Natural pipes in
75 peatlands have been most frequently reported in blanket peatlands (Holden, 2005; Jones,
76 1981; Jones et al., 1997; McCaig, 1983; Price, 1992). However, they have also been reported
77 in many other peatland types including low-gradient peatlands such as the James Bay
78 Lowlands of Canada (Glaser, 1998; Woo and DiCenzo, 1988), raised bogs (Ingram, 1983),
79 various peatlands in Germany (Dittrich, 1952; Egglesmann, 1960; Rudolf and Firbas, 1927)
80 and gully-head fens in New Zealand (Rapson et al., 2006).

81

82 Pipes appear to be important in the delivery of water to blanket peatland streams. Around 10
83 % of streamflow was found to move through pipe networks in Little Dodgen Pot Sike, a deep
84 blanket peat catchment of 0.44 km² in northern England (Holden and Burt, 2002), with
85 discharges over 4.6 L s⁻¹ from single pipes being reported. Similarly high discharges from
86 individual pipes have been reported in blanket peatland in Wales (Chapman, 1994), while
87 Jones and Crane (1984) found that 49 % of streamflow was produced by soil pipes in histic
88 podzols at a site in mid-Wales. The relative contribution of pipeflow varies with antecedent
89 conditions (Chapman, 1994; Holden and Burt, 2002; Jones, 1990), and flow within individual
90 pipes may be perennial (continuously-flowing) or ephemeral (intermittently-flowing)
91 depending on water sources (Holden and Burt, 2002).

92

93 Despite their important role as a pathway for water it is not known whether pipes are
94 relatively static features of blanket peat systems – changing slowly, if at all, over decades – or
95 whether their morphology and frequency varies continuously through time.. In some
96 environments pipe life cycles may be short such as in some semi-arid loess soils where pipe

97 outlets have been reported to open and close from one storm to the next (Zhu, 1997; Zhu,
98 2003). Jones and Cottrell (2007) reported data on pipe locations and sizes from a 250-m
99 stretch of streambank consisting of humo-ferric podzols. Here the time period between
100 surveys was 35 years and part of the catchment had been afforested during that time. They
101 found a marked reduction in the number and size of pipes on the forested bank, but no
102 significant change on the opposite moorland bank. While there is evidence for palaeo pipes in
103 peat profiles (Thorp and Glanville, 2003), it is not known how rapidly pipe systems change in
104 peatlands. Holden's (2005; 2006) use of ground-penetrating radar showed that the frequency
105 of large pipes (> 10 cm diameter) was greater on topslopes and footslopes in peatlands
106 compared to midslopes and also that piping was greater where artificial drainage of peatlands
107 had taken place. There was evidence that pipe density increased with the age of the drainage
108 scheme, suggesting that pipe networks could expand relatively quickly in peatlands.
109 However, these measurements were taken at different places rather than at the same site over
110 time. Many gullies in degraded peatlands are also thought to form when pipes collapse, and
111 pipes can often be found at the head of gullies (Holden and Burt, 2002). However, there have
112 been no direct observations of changes of pipe features at one peatland site.

113

114 The aim of the work reported in this paper was to examine changes in the morphology of pipe
115 outlets in a deep blanket peat catchment over a 33 month period; a period that included the
116 UK winter of 2009/10 which was the coldest for 31 years (Eden, 2010).. In particular, the
117 research reported herein sought to test whether or not blanket peat pipe outlets are stable (e.g.
118 continue to remain open, maintain their location, size and shape) through time or whether
119 they are dynamic features that undergo changes in size, shape, and frequency.

120

121 **Study Site**

122 The work was conducted at Cottage Hill Sike (54°41'N, 2°23'W), a small stream network
123 located within the Moor House National Nature Reserve in Cumbria, northern England. The
124 stream network has a catchment area of 17.4 ha and the catchment has an altitudinal range of
125 545 m to 580 m above mean sea level (Figure 1). Cottage Hill Sike is a tributary of Trout
126 Beck which, in turn, flows into the River Tees, 750 m downstream of the Cottage Hill Sike
127 confluence. Lower Carboniferous sequences of interbedded limestone, sandstone and shale
128 provide a base for glacial boulder clay at the site. This clay impedes drainage allowing
129 blanket peat to develop. 98 % of the catchment is covered in blanket peat (Adamson et al.,
130 1998; Miller et al., 2001) which is typically 3 to 4 m thick, although in places (e.g. at
131 54.694N, 2.390W, decimal degrees) a GPR survey carried out by the authors showed it
132 reaches 8 m in thickness. Slope angles within the catchment vary between 0 and 15°, with the
133 majority of the catchment (>80%) being between 0 and 5°. Catchment aspect is dominated by
134 east to southeast facing slopes.

135

136 The catchment contains a UK Environmental Change Network (ECN) target monitoring site
137 {Sykes, 1996 #674} where vegetation, water table, soil water chemistry and other parameters
138 have been monitored under strict protocols since 1992 (Sykes and Lane, 1996). Vegetation
139 cover is most commonly *Calluna vulgaris* (L.) Hull. and *Eriophorum vaginatum* L., with
140 some *Empetrum nigrum* L. and *Sphagnum capillifolium* (Ehrh.) Hedw.. The climate is
141 classified as sub-arctic oceanic (Manley, 1936; Manley, 1942). Holden and Rose (2011) have
142 produced a corrected and homogenised temperature record for the site dating back to 1931
143 and provide full details of the location and types of temperature recording equipment,
144 frequency of recording and changes and calibrations between instruments. The mean annual

145 temperature at the site between 1931 and 2006 was 5.3°C and was 5.8°C for 1991 to 2006
146 (5.1°C from 1961-1990). These means are based on averages of daily maximum and
147 minimum temperatures. Mean annual precipitation was 2012 mm (records from 1951-1980
148 and 1991-2006; first period of data based on daily manual readings, latter data based on
149 tipping bucket raingauge with hourly records). Precipitation is only slightly seasonal with 57
150 % occurring between October and March.

151

152 Mean monthly temperatures and precipitation totals between 1991 and 2006 are shown in
153 Figure 2 along with the mean monthly temperatures and monthly precipitation totals
154 experienced during the course of this study. Mean summer temperatures for 2007-2009 (10.8
155 °C) were similar to the 1991-2006 average (11.4 °C) but winter temperatures for 2008-9 and
156 2009-10 were colder than average (winter means of 0.1°C and -1.6 °C respectively, while the
157 1991-2006 average was 1.3 °C). The 2009-10 winter was particularly cold, with mean
158 monthly temperatures for January and February 2010 being 3.8 and 2.9 °C below the 1991-
159 2006 mean for those months. Therefore, there may have been enhanced frost action on the
160 peat during the 2009-10 winter. Summer rainfall was greater during 2007-09 (525, 562 and
161 548 mm) than the long-term summer average (312 mm), but winter totals were close to the
162 average except in November 2009 when 2.3 times the average November volume of
163 precipitation fell.

164

165 The stream flow regime of the blanket peatland across the Moor House Reserve is flashy with
166 rapid rising and falling limbs on hydrographs. Cottage Hill Sike (17.4 ha) displays a mean lag
167 time of 4.5 hours between peak rainfall and peak discharge (based on an analysis of 40
168 storms between April 2008 and May 2009) and an annual runoff coefficient of 86 %. Water

169 tables at the ECN target site (five automated dipwells) are within 5 cm of the surface for 83
170 % of the time and rarely fall below 20 cm depth (Evans et al., 1999). Overland flow and
171 shallow throughflow in the upper few centimetres of the peat dominate runoff response, and
172 there appears to be little deeper flow through the peat matrix (Holden and Burt, 2003b), with
173 low, but highly variable, hydraulic conductivities measured at depths greater than 5 cm
174 (Holden and Burt, 2003a). The mean pH for Cottage Hill Sike streamwater is 4.1 suggesting
175 that there is little groundwater sourced from below the peat (Adamson et al., 1998); Cottage
176 Hill Sike is a DOC-rich stream with an average (1993-2007) annual flux of $23.4 \text{ g C m}^{-2} \text{ y}^{-1}$
177 (Billett et al., 2010) , and highest fluxes observed during the wettest years (Clark et al., 2007).
178 Isotopic evidence and modelling suggest that all of the DOC in Cottage Hill Sike is derived
179 from near surface peat (Tipping et al., 2010).

180

181 **Methods**

182 Three pipe outlet surveys at Cottage Hill Sike were carried out over a 33-month period
183 starting in August 2007. Surveys were completed on 15th-16th August 2007, 21st July 2009
184 and 26th April 2010. The pipes were surveyed using identical methods on each occasion. The
185 surveyor walked along the various branches of the stream channel and identified pipe outlets
186 in the bank or head of the channel by eye. Pipe outlets found within the catchment but not
187 directly on a streambank were also included in the survey. Positions of all pipe outlets were
188 recorded using a hand-held GPS. To be sure that we revisited the same pipe outlets during
189 each survey, the pipe outlets were marked with labelled canes and also photographed to show
190 their relative position in the landscape. Observer familiarity with the pipes was also strong
191 because pipe outlets were revisited under different flow conditions to establish whether flows
192 were ephemeral or perennial (see below). Field notes were also taken to identify pipe position

193 within the landscape. Pipe outlet dimensions were measured along both the horizontal and
194 vertical axes on all occasions where possible; 5 mm was taken to be the minimum diameter of
195 a pipe following the method of Jones and Cottrell (2007). To allow comparison with the work
196 of Jones and Cottrell (2007), pipe cross sectional shapes were also classified as horizontally-
197 lenticular or vertically-lenticular if one axis exceeded the other by more than 10 mm (Figure
198 3). Circular pipes were classified as such if horizontal and vertical axes lengths were within
199 10 mm of each other. Pipe outlets were also characterised by their height to width ratios. As
200 noted by Jones and Cottrell (2007), vertically-elongated cross sections suggest active
201 downcutting, whereas horizontally-elongated outlets suggest that pipe floor erosion is being
202 inhibited by a less erodible soil horizon. We recognise these are process inferences from
203 morphological characteristics. Vertical cracks (Figure 3d) were defined as those pipe outlets
204 where both the top and base of the pipe outlet closed to a sharp point and an obvious crack
205 within the peat extended upwards from the outlet. Rectangular pipe outlets (Figure 3f) were
206 defined as those with a flat base and vertical sides. Triangular pipe outlets were classified as
207 those with a flat base but with sloping sides that came to a point (see Figure 3e). While pipe
208 outlet shape and size may not necessarily be a direct guide to the shape and size of the pipe
209 within the peat mass, Jones and Cottrell (2007) use pipe outlet shape to infer processes
210 operating within pipe systems. Here we recognise that both internal (e.g. flow regime) and
211 external (e.g. freeze-thaw activity on a stream bank) processes may affect pipe outlet
212 morphology, but in line with Jones and Cottrell (2007) and Jones (1981) we use changes in
213 pipe outlet shape and size as a guide to inform future process investigations and as evidence
214 of the dynamism of pipe outlet morphology. Pipe outlet depths (to the base of the pipe) from
215 the peat surface were measured on each occasion. On each survey occasion it was noted
216 whether the pipes were flowing or not. An additional 12 visits to each pipe outlet during
217 storms and dry periods between 2007 and 2010 were used to determine whether pipe

218 discharge was ephemeral or perennial. Pipe outlets were found at up to 2 metres depth on
219 peat faces (i.e. the maximum depth of visible stream banks). Piping probably occurred at
220 much deeper levels within the catchment but in this study only visible pipe outlets were
221 surveyed. Most of the peat within the catchment is between 3 and 4 m thick. Most streams
222 within the network flow over mineral substrate. Hence pipes that flow below peat-based
223 stream beds which did not have an observable outlet could not be considered in this study.

224

225 **Results**

226 The locations of pipe outlets mapped within the catchment are shown in Figure 1. Ninety-one
227 pipe outlets were identified in August 2007, 86 in July 2009 and 77 in April 2010. Figure 4
228 illustrates the distribution of cross-sectional areas for pipe outlets across the catchment on the
229 three survey dates. The largest pipe surveyed had a cross-sectional area of 1413 cm². The
230 tallest pipe was 60 cm while the widest pipe was 30 cm.

231

232 Table 1 presents summary data for the three survey dates. There was a 12.0 % increase in the
233 mean horizontal width of ephemeral-flowing pipe outlets between August 2007 and April
234 2010, and a 13.9 % increase in the mean vertical height of ephemeral-flowing pipe outlets.
235 This increase in the size of ephemeral-flowing pipe outlets was countered by a decrease in
236 the width and height of perennial-flowing pipe outlets during the same period (10.4% and
237 9.9 % respectively). The overall result was a very small mean change in pipe outlet area
238 averaged across all pipes (-2.8%) between August 2007 and April 2010. However, the
239 direction of change was not constant with time. Mean pipe outlet area for the whole
240 catchment increased by 4.2 % between August 2007 and July 2009 and then decreased
241 between July 2009 and April 2010. The largest increase for a single pipe outlet cross-

242 sectional area was 263 cm² between the first and last survey while the largest decrease for a
243 single pipe outlet was 312 cm² (Figure 5).

244

245 The total area of pipe outlets across the catchment declined through the study, and is related
246 to a decrease in the number of pipe outlets present (Table 1). Perennially-flowing pipe outlets
247 were significantly larger (Mann-Whitney U-test, $p < 0.01$) than ephemeral-flowing pipe
248 outlets for all survey dates (Table 2), with the mean area of perennially-flowing pipes being
249 around three times greater than that for ephemeral-flowing pipes. Hence, despite there
250 being less than half the number of perennially-flowing pipes than ephemeral-flowing pipes,
251 the total pipe outlet area for the catchment was dominated by perennially-flowing pipes. The
252 total cross-sectional area of pipe outlets for the catchment declined by 18 % between 2007
253 and 2010 (Table 1) with nine tenths of this decline occurring between 2009 and 2010.
254 Ephemeral-flowing pipe outlet floors were significantly deeper than the floors of
255 perennially-flowing pipe outlets, with $p < 0.001$ for all three surveys (mean depth over study
256 period was 100 cm for ephemeral pipe outlets compared to 56 cm for perennially-flowing
257 pipe outlets). There was no significant change in pipe floor outlet depths between survey
258 dates (Friedman's repeated measures test, $p = 0.717$).

259

260 Over the 33-month survey period only 13 pipes experienced no change in outlet cross-
261 sectional area; i.e., over 85 % of pipes changed their outlet area during that time (Table 3).
262 However, 37 pipe outlets remained stable between August 2007 and July 2009, while 22 pipe
263 outlets remained stable, with no changes in cross-sectional area between July 2009 and April
264 2010. Of the 13 pipes that remained geomorphologically stable at their outlets during the 33
265 months of the study, 10 were ephemeral.

266

267 Eighteen pipe outlets disappeared (infilled or collapsed) during the study. Eight pipe outlets
268 disappeared during 23 months between 2007 and 2009 and ten disappeared during the nine
269 months in 2009-2010. Four new pipe outlets also opened up during the study. One new pipe
270 outlet emerged between 2007 and 2009 (225 cm² area) but then closed up again by 2010.
271 Another pipe outlet present in 2007 (6 cm² area) had closed by 2009, but then re-opened by
272 2010.

273

274 There was a trend over the survey period for an increase in the vertical size of the pipe outlets
275 and a decrease in horizontal size (Table 3). Paired t-tests showed axis ratio changes were not
276 significant between August 2007 and July 2009, but were significant ($p < 0.05$) between July
277 2009 and April 2010. The changes resulted in an increase in the number and proportion of
278 pipe outlets that were vertically-lenticular (25 %, 31 % and 34 % for the three survey dates
279 respectively) and a decrease in the number and proportion of circular pipes (43 %, 34 % 17 %
280 for the three survey dates) (Figure 6). It is notable that only vertically-lenticular or circular
281 pipe outlets closed up during the study period. All new or re-appearing pipes were vertically-
282 lenticular or vertical cracks. The pipes with the largest outlet cross-sectional areas also tended
283 to be those that were more circular in shape.

284

285 Of the circular pipe outlets that were identified in April 2010, 80 % were ephemerally-
286 flowing compared to 67% and 69 % of the circular pipe outlets found on the earlier two
287 survey dates (Table 4). The majority of the perennially-flowing circular pipe outlets either
288 closed or became lenticular; there was an increase in the proportion of lenticular-shaped pipe
289 outlets that were perennially flowing in the April 2010 survey (Table 4). All vertical crack-

290 shaped pipe outlets were ephemerally-flowing, with floors deep within the peat (c. 150 cm).
291 For the other shapes of pipe outlets, approximately two thirds were ephemeral (Table 4). All
292 pipe outlets with a pipe height to width ratio greater than 2.5 (i.e. vertically-elongated) had
293 ephemeral discharge while seven of the eight largest pipe outlets surveyed had perennial
294 discharge (Figure 7).

295

296 **Discussion and conclusions**

297 A number of researchers have measured the density of piping as a frequency per length of
298 streambank, with values reported of 36 km⁻¹ and 56 km⁻¹ respectively for Cerrig yr Wyn and
299 Nant Gerig (Gilman and Newson, 1980), 14.5 km⁻¹ for Maesnant, (Jones and Crane, 1984)
300 and 80 km⁻¹ for Afon Cerist (Jones, 1975), all in the Welsh uplands, and 184 km⁻¹ for
301 Burbage Brook in the English Peak District which reduced to 134 km⁻¹ 35 years later after
302 afforestation and likely reduced runoff on one side of the catchment (Jones and Cottrell,
303 2007). None of the above studies were in deep peat. In terms of deep peat pipe densities, the
304 only report is from Little Dodgen Pot Sike in the English North Pennines where streambank
305 pipe density was 9.5 km⁻¹ (Holden and Burt, 2002). Our results indicate that the streambank
306 pipe frequency at Cottage Hill Sike ranged from 36.6 km⁻¹ (August 2007) to 31.7 km⁻¹ (April
307 2010). Because pipe flows accounted for around 10 % of the stream discharge in Little
308 Dodgen Pot Sike (Holden and Burt, 2002) it is likely that pipes are an even more important
309 hydrological and carbon flux contributor in the deep peat of Cottage Hill Sike given its
310 greater density of streambank pipe outlets. Holden (2005a) reported densities of pipes across
311 789 plots (rather than on streambanks) located on 160 UK blanket peatlands based on
312 ground-penetrating radar surveys and showed that, for peat that was not artificially-drained,
313 the mean density was 56.6 km⁻¹ for transects across peat.

314

315 The fact that 18 pipe outlets closed during the study is important because it is a strong
316 indicator that natural pipes in blanket peat are more morphologically dynamic than previously
317 thought. Holden and Burt (2002) reported one pipe that they had begun to monitor for
318 discharge in Little Dodgen Pot Sike which stopped flowing during their study and never re-
319 opened. However, data from Cottage Hill Sike provides the first complete survey of medium-
320 term change in pipe outlet morphologies across a deep peat catchment, with the suggestion
321 that change is typical rather than unusual. In this way peatland pipe systems may have
322 similarities with dynamic pipe systems reported in other environments, such as gullied semi
323 arid environments, where pipes are considered to be geomorphologically dynamic (Bryan and
324 Yair, 1982). The opening and closing of pipes is also analogous to both karst cave systems
325 and englacial or subglacial tunnels which have been reported to become periodically choked
326 with sediment while other routes can eventually open up through phreatic forces, weathering
327 and erosion (e.g. Menzies and Shilts, 2002; Moldovan et al., 2011).

328

329 The morphology of pipe outlets at Cottage Hill Sike changed for more than 85 % of pipes
330 during the course of the study. The changes in pipe outlet morphology were greatest between
331 July 2009 and April 2010 compared to between August 2007 and July 2009. Indeed, the
332 morphology of 41 % of pipe outlets remained unchanged between August 2007 and July
333 2009. Furthermore, complete pipe outlet closure occurred at three times the rate between July
334 2009 and April 2010 than between the 2007 and 2009 sample dates.

335

336 The winter of 2009/10 was the coldest since 1978/9 (Eden, 2010).. During freezing
337 conditions, needle ice formation within peat can force soil to be thrust upwards on exposed

338 peat surfaces (Evans and Warburton, 2007; Tallis, 1985). Upon thawing mobile peat can be
339 available for transport. It may be that the weather experienced during the winter of 2009/10
340 created conditions conducive to the production of large amounts of friable peat. This
341 sediment may have been loosened not only on the peat surface but on pipe walls near the peat
342 surface (freezing conditions penetrated to at least 10 cm soil depth according to soil probes at
343 the ECN monitoring site within the catchment and air temperatures fell as low as -18°C). This
344 may have resulted in a larger amount of sediment than normal becoming available for
345 transport along pipe networks, potentially altering their internal morphology and flow
346 conditions (e.g. choking some parts of pipe networks). Alternatively, at exposed pipe outlets
347 on stream banks the build up of ice and loosening of peat may have modified the morphology
348 of the pipe outlet directly or have modified the outlet indirectly by causing peat to slump
349 down an exposed bank above the outlet which then blocked the pipe. However, it would be
350 surprising if the water pressure in the pipe next time it filled was insufficient to reopen the
351 pipe outlet.

352

353 The outlets of ephemeral-flowing pipes were significantly deeper than perennially-flowing
354 pipes and there were no significant changes to pipe depth during the study. While most of the
355 largest pipe outlets in the catchment were perennially flowing as one would expect, during
356 the course of the study the ephemeral pipe outlets increased in size (and ephemeral-flowing
357 pipes represented around 70 % of pipes in the catchment) while perennial pipe outlets
358 decreased in size. We recorded no cases where ephemeral-flowing pipe outlets became
359 perennially-flowing pipe outlets. The location of perennially-flowing pipe outlets nearer the
360 peat surface suggests that they are fed by shallow throughflow from the near-surface layer
361 that is unable to percolate into much less permeable and saturated deeper parts of the peat.
362 Deeper ephemeral-flowing pipe outlets may be explained in terms of seepage rates into the

363 pipes from the surrounding peat matrix being so slow during ‘normal’ conditions that
364 insufficient water is released into the pipes to generate flow. However, the pipes may have
365 macropore connections that allow water to pass directly to those pipes from the surface or
366 from overflows from perennial pipes during rainfall events.

367

368 There were significantly more vertically-lenticular pipe outlets and significantly fewer
369 circular pipe outlets between July 2009 and April 2010. This is indicative of enhanced active
370 pipe erosion during this period. November 2009 was unusually wet (517 mm of precipitation
371 compared to the 1991-2006 November mean of 225 mm) and it may be the case that pipe
372 morphological change observed at the site was driven by substantial flows during this short
373 period of time. Indeed, 104 mm of rainfall occurred between 18 and 20 November. This
374 heavy rainfall led to flooding in other parts of the region during this time (e.g. Sibley, 2010).
375 However, why this would increase the size of ephemeral pipe outlets and yet cause a decrease
376 in the size of perennial pipe outlets is unclear. It may be that ephemeral pipes were more
377 actively forming and eroding whereas larger perennial pipes were more susceptible to
378 infilling given their larger size and greater sediment availability within the pipe network.

379

380 Summer drying may also cause changes in peat around pipe outlets through shrinkage and
381 consolidation of exposed peat on stream banks. However, summer conditions would be more
382 likely to cause shrinkage of ephemerally-flowing pipe outlets than perennially-flowing ones
383 as water flowing from the latter would keep the surrounding peat wet on the streambank.
384 Nevertheless, more frequent sampling of pipe morphology through time is required to help
385 fully understand the drivers of change.

386

387 It is recognised that this study has only examined pipe outlets and that pipe networks within
388 the main body of the peat will be more complicated, branching and undulating than their
389 outlets portray (Holden, 2004). More comprehensive studies of pipe morphological change
390 within peatlands through geophysical survey may help address our lack of knowledge about
391 pipe morphology within peat as would longer-term monitoring. Our results do have several
392 implications for the study of peatland geomorphology. For example, they suggest that
393 peatland pipes may infill or open up over relatively short periods of time. This increases the
394 possibility that peat sampling with depth for physical (e.g. bulk density or hydraulic
395 conductivity), chemical (e.g. pH, radiocarbon isotopes) or biological features (e.g. pollen or
396 macrofossils) may inadvertently cut through the former route of an infilled pipe (Thorp and
397 Glanville, 2003) and data may then be misinterpreted when upscaled across the whole
398 peatland unless sampling is well replicated.

399

400 Data from Plynlimon, Wales, suggested that areas of peaty catchments which seemed to
401 contain more pipes also yielded more sediment to the stream network (Jones, 2004). Since
402 particulate peat in streams tends to contain around 50 % carbon then the dynamism and non-
403 linearity of pipe systems (e.g. opening and closing of pipe outlets) needs to be investigated
404 further if we are to understand carbon dynamics in these systems. Subsurface routes for
405 particulate carbon release have rarely been considered in peatlands and there are no complete,
406 direct measurements that enable the role of pipes in aquatic carbon production within deep
407 peatlands to be established. At Cottage Hill Sike our initial studies suggest that pipes release
408 much of their sediment in short episodic pulses which are not linearly related to discharge
409 (Holden *et al.*, 2009). It appears that subsurface particulate carbon transport systems are
410 active, dynamic and may switch on and off. In addition, a related study (Dinsmore *et al.*, in
411 press) has demonstrated the importance of the pipe system as a pathway for greenhouse gas

412 transport from the peat to the stream system in the Cottage Hill Sike catchment. Our
413 geomorphological survey suggests that peat pipe systems may be particularly responsive to
414 extreme weather conditions (e.g. large flows, severe frost). Dynamic change in pipe
415 morphology is also likely to have a significant effect on medium-term hydrological response,
416 because pipe constriction or a decrease in pipe density slows down water movement within
417 the peatland. However, further process-based assessment is now needed to establish more
418 thoroughly the controls on pipe morphology and the role of pipes in transporting sediment
419 and carbon in peatland systems.

420

421 **Acknowledgements**

422 The research was funded by UK Natural Environment Research Council (NERC) grant
423 NE/E003168/1. Cottage Hill Sike is a NERC Centre for Ecology and Hydrology Carbon
424 Catchment and is part of the Moor House Environmental Change Network site. We are
425 grateful to ECN for background data from the catchment and to Natural England for granting
426 access.

Table 1. Comparison of ephemeral and perennial pipe outlet morphology for 2007, 2009 and 2010.

Survey and pipe flow condition	Number of pipes	Mean diameter of pipes (horizontal) (cm)	Mean diameter of pipes (vertical) (cm)	Mean area of pipes (cm ²)	Total area of pipe outlets (cm ²)	Density of piping along stream banks (m ² km ⁻¹)	Pipe frequency per km of stream bank
2007 (E)	63	6.16	8.21	60.30	3499.10	0.144	25.93
2009 (E)	57	6.33	9.30	67.60	3583.70	0.147	23.46
2010 (E)	50	6.90	9.35	73.00	3357.60	0.138	20.58
2007 (P)	27	13.65	15.73	233.90	5612.90	0.231	11.11
2009 (P)	28	13.04	16.13	222.40	5337.80	0.220	11.52
2010 (P)	26	12.23	14.18	180.30	3967.70	0.163	10.70
2007 (total)*	91	8.32	10.36	110.10	9140.28	0.376	36.63
2009 (total)*	86	8.39	11.36	114.70	8949.79	0.368	34.57
2010 (total)*	77	8.64	10.94	107.00	7491.83	0.308	31.69

*For one pipe the flow regime (E or P) could not be clearly determined and hence the sum of E and P for a survey is less than the total number of pipes observed.

Table 2. Comparison of mean pipe outlet horizontal and vertical diameters and pipe outlet areas over time. Significance was tested using Mann-Whitney U tests.

	Mean horizontal diameter (cm)	Mean vertical diameter (cm)	Mean area (cm²)
2007 ephemeral	6.16	8.21	60.30
2007 perennial	13.65	15.73	233.90
<i>p</i>	<0.001	0.001	<0.001
2009 ephemeral	6.33	9.30	6760
2009 perennial	13.04	16.13	222.40
<i>p</i>	<0.001	0.006	<0.001
2010 ephemeral	6.90	9.35	7300
2010 perennial	12.23	14.18	180.30
<i>p</i>	0.003	0.032	0.008

Table 3. The number of changes over time in pipe outlet horizontal and vertical diameter and pipe outlet area.

	Number of pipes								
	Horizontal diameter			Vertical diameter			Area		
	no change	increase	decrease	no change	increase	decrease	no change	increase	decrease
2007 - 2010	23	22	21	17	31	18	13	30	23
2007 - 2009	42	17	14	39	21	13	38	22	18
2009 - 2010	29	20	18	30	21	17	22	26	20

Table 4. Mean depth of pipe floors by shape and survey date and per cent of pipe outlet shapes that were ephemerally- or perennially-flowing for the four most common pipe outlet shapes.

Pipe shape category	August 2007	July 2009	April 2010
<u>Circular</u> Mean floor depth, cm % of pipes ephemeral % of pipes perennial	83.9 69 31	82.5 67 33	92.5 80 20
<u>Vertically-lenticular</u> mean floor depth, cm % of pipes ephemeral % of pipes perennial	93.7 69 31	81.5 64 36	90.5 60 40
<u>Horizontally-lenticular</u> mean floor depth, cm % of pipes ephemeral % of pipes perennial	83.9 67 33	120.0 67 33	66.7 58 42
<u>Vertical crack</u> mean floor depth, cm % of pipes ephemeral % of pipes perennial	152.0 100 0	131.7 100 0	141.4 100 0

Figure captions

Figure 1. Location of the study site and pipe outlets within Cottage Hill Sike.

Figure 2. Mean (a) temperature and (b) precipitation by months for 1991-2006 at Cottage Hill Sike and monthly mean temperature and rainfall totals during the study period for January 2007 to April 2010. Data from the Moor House meteorological station, 54.690N, 2.375W (decimal degrees) managed by the Environmental Change Network.

Figure 3. Photographs showing different shapes of pipe outlet morphology (a) vertically-lenticular (b) horizontally-lenticular peat pipe (c) circular (d) vertical crack (e) triangular (f) rectangular.

Figure 4. Frequency distribution for pipe outlet cross-sectional area on each survey date.

Figure 5. Distribution of change in cross-sectional area of surveyed pipe outlets between each of the three surveys.

Figure 6. Proportion of different pipe outlet shapes identified during each survey.

Figure 7. Pipe outlet cross-sectional area against the height to width ratio of pipe outlets.

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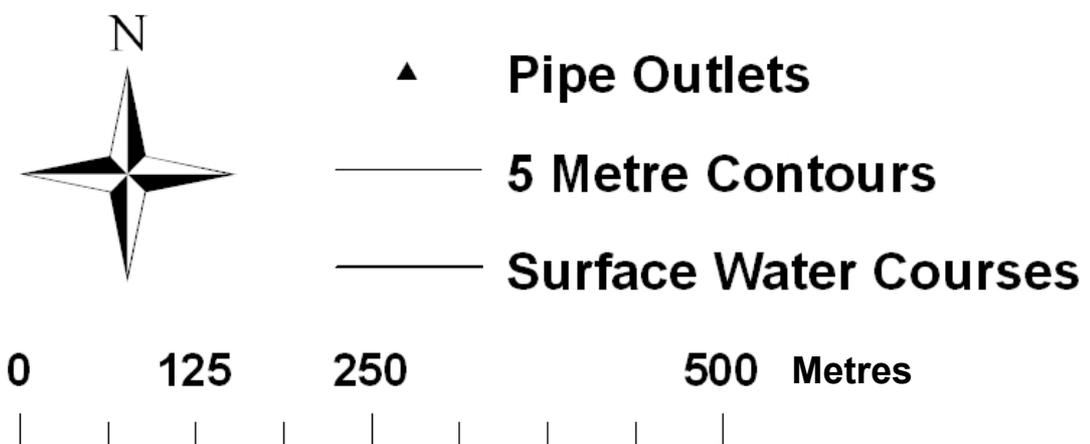
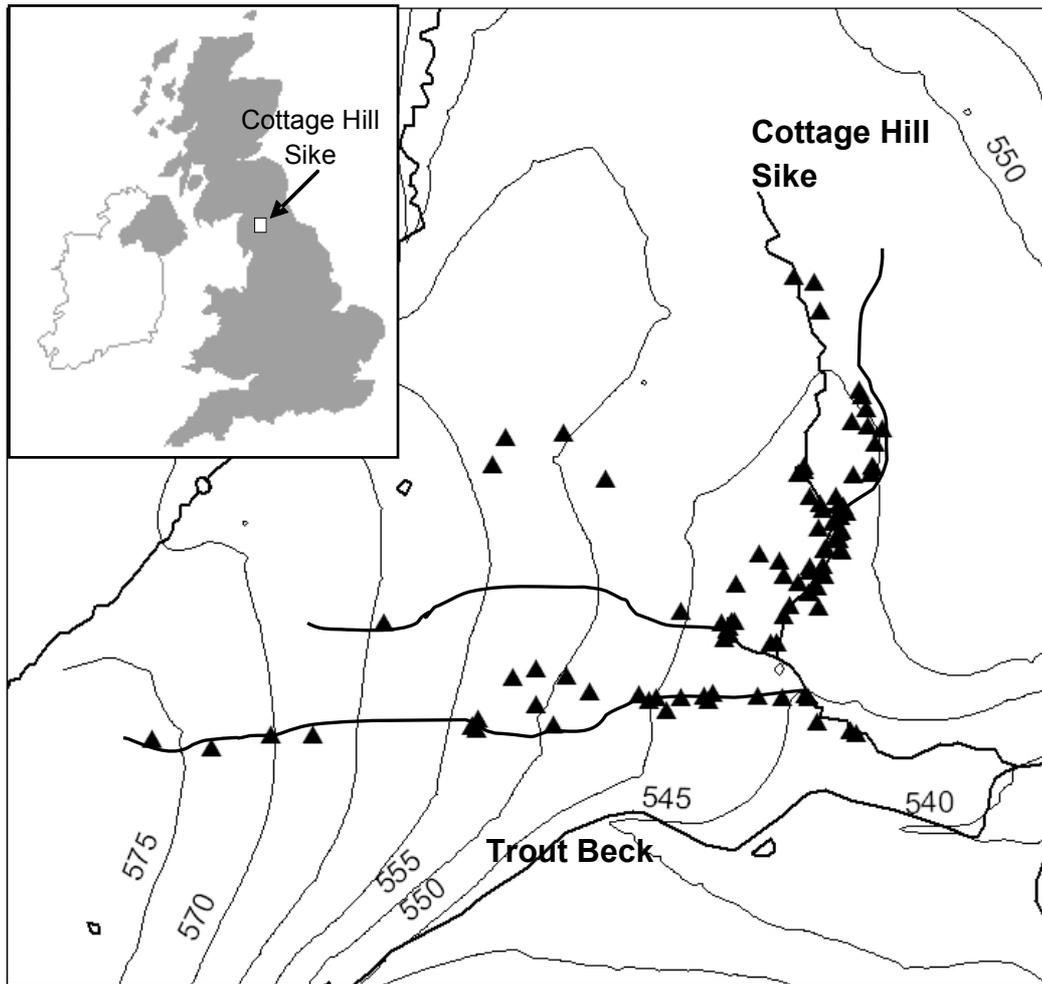
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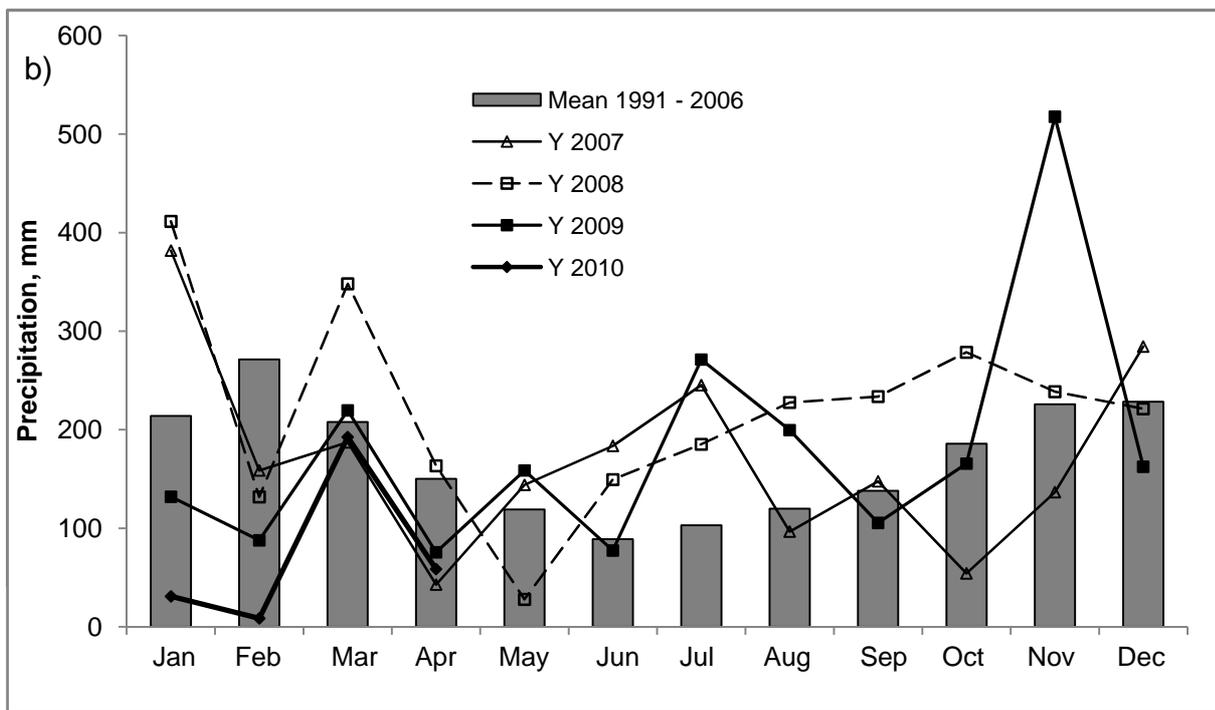
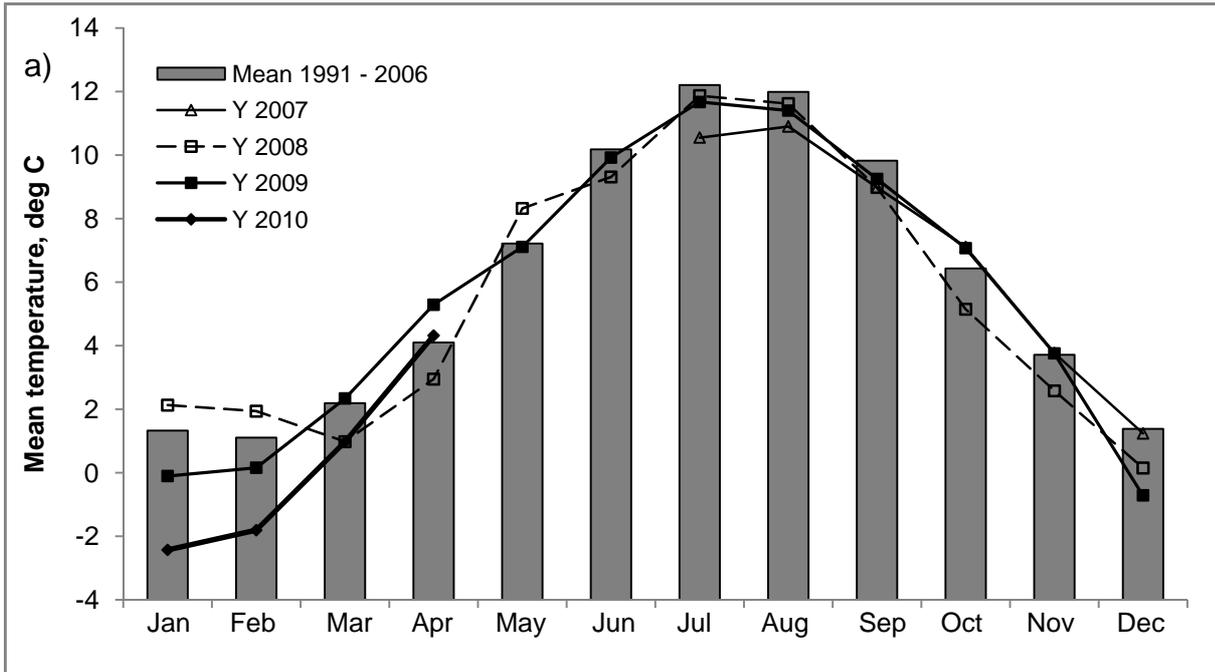
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a)



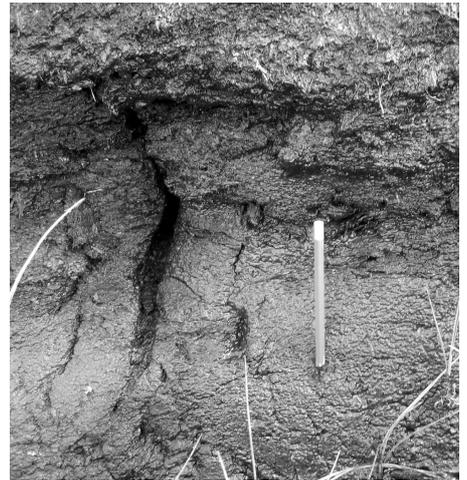
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c)



d)

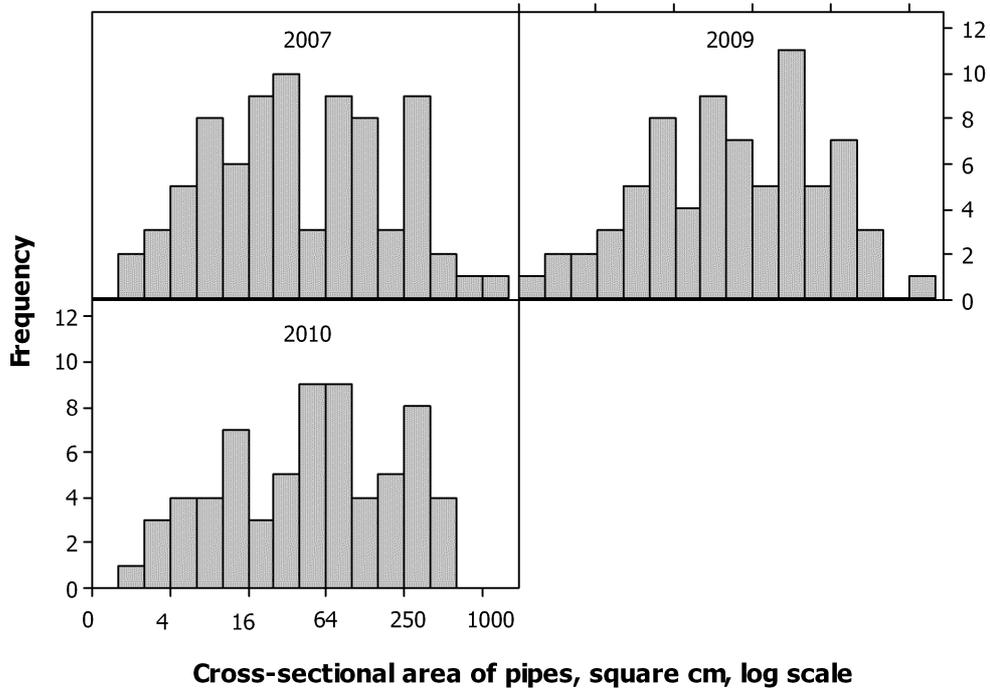


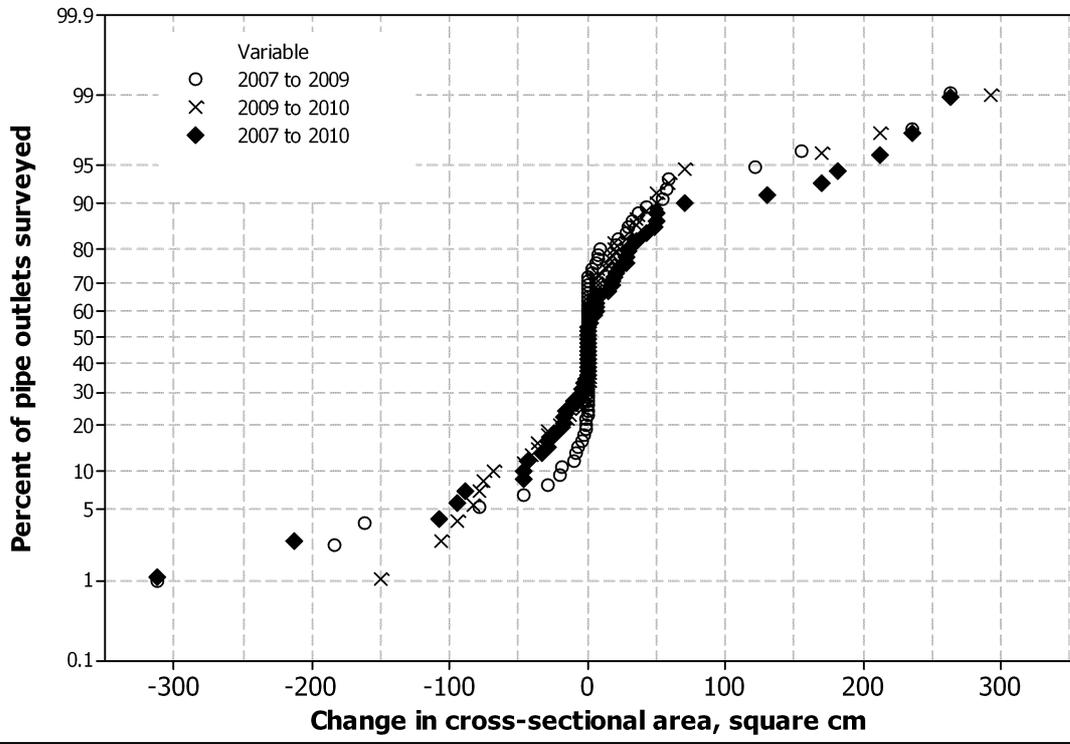
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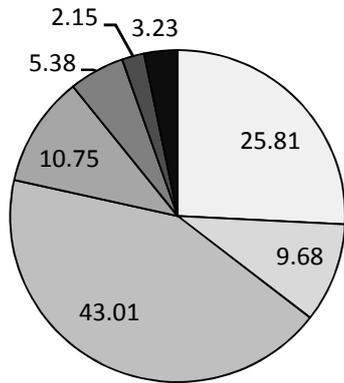
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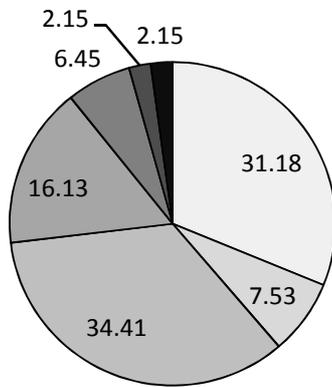




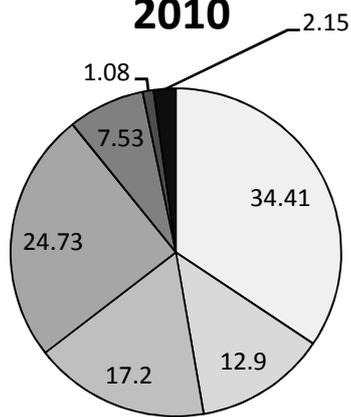
2007



2009



2010



- vertical lenticular
- horizontal lenticular
- circular
- unknown/disappeared
- vertical crack
- triangular
- rectangular

