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Morphological change of natural pipe outlets in blanket peat

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Abstract

Peatlands are important carbon stores and many have natural pipes (tunnels) that transport water and carbon. Pipes are often viewed as passive and slowly changing features of peatland landscapes, particularly for sites that are relatively undisturbed by land management. However, there is a lack of data on pipe morphology change over time. This paper presents the first survey of natural pipe outlets in a peatland in which morphological changes in pipe outlets through time were measured. Three surveys of natural pipe outlets between 2007-2010 were conducted in a 17.4 hectare, relatively undisturbed, blanket-peat-covered catchment in northern England. 27 of the 91 pipe outlets mapped in the first survey had perennial discharge and these outlets were significantly larger and shallower than those from ephemerally-flowing pipes. The cross-sectional area of 85 % of pipe outlets changed (increased or decreased) during the study, with 20 % of pipe outlet areas changing by more than 50 cm^2 (equivalent to a median 207 % change in area for this upper fifth of pipes) up to a maximum of 312 cm^2 for one pipe outlet. During the study, 18 pipe outlets completely infilled, while four new ones appeared. Mean pipe outlet area increased between August 2007 and July 2009 but decreased from July 2009 to April 2010. The largest changes in pipe morphology occurred between July 2009 and April 2010, which spanned the coldest winter for 31 years in the UK. During this period there was a significant increase in the proportion of vertically-elongated pipes and a decrease in the proportion of circular pipes. Pipe outlet morphology in blanket peat catchments is shown to be dynamic and may respond relatively quickly to changes in flow or extreme events, linked to short-term changes in weather and hence potentially to longer-term changes in climate or land management.

Keywords

Peatland, piping, macropores, tunnel erosion, carbon, geomorphology, sediment, Environmental Change Network

Introduction

Peatlands contain over one third of the world's soil carbon pool (e.g. Gorham, 1991). It is therefore important to understand the processes that transfer carbon within and from peatlands. Recent carbon cycle research within peatlands has focussed on relationships between water-table position, temperature, plants, microbes, carbon sequestration and greenhouse gas release (Billett et al., 2006; Cole et al., 2002; Dinsmore et al., 2009; McNeil and Waddington, 2003; Strack et al., 2008; Worrall et al., 2006). There is very little work examining the role that water movement through peatlands plays in the retention and release of carbon. However, where measurements have been undertaken, fluvial fluxes of carbon in peatlands appear to account for losses of carbon equivalent to 30 to 40 % of net annual carbon uptake by the peatland through gaseous exchange with the atmosphere (Dinsmore et al., 2010; Nilsson et al., 2008; Roulet et al., 2007). Most aquatic carbon measurements in peatland systems have focussed on dissolved organic carbon, yet the release of particulate carbon may also be very important (Evans *et al.*, 2006; Pawson *et al.*, 2008), even in well-vegetated peatlands (Evans and Warburton, 2007).

It is known that macropores play a significant role in transporting water in peatlands (Baird, 1997; Holden, 2009a; Holden, 2009b; Holden et al., 2001). Natural soil pipes are large macropores that typically consist of conduits, often many centimetres in diameter, via which water, sediment, solutes and dissolved gases may move through the soil. Natural piping is sometimes referred to as ‘tunnel erosion’ (Crouch et al., 1986; Zhu, 1997; Zhu, 2003). The pipes or tunnels can often be several hundred metres in length and typically form branching networks. Natural soil pipes have been reported in a broad range of environments, but most commonly in tropical forest soils (Baillie, 1975; Chappell and Sherlock, 2005; Sayer et al., 2006), collapsible loess soils (Zhu, 2003), boreal forests (Roberge and Plamondon, 1987), subarctic hillslopes (Carey and Woo, 2000), steep, temperate, humid hillslopes (Terajima et al., 2000; Uchida et al., 1999; Uchida et al., 2005), dispersive semi-arid soils, where severe gully erosion has often resulted from pipe development (Bryan and Jones, 1997; Crouch et al., 1986; Gutierrez et al., 1997), and the peatlands of Europe, New Zealand, Tasmania, Indonesia, Canada and Siberia (e.g. Gunn, 2000; Holden, 2005; Holden and Burt, 2002; Holden et al., 2004; Jones, 1981; Jones et al., 1997; Markov and Khoroshev, 1988; Norrstrom and Jacks, 1996; Price, 1992; Rapson et al., 2006; Thorp and Glanville, 2003). It is thought that peatlands are conducive to piping because of the combined effect of a plentiful supply of water, their capacity to retain water, and the sharp transitions in hydraulic conductivity that occur both laterally and vertically within the peat profile (Holden and Burt, 2003a; Rosa and Larocque, 2008). While pipe formation instigated by faunal burrows (e.g. small mammals, earthworms, and crustaceans) is common in many environments (e.g. Onda and Itakura, 1997; Wilson and Smart, 1984), pipes have been reported in peatlands where the environmental conditions are generally too harsh for such fauna to exist. Natural pipes in peatlands have been most frequently reported in blanket peatlands (Holden, 2005; Jones, 1981; Jones et al., 1997; McCaig, 1983; Price, 1992). However, they have also been reported in many other peatland types including low-gradient peatlands such as the James Bay Lowlands of Canada (Glaser, 1998; Woo and DiCenzo, 1988), raised bogs (Ingram, 1983), various peatlands in Germany (Dittrich, 1952; Egglesmann, 1960; Rudolf and Firbas, 1927) and gully-head fens in New Zealand (Rapson et al., 2006).

Pipes appear to be important in the delivery of water to blanket peatland streams. Around 10 % of streamflow was found to move through pipe networks in Little Dodgen Pot Sike, a deep blanket peat catchment of 0.44 km^2 in northern England (Holden and Burt, 2002), with discharges over 4.6 L s^{-1} from single pipes being reported. Similarly high discharges from individual pipes have been reported in blanket peatland in Wales (Chapman, 1994), while Jones and Crane (1984) found that 49 % of streamflow was produced by soil pipes in histic podzols at a site in mid-Wales. The relative contribution of pipeflow varies with antecedent conditions (Chapman, 1994; Holden and Burt, 2002; Jones, 1990), and flow within individual pipes may be perennial (continuously-flowing) or ephemeral (intermittently-flowing) depending on water sources (Holden and Burt, 2002).

Despite their important role as a pathway for water it is not known whether pipes are relatively static features of blanket peat systems – changing slowly, if at all, over decades – or whether their morphology and frequency varies continuously through time.. In some environments pipe life cycles may be short such as in some semi-arid loess soils where pipe outlets have been reported to open and close from one storm to the next (Zhu, 1997; Zhu, 2003). Jones and Cottrell (2007) reported data on pipe locations and sizes from a 250-m stretch of streambank consisting of humo-ferric podzols. Here the time period between surveys was 35 years and part of the catchment had been afforested during that time. They found a marked reduction in the number and size of pipes on the forested bank, but no significant change on the opposite moorland bank. While there is evidence for palaeo pipes in peat profiles (Thorp and Glanville, 2003), it is not known how rapidly pipe systems change in peatlands. Holden's (2005; 2006) use of ground-penetrating radar showed that the frequency of large pipes (> 10 cm diameter) was greater on topslopes and footslopes in peatlands compared to midslopes and also that piping was greater where artificial drainage of peatlands had taken place. There was evidence that pipe density increased with the age of the drainage scheme, suggesting that pipe networks could expand relatively quickly in peatlands. However, these measurements were taken at different places rather than at the same site over time. Many gullies in degraded peatlands are also thought to form when pipes collapse, and pipes can often be found at the head of gullies (Holden and Burt, 2002). However, there have been no direct observations of changes of pipe features at one peatland site.

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

Study Site

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

The catchment contains a UK Environmental Change Network (ECN) target monitoring site {Sykes, 1996 #674} where vegetation, water table, soil water chemistry and other parameters have been monitored under strict protocols since 1992 (Sykes and Lane, 1996). Vegetation cover is most commonly *Calluna vulgaris* (L.) Hull. and *Eriophorum vaginatum* L., with some *Empertrum nigrum* L. and *Sphagnum capillifolium* (Ehrh.) Hedw.. The climate is classified as sub-arctic oceanic (Manley, 1936; Manley, 1942). Holden and Rose (2011) have produced a corrected and homogenised temperature record for the site dating back to 1931 and provide full details of the location and types of temperature recording equipment, frequency of recording and changes and calibrations between instruments. The mean annual temperature at the site between 1931 and 2006 was 5.3^{o}C and was 5.8^{o}C for 1991 to 2006 (5.1^{o}C from 1961-1990). These means are based on averages of daily maximum and minimum temperatures. Mean annual precipitation was 2012 mm (records from 1951-1980 and 1991-2006; first period of data based on daily manual readings, latter data based on tipping bucket raingauge with hourly records). Precipitation is only slightly seasonal with 57 % occurring between October and March.

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

The stream flow regime of the blanket peatland across the Moor House Reserve is flashy with rapid rising and falling limbs on hydrographs. Cottage Hill Sike (17.4 ha) displays a mean lag time of 4.5 hours between peak rainfall and peak discharge (based on an analysis of 40 storms between April 2008 and May 2009) and an annual runoff coefficient of 86 %. Water tables at the ECN target site (five automated dipwells) are within 5 cm of the surface for 83 % of the time and rarely fall below 20 cm depth (Evans et al., 1999). Overland flow and shallow throughflow in the upper few centimetres of the peat dominate runoff response, and there appears to be little deeper flow through the peat matrix (Holden and Burt, 2003b), with low, but highly variable, hydraulic conductivities measured at depths greater than 5 cm (Holden and Burt, 2003a). The mean pH for Cottage Hill Sike streamwater is 4.1 suggesting that there is little groundwater sourced from below the peat (Adamson et al., 1998); Cottage Hill Sike is a DOC-rich stream with an average (1993-2007) annual flux of 23.4 g C m^{-2} y^{-1} (Billett et al., 2010) , and highest fluxes observed during the wettest years (Clark et al., 2007). Isotopic evidence and modelling suggest that all of the DOC in Cottage Hill Sike is derived from near surface peat (Tipping et al., 2010).

Methods

Three pipe outlet surveys at Cottage Hill Sike were carried out over a 33-month period starting in August 2007. Surveys were completed on 15th-16th August 2007, 21st July 2009 and 26th April 2010. The pipes were surveyed using identical methods on each occasion. The surveyor walked along the various branches of the stream channel and identified pipe outlets in the bank or head of the channel by eye. Pipe outlets found within the catchment but not directly on a streambank were also included in the survey. Positions of all pipe outlets were recorded using a hand-held GPS. To be sure that we revisited the same pipe outlets during each survey, the pipe outlets were marked with labelled canes and also photographed to show their relative position in the landscape. Observer familiarity with the pipes was also strong because pipe outlets were revisited under different flow conditions to establish whether flows were ephemeral or perennial (see below). Field notes were also taken to identify pipe position within the landscape. Pipe outlet dimensions were measured along both the horizontal and vertical axes on all occasions where possible; 5 mm was taken to be the minimum diameter of a pipe following the method of Jones and Cottrell (2007). To allow comparison with the work of Jones and Cottrell (2007), pipe cross sectional shapes were also classified as horizontally-lenticular or vertically-lenticular if one axis exceeded the other by more than 10 mm (Figure 3). Circular pipes were classified as such if horizontal and vertical axes lengths were within 10 mm of each other. Pipe outlets were also characterised by their height to width ratios. As noted by Jones and Cottrell (2007), vertically-elongated cross sections suggest active downcutting, whereas horizontally-elongated outlets suggest that pipe floor erosion is being inhibited by a less erodible soil horizon. We recognise these are process inferences from morphological characteristics. Vertical cracks (Figure 3d) were defined as those pipe outlets where both the top and base of the pipe outlet closed to a sharp point and an obvious crack within the peat extended upwards from the outlet. Rectangular pipe outlets (Figure 3f) were defined as those with a flat base and vertical sides. Triangular pipe outlets were classified as those with a flat base but with sloping sides that came to a point (see Figure 3e). While pipe outlet shape and size may not necessarily be a direct guide to the shape and size of the pipe within the peat mass, Jones and Cottrell (2007) use pipe outlet shape to infer processes operating within pipe systems. Here we recognise that both internal (e.g. flow regime) and external (e.g. freeze-thaw activity on a stream bank) processes may affect pipe outlet morphology, but in line with Jones and Cottrell (2007) and Jones (1981) we use changes in pipe outlet shape and size as a guide to inform future process investigations and as evidence of the dynamism of pipe outlet morphology. Pipe outlet depths (to the base of the pipe) from the peat surface were measured on each occasion. On each survey occasion it was noted whether the pipes were flowing or not. An additional 12 visits to each pipe outlet during storms and dry periods between 2007 and 2010 were used to determine whether pipe discharge was ephemeral or perennial. Pipe outlets were found at up to 2 metres depth on peat faces (i.e. the maximum depth of visible stream banks). Piping probably occurred at much deeper levels within the catchment but in this study only visible pipe outlets were surveyed. Most of the peat within the catchment is between 3 and 4 m thick. Most streams within the network flow over mineral substrate. Hence pipes that flow below peat-based stream beds which did not have an observable outlet could not be considered in this study.

Results

The locations of pipe outlets mapped within the catchment are shown in Figure 1. Ninety-one pipe outlets were identified in August 2007, 86 in July 2009 and 77 in April 2010. Figure 4 illustrates the distribution of cross-sectional areas for pipe outlets across the catchment on the three survey dates. The largest pipe surveyed had a cross-sectional area of 1413 cm^2. The tallest pipe was 60 cm while the widest pipe was 30 cm.

Table 1 presents summary data for the three survey dates. There was a 12.0 % increase in the mean horizontal width of ephemerally-flowing pipe outlets between August 2007 and April 2010, and a 13.9 % increase in the mean vertical height of ephemerally-flowing pipe outlets. This increase in the size of ephemerally-flowing pipe outlets was countered by a decrease in the width and height of perennially-flowing pipe outlets during the same period (10.4% and 9.9 % respectively). The overall result was a very small mean change in pipe outlet area averaged across all pipes (-2.8%) between August 2007 and April 2010. However, the direction of change was not constant with time. Mean pipe outlet area for the whole catchment increased by 4.2 % between August 2007 and July 2009 and then decreased between July 2009 and April 2010. The largest increase for a single pipe outlet cross-sectional area was 263 cm^2 between the first and last survey while the largest decrease for a single pipe outlet was 312 cm^2 (Figure 5).

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

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

Eighteen pipe outlets disappeared (infilled or collapsed) during the study. Eight pipe outlets disappeared during 23 months between 2007 and 2009 and ten disappeared during the nine months in 2009-2010. Four new pipe outlets also opened up during the study. One new pipe outlet emerged between 2007 and 2009 (225 cm^2 area) but then closed up again by 2010. Another pipe outlet present in 2007 (6 cm^2 area) had closed by 2009, but then re-opened by 2010.

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

Of the circular pipe outlets that were identified in April 2010, 80 % were ephemerally-flowing compared to 67% and 69 % of the circular pipe outlets found on the earlier two survey dates (Table 4). The majority of the perennially-flowing circular pipe outlets either closed or became lenticular; there was an increase in the proportion of lenticular-shaped pipe outlets that were perennially flowing in the April 2010 survey (Table 4). All vertical crackshaped pipe outlets were ephemerally-flowing, with floors deep within the peat (c. 150 cm). For the other shapes of pipe outlets, approximately two thirds were ephemeral (Table 4). All pipe outlets with a pipe height to width ratio greater than 2.5 (i.e. vertically-elongated) had ephemeral discharge while seven of the eight largest pipe outlets surveyed had perennial discharge (Figure 7).

Discussion and conclusions

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

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

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

The winter of 2009/10 was the coldest since 1978/9 (Eden, 2010).. During freezing conditions, needle ice formation within peat can force soil to be thrust upwards on exposed peat surfaces (Evans and Warburton, 2007; Tallis, 1985). Upon thawing mobile peat can be available for transport. It may be that the weather experienced during the winter of 2009/10 created conditions conducive to the production of large amounts of friable peat. This sediment may have been loosened not only on the peat surface but on pipe walls near the peat surface (freezing conditions penetrated to at least 10 cm soil depth according to soil probes at the ECN monitoring site within the catchment and air temperatures fell as low as -18^{o}C). This may have resulted in a larger amount of sediment than normal becoming available for transport along pipe networks, potentially altering their internal morphology and flow conditions (e.g. choking some parts of pipe networks). Alternatively, at exposed pipe outlets on stream banks the build up of ice and loosening of peat may have modified the morphology of the pipe outlet directly or have modified the outlet indirectly by causing peat to slump down an exposed bank above the outlet which then blocked the pipe. However, it would be surprising if the water pressure in the pipe next time it filled was insufficient to reopen the pipe outlet.

The outlets of ephemerally-flowing pipes were significantly deeper than perennially-flowing pipes and there were no significant changes to pipe depth during the study. While most of the largest pipe outlets in the catchment were perennially flowing as one would expect, during the course of the study the ephemeral pipe outlets increased in size (and ephemerally-flowing pipes represented around 70 % of pipes in the catchment) while perennial pipe outlets decreased in size. We recorded no cases where ephemerally-flowing pipe outlets became perennially-flowing pipe outlets. The location of perennially-flowing pipe outlets nearer the peat surface suggests that they are fed by shallow throughflow from the near-surface layer that is unable to percolate into much less permeable and saturated deeper parts of the peat. Deeper ephemerally-flowing pipe outlets may be explained in terms of seepage rates into the pipes from the surrounding peat matrix being so slow during ‘normal’ conditions that insufficient water is released into the pipes to generate flow. However, the pipes may have macropore connections that allow water to pass directly to those pipes from the surface or from overflows from perennial pipes during rainfall events.

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

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

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

Data from Plynlimon, Wales, suggested that areas of peaty catchments which seemed to contain more pipes also yielded more sediment to the stream network (Jones, 2004). Since particulate peat in streams tends to contain around 50 % carbon then the dynamism and non-linearity of pipe systems (e.g. opening and closing of pipe outlets) needs to be investigated further if we are to understand carbon dynamics in these systems. Subsurface routes for particulate carbon release have rarely been considered in peatlands and there are no complete, direct measurements that enable the role of pipes in aquatic carbon production within deep peatlands to be established. At Cottage Hill Sike our initial studies suggest that pipes release much of their sediment in short episodic pulses which are not linearly related to discharge (Holden *et al.*, 2009). It appears that subsurface particulate carbon transport systems are active, dynamic and may switch on and off. In addition, a related study (Dinsmore et al., in press) has demonstrated the importance of the pipe system as a pathway for greenhouse gas transport from the peat to the stream system in the Cottage Hill Sike catchment. Our geomorphological survey suggests that peat pipe systems may be particularly responsive to extreme weather conditions (e.g. large flows, severe frost). Dynamic change in pipe morphology is also likely to have a significant effect on medium-term hydrological response, because pipe constriction or a decrease in pipe density slows down water movement within the peatland. However, further process-based assessment is now needed to establish more thoroughly the controls on pipe morphology and the role of pipes in transporting sediment and carbon in peatland systems.

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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 (cm^2)**
2007 ephemeral	6.16	8.21	60.30
2007 perennial	13.65	15.73	233.90
p	<0.001	0.001	<0.001
2009 ephemeral	6.33	9.30	6760
2009 perennial	13.04	16.13	222.40
p	<0.001	0.006	<0.001
2010 ephemeral	6.90	9.35	7300
2010 perennial	12.23	14.18	180.30
p	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**
Circular			
Mean floor depth, cm	83.9	82.5	92.5
% of pipes ephemeral	69	67	80
% of pipes perennial	31	33	20
Vertically-lenticular			
mean floor depth, cm	93.7	81.5	90.5
% of pipes ephemeral	69	64	60
% of pipes perennial	31	36	40
Horizontally-lenticular			
mean floor depth, cm	83.9	120.0	66.7
% of pipes ephemeral	67	67	58
% of pipes perennial	33	33	42
Vertical crack			
mean floor depth, cm	152.0	131.7	141.4
% of pipes ephemeral	100	100	100
% of pipes perennial	0	0	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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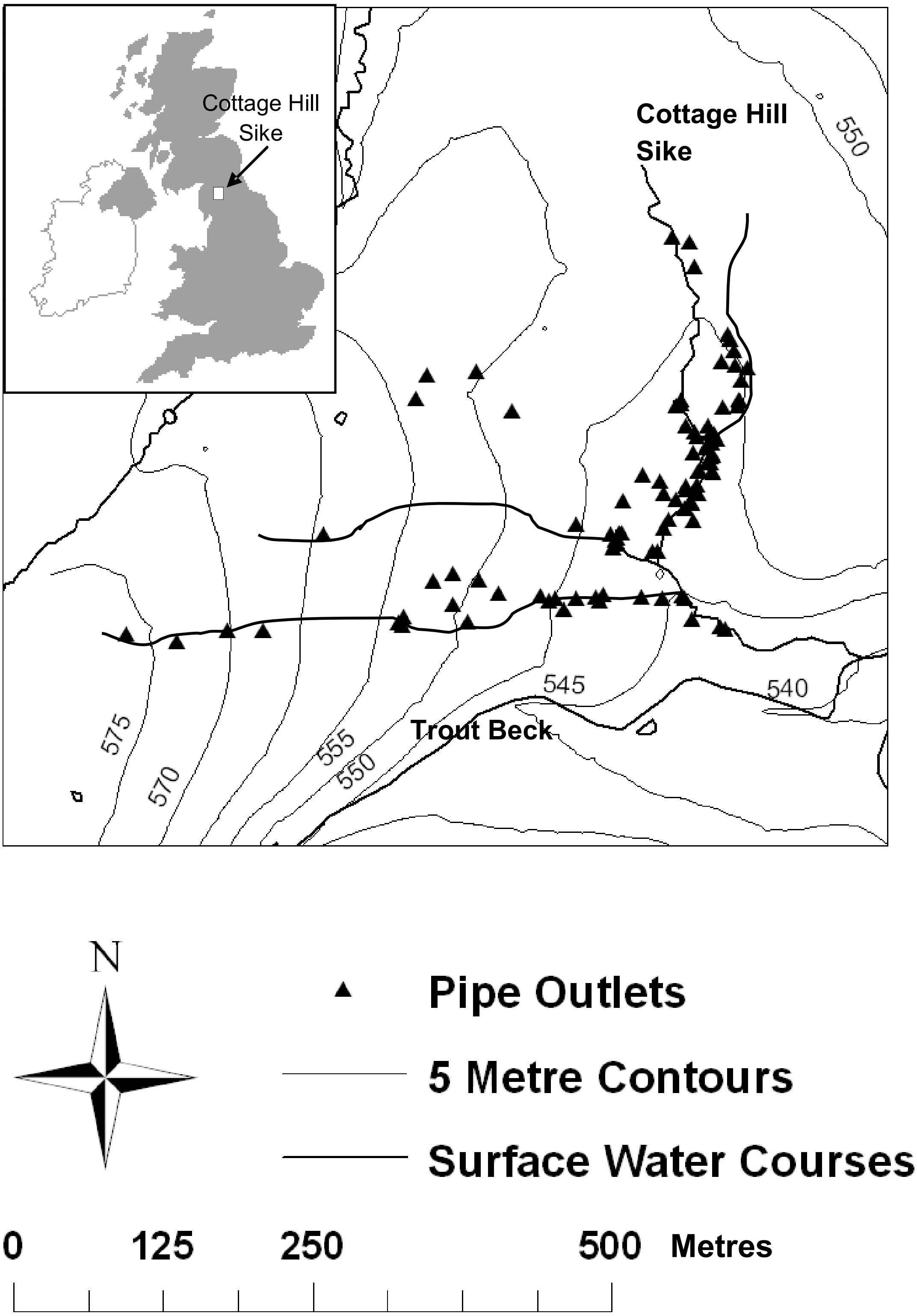
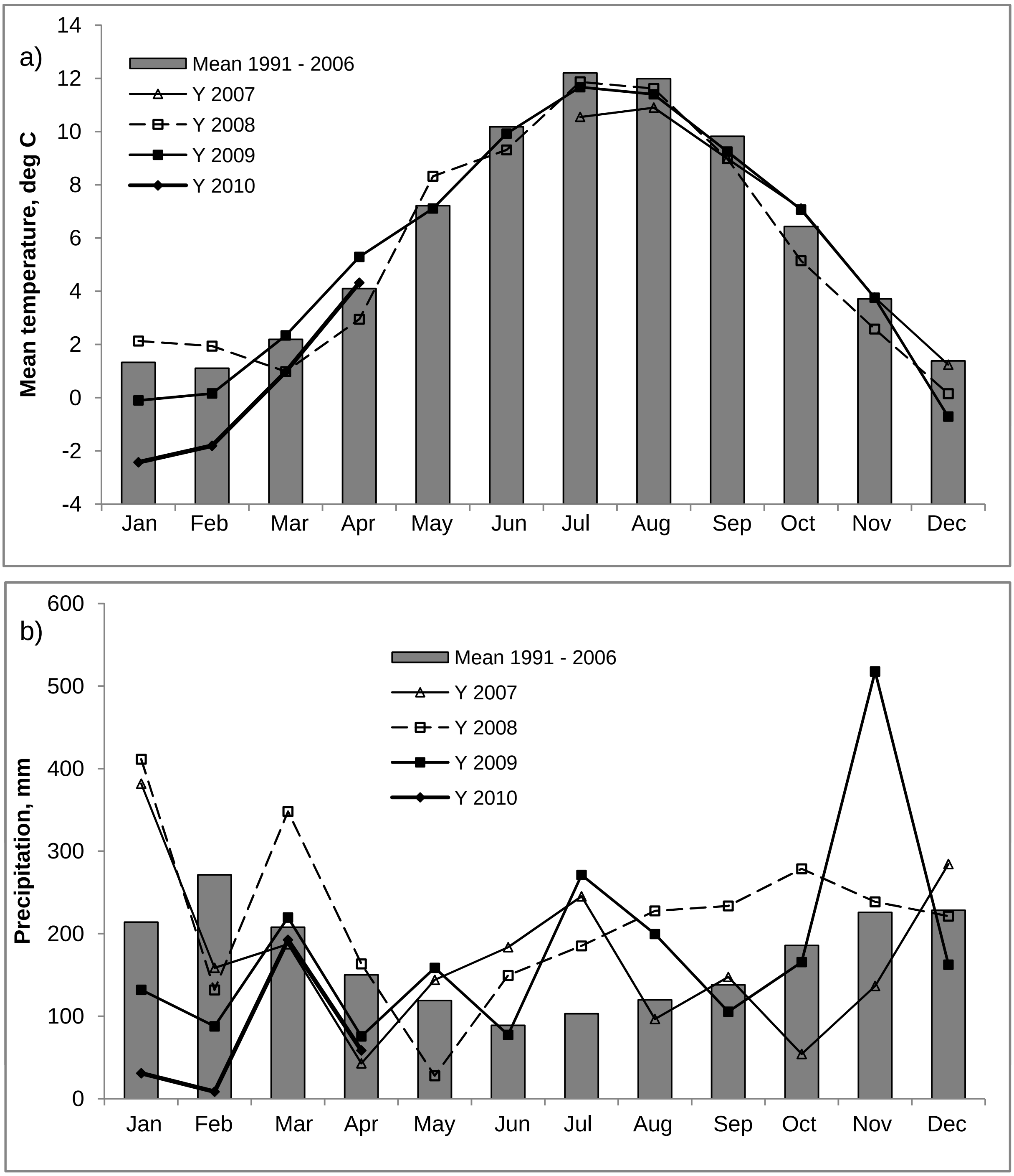

Cottage Hill
Sike
Cottage Hill
Sike
550
545
540
Trout Beck
575
570
555
550
N
Pipe Outlets
5 Metre Contours
Surface Water Courses
0
125
250
500
Metres

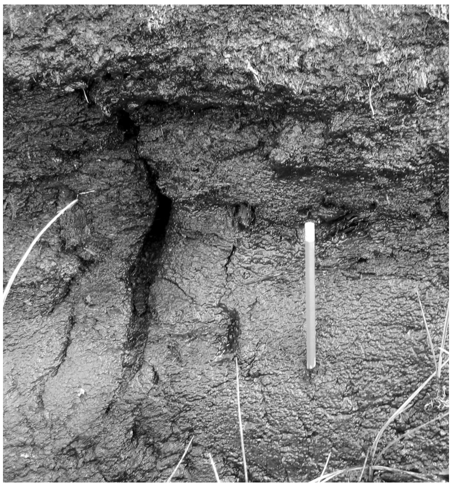

a)
Mean temperature, deg C
Mean 1991 - 2006
Y 2007
Y 2008
Y 2009
Y 2010
14
12
10
8
6
4
2
0
-2
-4
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
b)
Precipitation, mm
Mean 1991 - 2006
Y 2007
Y 2008
Y 2009
Y 2010
600
500
400
300
200
100
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

a)

b)

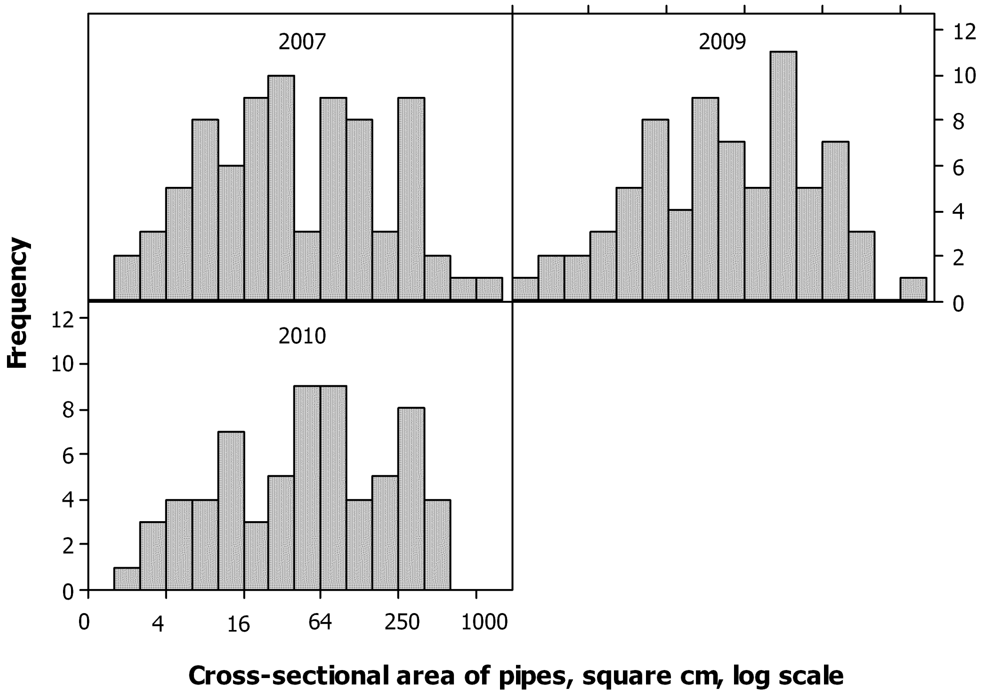
c)

d)

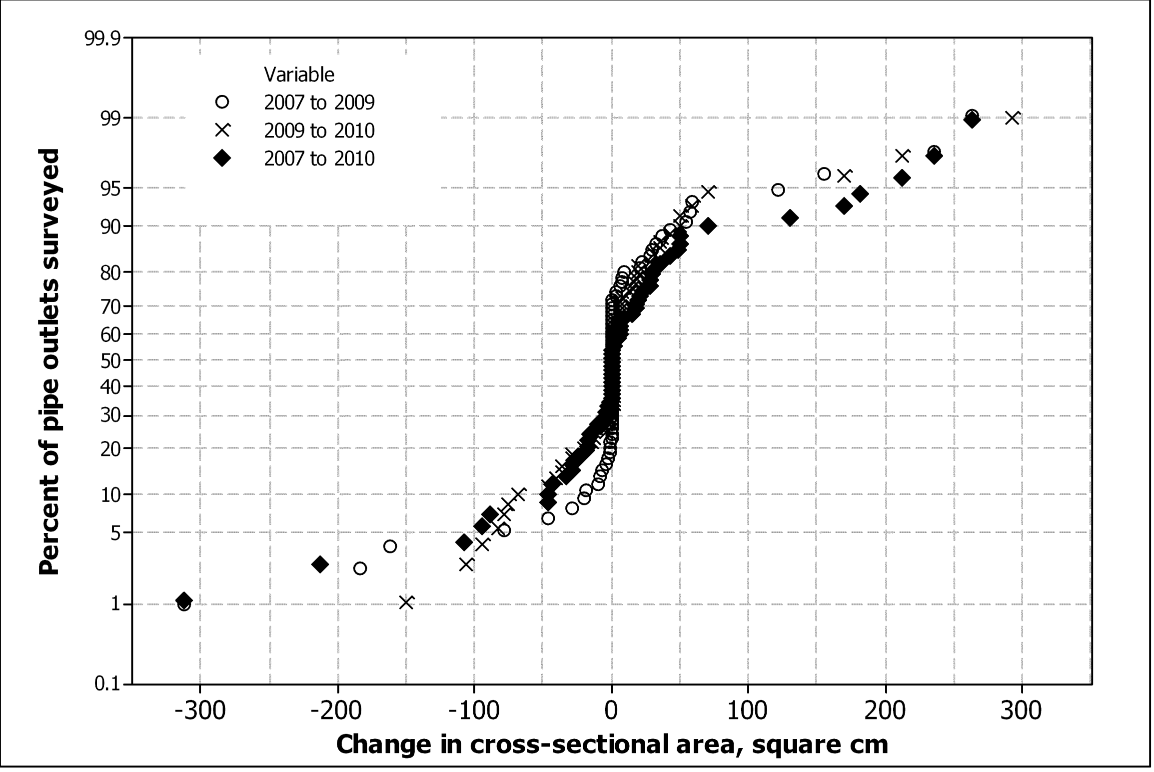


e)

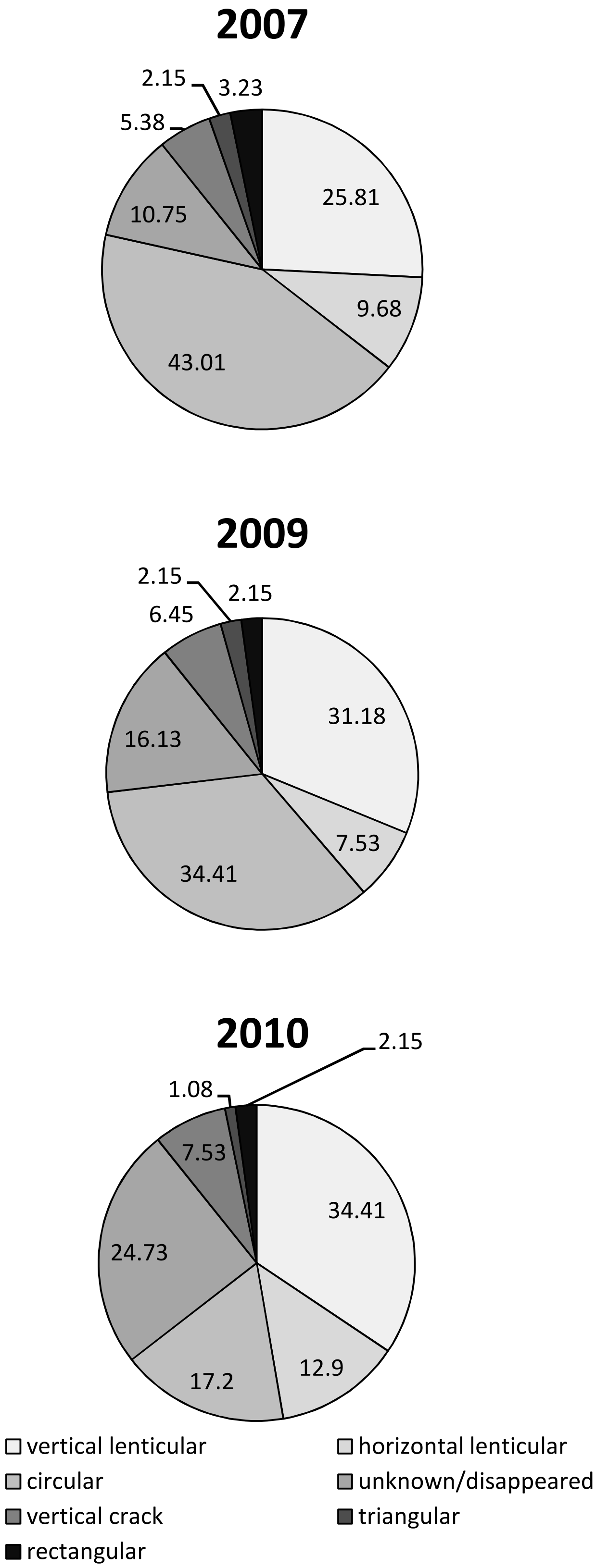
f)

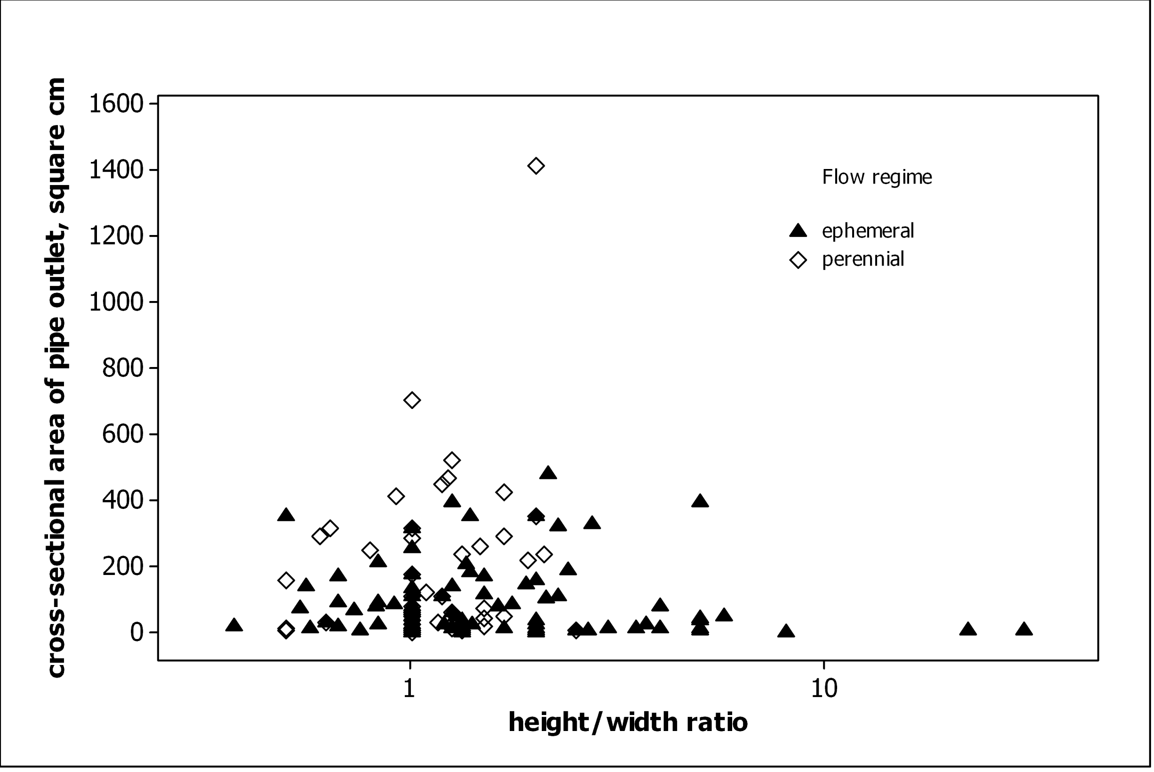


2007
2009
2010
Frequency
0
2
4
6
8
10
12
0
4
16
64
250
1000
Cross-sectional area of pipes, square cm, log scale



Variable
2007 to 2009
2009 to 2010
2007 to 2010
Percent of pipe outlets surveyed
99.9
99
95
90
80
70
60
50
40
30
20
10
5
1
0.1
-300
-200
-100
0
100
200
300
Change in cross-sectional area, square cm


2007
2.15
3.23
5.38
25.81
10.75
9.68
43.01
2009
2.15
2.15
6.45
31.18
16.13
7.53
34.41
2010
2.15
1.08
7.53
34.41
24.73
12.9
17.2
vertical lenticular
horizontal lenticular
circular
unknown/disappeared
vertical crack
triangular
rectangular



cross-sectional area of pipe outlet, square cm
1600
1400
1200
1000
800
600
400
200
0
1
10
height/width ratio
Flow regime
ephemeral
perennial