Piping and pipe blocking impacts on degraded blanket bog hydrology and aquatic carbon

Taco Helmar Regensburg

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Chapter 2

Regensburg, T.H., Chapman, P.J., Pilkington, M.G., Chandler, D.M., Evans, M.G., Holden, J., 2020. Controls on the spatial distribution of natural pipe outlets in heavily degraded blanket peat. *Geomorphology*, 367, 107322. https://doi.org/10.1016/j.geomorph.2020.107322

THR (the candidate) designed the survey, led the volunteer group when conducting survey, processed and triangulated survey data, performed spatial and statistical analyses, and wrote the manuscript. MGP arranged the volunteer group and accompanied THR to the site from time to time and assisted with the field survey. JH and PJC (1st and 2nd PhD supervisor) reviewed all drafts of the manuscript and gave critical feedback, advice and guidance. MGP, DMC, and MGE (3rd PhD supervisor) reviewed only final drafts of the manuscript and gave critical feedback, advice and guidance.

Chapter 3

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THR came up with the experimental study design, developed and constructed pipeflow gauges, weirs and bulk rainfall gauges, installed all equipment in the field, maintained sensors, extracted data from them, performed weir calibrations, led the volunteer group to collect sensor data and execute dipwell monitoring, designed and performed hydrograph analyses, performed statistical analyses, and wrote the manuscript. All authors reviewed the initial experimental design and identified aspects of the design that needed changes. MGP was involved in planning the experiment, identifying weir locations, constructing and installing field equipment, and collecting field data. JH and PJC reviewed all drafts of the manuscript and gave critical feedback, advice and guidance. MGP, DMC, and MGE reviewed only final drafts of the manuscript and gave critical feedback, advice and guidance.

Chapter 4

Chapter 4 formed the basis for the following publication:

Regensburg, T.H., Holden, J., Pilkington, M., Evans, M.G., Chandler, D., Chapman, P.J. (2022) Aquatic carbon concentrations and fluxes in a degraded blanket peatland with piping and pipe outlet blocking. *Earth Surface Processes and Landforms,* 47(3), 872 – 887. https://doi.org/10.1002/esp.5290.

THR designed the experiment, installed all equipment used, organised and led volunteer groups to collect water samples, processed samples and conducted laboratory analysis, performed data analysis, and wrote the manuscript. MGP was involved in maintenance of field equipment and collecting water samples. JH and PJC reviewed all drafts of the manuscript and gave critical feedback, advice and guidance. MGP, DMC, and MGE reviewed only final drafts of the manuscript and gave critical feedback, advice and guidance.

Rationale for thesis by alternative format

This thesis is submitted as an alternative style of doctoral thesis including published material. This format is appropriate because two out of the three data chapters have been published in peer-reviewed journals. The third data chapter is currently in review. The thesis is divided into five chapters, which is in line with the Faculty of Environment protocol for presenting an alternative style of doctoral thesis including published material. Chapter 1 contains an overview of available literature which provides the context and relevance of the thesis and establishes research gaps and the rationale for the study, research questions and objectives, and an outline of the research approach. Chapters 2 to 4 are the three journal manuscripts described above. Chapter 5 is the synthesis of the main findings in the thesis. It draws together the findings in Chapters 2 – 4, and discusses the wider implications of the findings. Chapter 5 also outlines some limitations of the study, directions for future work, and a summary of conclusions from the thesis.

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Abstract

This thesis sought to improve our understanding of soil piping in a heavily degraded headwater blanket peatland in the Peak District of northern England. In particular, it investigated the frequency and extent of piping and the hydrological and erosional contribution of pipeflow to streams, and whether it is possible to moderate streamflow and associated carbon export by blocking pipe outlets. Two distinct types of pipe outlet were identified; head and edge. Head pipe outlets were observed on streambanks with signs of headward retreat and were significantly larger and closer to the peat surface compared to edge pipe outlets that issued onto uniform streambanks. Southwest and west-facing streambanks hosted more than 43 % of the identified pipe outlets. The hydrological responses and associated carbon export for two headwater catchments were compared for nine months before and six months after half of the pipe outlets in one catchment were blocked. Pipeflow was impeded either by inserting a plug-like structure in the pipe-end or by the insertion of a vertical screen at the pipe outlet. Seepage appeared at all blocks, while new pipe outlets were only formed around vertical screens. Pre-blocking, two head pipes accounted for 9.3 % of streamflow compared with 2.0 % for edge pipes. One head pipe accounted for 2.1 % of dissolved organic carbon and 5.8 % of particulate organic carbon stream flux. Water-table level sat much deeper at edge locations than at head locations. The results suggest that impeding pipeflow at pipe outlets did not reduce streamflow and associated aquatic carbon export at the stream scale, but could potentially exacerbate pipe development in streambanks. Therefore, future restoration works in blanket peatlands should prioritise limiting surface runoff inputs to pipe networks, and revegetate bare gullies to reduce the incidence of desiccation on streambanks, to eliminate pipe development.

Contents

List of Figures

Appendix A: Figures

Appendix B: Figures

List of Tables

Appendix B: Tables

List of Abbreviations and Symbols

%	pro cent (percentage)
°	degrees of surface slope
°C	(temperature in) degrees Celsius
a	slope of line fit to determine r-square
AMD	above median discharge
API	antecedent precipitation index
BACI	study design involving a before-after-control-intervention approach
BMD	below median discharge
c	conversion factor
Ca	Calcium
CAP	common agricultural policy of the European Union
Catchment C	the control catchment
Catchment T	the treatment catchment
CH_4	methane
C_i	concentration measured at an instantaneous discharge Q_i
cm	centimetre
CO_2	carbon dioxide
CSA	cross-sectional area of pipe outlet
DCA	dynamic contribution area of a pipe
DIC	dissolved inorganic carbon
DJF	December-January-February
DOC	dissolved organic carbon
DOC$_{254}$	proxy for dissolved organic carbon based on spectral absorbance at 254 nm
D_s	streambank height
DTM	digital terrain model
DTPS	depth to peat surface
D_v	depth to pipe roof
Ec	pipe outlet at edge location with circular shape
Edge (E)	pipe outlet on a straight section of a streambank
Eh	pipe outlet at edge location with horizontally lenticular shape
Ev	pipe outlet at edge location with vertically lenticular shape
FAO	Food and Agriculture Organization of the United Nations
FCA	flow contribution area
G1	the treatment catchment
G2	the control catchment
GPR	Ground Penetrating Radar
GPS	Global Positioning System
h	hour
ha	hectare
Hc	pipe outlet at head location with circular shape
HCO_3	bicarbonate
Head (H)	pipe outlet on a streambank that shown signs of headward retreat
Hh	pipe outlet at head location with horizontally lenticular shape
HL	horizontal length of pipe outlet diameter
Hv	pipe outlet at head location with vertically lenticular shape

JJA	June-July-August
K	hydraulic conductivity
k	recession coefficient
KHP	potassium hydrogen phthalate
km	kilometre
Ks	saturated hydraulic conductivity
L	litre
LiDAR	Light Detection And Ranging technology
m	metre
MAM	March-April-May
MFFP	Moors for the Future Partnership
mg	milligram
mm	millimetre
MoorLIFE2020	EU LIFE2020 project that aims to restore active blanket bog in UK SAC
MWU	Mann-Whitney U test output
n	number of samples
NA	data error
NEE	net ecosystem exchange
NF	no flow
nm	nanometre
p	probability
P	precipitation
P_{exceed}	exceedance probability
pH	level of acidity
POC	particulate organic carbon
Q	discharge
Q_i	instantaneous discharge
Q_r	hourly discharge
r^2	root square
RF	Rainfall station
RP	relative position of pipe outlet on streambank
r_s	Spearman's Rank Correlation Coefficient
SAC	Special Area for Conservation
S_b	streambank slope
SON	September-October-November
SUVA	specific ultra-violet absorbance
U	statistic of Mann–Whitney U test
UC	Urchin Clough
UK	United Kingdom
UNG	Upper North Grain
UV-VIS	ultraviolet–visible spectrophotometry
V	V-shape of weir crest
VL	vertical length of pipe outlet diameter
WT	water table
yr	year
Z	standardised test statistic in the Mann Whitney U test
α	dipwell transect parallel to the projected pipe course

β	dipwell transect perpendicular to the projected pipe course at 1 m from pipe outlet
γ	dipwell transect perpendicular to the projected pipe course at 3 m from pipe outlet
η^2	statistical response variable eta-squared - effect size measure
τ	statistic for Kendall’s Tau
χ^2	statistic for *chi* square goodness of fit test

Chapter 1: Introduction

Peatlands provide a wide range of ecosystem services that contribute to human well-being, including climate regulation, water purification, biodiversity, recreational and educational opportunities, and, increasingly, tourism (Kimmel and Mander, 2010). However, human interaction with peatlands has led to their degradation, which has frequently resulted in a fall of the water table and change in vegetation cover. In sloping blanket peatlands, loss of vegetation has led to erosion and rapid development of incising gullies. Therefore, many peatlands are undergoing programmes of restoration, which have been funded via a range of sources including public (e.g. EU LIFE projects and Common Agricultural Policy (CAP) funding via agri-environment schemes), private (e.g. water utilities) and charity funding. Peatland restoration projects usually include one or more of water management, re-vegetation, and vegetation management, with the aim of restoring hydrological function and active peat forming vegetation. In the UK, due to the sloping nature of dominant blanket peat cover, many restoration projects have sought to quickly re-establish vegetation cover on the main peat mass, and where there are ditches and gullies to block them to trap sediment and slow water flow, encouraging bankside stabilisation and revegetation where possible a (Armstrong *et al.*, 2009; Shuttleworth *et al.*, 2019; Wallage *et al.*, 2006; Worrall *et al.*, 2007). The challenges associated with blanket bog restoration have been addressed in a number of recent reviews (Holden *et al.*, 2017; Lindsay and Clough, 2016; O'Brien *et al.*, 2007; Parry *et al.*, 2014), which have outlined the techniques used, the spatial and temporal heterogeneity in peatland response and uncertainties regarding the timeframe for peatland functions to recover.

Many blanket peatlands contain soil pipes and degraded systems have been associated with greater densities of piping than more pristine systems (Holden, 2005a). In peatlands, soil pipes transport water via the subsurface through channels of varying sizes, while undulating through the peat profile (Holden and Burt, 2002b). While pipe networks can have complex hierarchal structures, they may provide transport of water, sediment and solutes throughout the peat profile during storms at flow velocities up to ~4 L s^{-1} (Holden *et al.*, 2012b; Smart *et al.*, 2013). As a result, these pipes are a cause of concern to peatland restoration practitioners as little is known about their prevalence and contribution to runoff, erosion and carbon export in degraded blanket peatlands, or how their contribution can be reduced.

Various field observations have led to speculation on the role of piping (see next section for an overview of pipes and piping) in embankment failures, landslides and gully erosion (Faulkner *et al.*, 2004; Faulkner *et al.*, 2008; Wilson, 2011; Wilson, 2009; Wilson *et al.*, 2008; Wilson *et al.*, 2015), but information about their functioning in peatlands are rare. While Parry *et al.* (2014) mentioned pipe blocking as a restoration technique, there have been very few studies to date, that have looked at the impact of blocking soil pipes on runoff and carbon export from blanket peatlands. Therefore, there is an urgent need to understand whether pipe outlet blocking along gully banks as part of ongoing gully damming in restoration schemes can be used to control subsurface flow, erosion and carbon export in degraded blanket peatlands.

The research in this thesis has been partly funded by MoorLIFE2020, via a grant from the European Commission LIFE Nature programme to Moors for the Future Partnership (MFFP), led by the Peak District National Park Authority, with financial support from the Environment Agency, National Trust, Royal Society for the Protection of Birds, Severn Trent, United Utilities, Yorkshire Water, Pennine Prospects, and representatives of the moorland owner and farming community. The MoorLIFE2020 project aims to conserve and protect the EU priority habitat Active Blanket Bog within the South Pennine Moors Special Area for Conservation (SAC) and the ecosystem services it provides by undertaking specific conservation activities, environmental monitoring, communication, and education events. In that context, as part of MoorLIFE2020, MFFP sought a scientific evidence base for (i) the prevalence of pipes within degraded peatlands, (ii) the contribution of pipeflow to runoff, erosion and carbon export and (iii) whether pipe outlet blocking would reduce runoff, erosion and carbon export. The research carried out in this thesis provides answers to these questions.

This chapter reviews our current understanding about pipe development and impacts on hydrology, erosion and carbon export from blanket peatlands and identifies the knowledge gaps on the prevalence of piping in upland blanket peatlands, their role in peatland hydrology and carbon fluxes, and the potential of mitigating piping processes via restoration techniques. The review starts by introducing peatland types and their distribution, both globally and within the UK, before outlining the major functions of peatlands. It then focuses on blanket bogs; their distribution, and hydrological functioning, including piping, followed by a review of the wider literature on the processes involved in piping. The techniques and approaches used to restore peatlands are reviewed along with possible techniques for attenuating pipeflow. Research gaps are identified, and the overall aim and research questions of the thesis are presented before the research approach and methodology are summarised. Finally, this chapter ends with an outline of the remaining structure of the thesis and subsequent chapter contents.

1.1 Peat types and their distribution

1.1.1 Peat types

Peat consists of a heterogeneous mixture of more or less decomposed plant (humus) material. Its structure ranges from slightly decomposed plant remains to a fine amorphic, colloidal mass (Charman, 2002). Peat accumates where plant litter production exceeds its decay in the soil. The turnover rate of plant litter in soils is strongly dependent on oxygen supply. Where water has saturated the soil, anoxia slows down plant litter decomposition, enabling the accumulation of organic matter (Clymo, 1984). The hydrology of peat is an important determinant paramount to the type of peatland that is formed. Two main types of peatland are distinguished, which distinctively differ in hydrology, water chemistry, and peat-forming vegetation (Charman, 2002): fens and bogs.

Fens, or minerotrophic peatlands, are dependent on groundwater and/or river flooding for their water and nutrient supply and develop on flat to very gently sloping surfaces. The nutrient status and pH of fens varies much more than within bogs (Wheeler *et al.*, 2009), depending on their position in relation to the surrounding local geology and land use, with pH ranging from 4.5 to 7.5. Vegetation is dominated by brown mosses and herbaceous plants (grasses, sedges and rushes).

In contrast, bogs are ombrotrophic peatlands dependent on precipitation for water and nutrient supply. As a result, bogs are highly acidic (pH < 4), and are low in solutes, particularly those derived from weathering, such as Ca and HCO_3. Near-surface water-table levels in bogs are widely regarded as a key factor in maintaining the anoxic conditions necessary for peat accumulation (Joosten *et al.*, 2016), and the growth of peat-forming plants such as *Sphagnum ssp.* and *Eriophorum ssp.* (González *et al.*, 2014), which form a central role in carbon sequestration in peat bogs. Bogs can be classified further into raised bogs and blanket bogs. Raised bogs comprise a dome of saturated peat underlain by fen peat or waterlogged mineral sediments. Domes may be 2 to 5 m higher in the centre than the margins, with peat thicknesses as great as 8 m having been recorded (Foster and Glaser, 1986). In contrast, blanket bogs occur on rolling terrain and often consist of a mosaic of different peatland types, but the dominant type of peatland within them is a blanket of ombrotrophic peat, ranging from 0.4 to 8 m, sitting on bedrock or deposited material that impedes deep drainage (Bragg and Tallis, 2001; Parry *et al.*, 2014). This study will focus on blanket bog only.

The existence of blanket bog depends upon retaining water, and upon the origin, volume, chemical quality and variability of its water supply. It is important to note that blanket bog can form on steeper slopes than other types of peat, occasionally up to 20 degrees (Charman, 2002). However, this makes them vulnerable to wind and water erosion, particularly where vegetation is lost (Foulds and Warburton, 2007; Holden *et al.*, 2007). It also makes them difficult to revegetate (Parry *et al.*, 2014) as the peat becomes very mobile when erosion commences meaning that seedbanks are washed away and small plants trying to establish are removed (Evans and Warburton, 2007). Blanket bog often acts as a filter to adjacent aquatic ecosystems by cycling elements, storing organic material, and trapping pollutants received from the atmosphere. However, when degraded, these stored pollutants can be rapidly released into watercourses often bound to the peat (e.g. Rothwell *et al.* (2005)).

1.1.2 Spatial distribution of peatland

Globally, peatland occupy 2.84 % of the land surface, and occur in a range of climatic zones including tropical, temperate and cold climates (Figure 1.1). Peatlands are particularly widespread in regions where precipitation or groundwater influx exceeds evaporation and transpiration losses, and where impermeable substrates or topographic convergence maintain saturation (Xu *et al.*, 2018b). Within sites, local differences in inundation regime affect the rate of plant decay, therefore peat formation is a spatially non-uniform deposit (Holden, 2005a). Overall, the build-up of peat continually changes both spatially and temporally because of ongoing biogeochemical and physical processes, and hence it is very sensitive to perturbations (e.g. burning (Holden *et al.*, 2015), drainage (Ramchunder *et al.*, 2009), and climate change (Worrall *et al.*, 2004)).

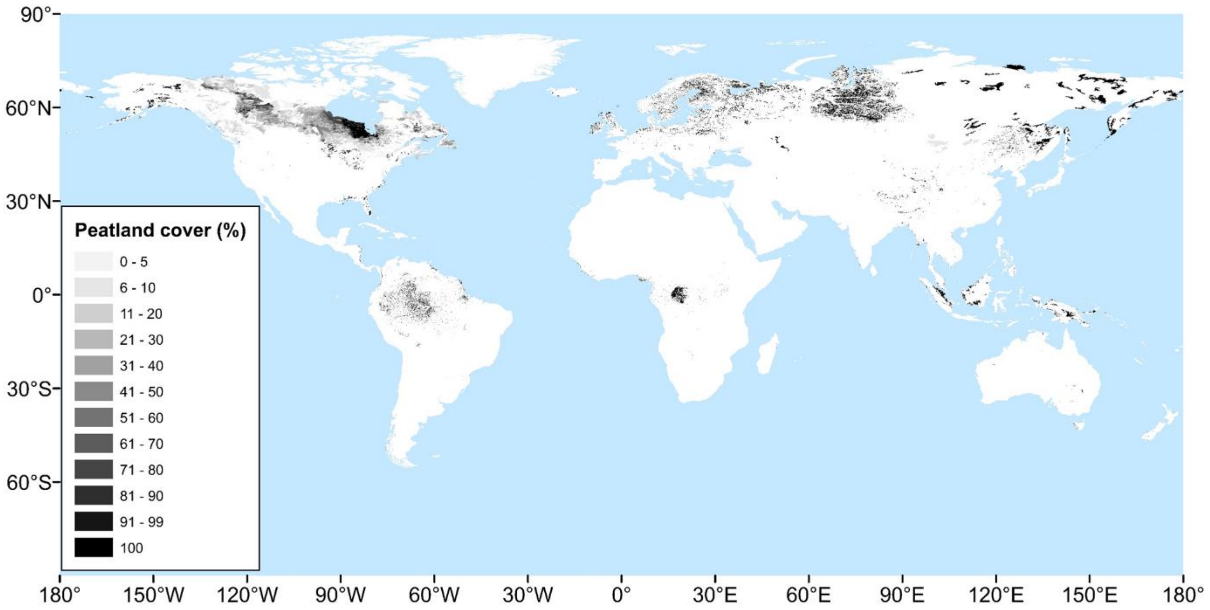

Figure 1.1. Overview of global peatland distribution, where peat presence is indicated by black shading. Grey shading in the legend (<100 %) is only adopted for Canada for which 12.4 % peatland cover was the best available dataset (adopted from Xu et al. (2018b)).

1.1.3 Spatial distribution of blanket bog

Blanket bogs are commonly found in temperate, hyperoceanic, coastal regions of the world (Lindsay *et al.*, 1988), including parts of Atlantic northwest Europe, western Canada, southern Alaska, Tasmania, the South Island of New Zealand, the southern tip of South America, and eastern Russia.

Blanket bog occurs on rolling terrain and sits on a substrate that impedes deep drainage (Bragg and Tallis, 2001; Parry *et al.*, 2014). Blanket bog vegetation consists of non-vascular land plants (bryophytes) including *Sphagnum* species, sedges such as *Eriophorum* species, and dwarf shrubs such as *Erica* and *Calluna* species (Charman, 2002). Different *Sphagnum* species, with different preferences for degree of ground wetness, form characteristic hummock and lawn systems and thus create micro-topographical variation. In the UK, blanket bogs cover around 7 % of the land mass (Baird *et al.*, 2009) and are typically found in the wetter, cooler upland areas (Charman, 2002). UK blanket peatlands represent around 10-15 % of the world's blanket bog resource (JNCC, 2011).

1.2 Major functions of peatlands

The focus of the work covered in this thesis is on restoring degraded blanket bog for the protection and production of clean water, slowing runoff and thus attenuating flood responses, and ultimately reducing erosion and gully formation. Given that the majority of restoration programmes aim to improve and support good water quality and restore the carbon sequestration potential of peatlands, the following peatland functions are reviewed in this section: flood attenuation, carbon storage / climate mitigation, and water provision / water quality.

1.2.1 Flood attenuation

Peatland vegetation has the ability to regulate runoff by slowing down water and helping to reduce flood peaks downstream during storms (Grayson *et al.*, 2010; Shuttleworth *et al.*, 2019). Restoring peatland vegetation via a combination of raising water tables and re-vegetation can benefit flood risk alleviation downstream by slowing the flow (Goudarzi *et al.*, 2021; Holden *et al.*, 2008) while also creating conditions suitable for the survival of peat-forming vegetation. The saturation of peat, and therefore the level of the water table, is a dominant control on the activity of runoff pathways in peat systems (Holden and Burt, 2002a, 2003)(see further details in section 1.3). In addition, the distribution of water between surface and subsurface components of the system is dependent on antecedent conditions and concurrent weather and can influence the storm response, such as the timing of peak flow, the total volume of runoff and its duration (Acreman and Holden, 2013). However, the direction of influence can have both a positive and a negative impact for water storage potential or flood risk alleviation. For instance, in dry conditions peatlands may buffer incoming precipitation through water-table recharge, whereas after prolonged wet periods, peat easily becomes fully saturated leaving little storage for any additional rainfall. As a result, surface vegetation roughness is crucial for slowing water flow during wet periods and bare areas are associated with higher flood peaks (Gao *et al.*, 2016; Grayson *et al.*, 2010).

1.2.2 Carbon storage / climate mitigation

Peatland ecosystems are an important store of terrestrial carbon globally (Leifeld and Menichetti, 2018). It is estimated that peatlands store 452 Gt of carbon (Joosten, 2009), which is attributed to the often thick layers of peat (up to 8 m of blanket peat has formed in some places during the past 10,000 years). Peat is a highly concentrated terrestrial store of carbon because it consists, by definition, of more than 30 % (dry mass) dead organic material that contains 48–63 % of carbon. Recent estimates on peatland cover by Xu *et al.* (2018b) suggest that it covers 423 million hectares globally. This is markedly higher than previous estimates of 331 - 381 million ha (FAO, 2012; Joosten, 2009), which infers that estimates of the total carbon pool in peat is also larger than previously thought. Although peatlands form a significant carbon reserve, they can act as both a sink and source of atmospheric carbon dioxide.

To be a carbon sink, the balance between photosynthesis and total ecosystem respiration, referred to as the net ecosystem exchange (NEE), needs to be negative. For UK peatlands, the evidence to date suggests that peatlands are a net carbon sink, unless they are affected by climatic and management pressures (Billett *et al.*, 2010). In highly degraded systems where the water table is low, the carbon sink–source relationship is likely to be disturbed because a greater proportion of the pore spaces are filled with oxygen (Holden *et al.*, 2004). In turn, the rate of peat decomposition will increase, as aerobic decomposition happens at a much faster rate, which results in more carbon dioxide being released to the atmosphere. Methane (CH_4) is produced in the unsaturated zone by oxidation of plant litter and in the saturated peat by anaerobic decomposition. Release of methane to the atmosphere takes place via diffusion (Lai, 2009), ebullition (bubbles released from saturated peat) (Ramirez *et al.*, 2017), and plant transport via root tissues (Garnett *et al.*, 2020). It should be noted that CH_4 is a powerful greenhouse gas with a 100-year global warming potential, which is 28-34 times that of CO_2 (Myhre *et al.*, 2013). Because of this it is possible for a peatland to be a net sink for carbon but at the same time to have a warming effect on climate (Baird *et al.*, 2009). In addition to gaseous carbon release from the peat to the atmosphere, dissolved CO_2 and CH_4 are also lost from peatlands in surface waters draining them and may be released from the aquatic system to the atmosphere further downstream (Palmer *et al.*, 2016). Therefore, peatland restoration is often being pursued as a climate change mitigation technique. However, Strack *et al.* (2016) showed that CO_2 and CH_4 dynamics in restored peatlands differed significantly from undisturbed peatlands, and controls on the flux varied between them. It is thought that the changed hydrological function and vegetation of a restored peatland may not quickly return to that of an undisturbed peatland (Gorham and Rochefort, 2003; Poulin *et al.*, 2013), which makes estimating the time span required for re-establishment of the net carbon sink function following restoration difficult to quantify (Bacon *et al.*, 2017). Where NEE is close to zero, export of carbon via the aquatic system as particulate organic carbon (POC), dissolved organic carbon (DOC), and dissolved CO_2 and CH_4, can turn a peatland into a source of carbon.

1.2.3 Water provision / water quality

Peatlands are dynamic, unbalanced ecosystems in which the accumulation of peat is determined by, and in turn controlled by, the flowpaths of water (Pastor *et al.*, 2003). Similarly, the amount of carbon exported from peatlands via streams and rivers is highly dependent on interactions between the flows of water through and across the peatland (Evans and Warburton, 2007). Peat dominated catchments are important sources for drinking water supply, particularly in the upland regions of the UK (Williamson *et al.*, 2020; Xu *et al.*, 2018a). Waters draining peatlands tend to be acidic, coloured and low in nutrients and other solutes. The water becomes discoloured due to the presence of naturally occurring high molecular weight organic carbon compounds, such as humic and fulvic acids, that are derived from the decomposition of the organic matter. Theses humic and fulvic acids make up 50–75 % of DOC in water and hence a strong relationship between water colour and DOC is usually observed (e.g. Tipping *et al.* (1988); Worrall *et al.* (2003)). Removal of colour comes at a high cost for water supply utilities (Bonn *et al.*, 2010; Fearing *et al.*, 2004; Van der Wal *et al.*, 2011). Particularly in blanket peats, DOC fluxes can be higher from more degraded catchments than from intact catchments (Armstrong *et al.*, 2010; Wallage *et al.*, 2006), and therefore water treatment costs are significantly enhanced. Thus, restoring degraded peatlands is often pursued with the aim to reduce the concentration and flux of DOC as this would provide an important ecosystem service benefit for drinking water supply (Bain *et al.*, 2011).

For temperate and boreal peatlands, DOC export can range between 10 - 65 g DOC m^{-2} yr^{-1} and POC export range from 1 to 340 g m^{-2} yr^{-1}, with intact bogs often producing larger DOC flux than POC, as opposed to disturbed bogs exporting fluvial carbon predominantly in particulate form (Billett *et al.*, 2010; Holden *et al.*, 2012b; Li *et al.*, 2019; Pawson *et al.*, 2008; Worrall *et al.*, 2009). DOC can exert a significant control over aquatic ecosystems via productivity, biogeochemical cycles and attenuation of visible and UV radiation (Pastor *et al.*, 2003). As a result, DOC affects water quality in terms of colour, taste, pH and can flocculate with heavy metals in soil- and stream-water. Stream water DOC concentrations often show a seasonal pattern with greatest values following periods of warm, dry conditions as DOC can accumulate within the peat pore water, and is then flushed out by water movement through the peat (Chapman *et al.*, 2010). POC on the other hand, is much less frequently measured, but breakdown of POC further downstream may contribute to DOC and stream degassing (Palmer *et al.*, 2016).

1.3 Hydrology of blanket bog

The hydrology of blanket bog is strongly influenced by its capacity to hold water and its formation on impermeable substrates, restricting drainage losses to deeper layers. Depending on the density of vegetation cover in blanket bog, some raindrops will be intercepted and used directly for plant respiration (transpiration). Figure 1.2 shows when rain reaches the ground it may, depending on slope characteristics, either directly evaporate from the peat surface to the atmosphere, or leave the system via surface runoff and throughflow in the peat mass. In the following sub-sections I further detail the inputs, outputs and storage components that characterise the hydrology of blanket bog systems before summarizing their part in a water budget approach.

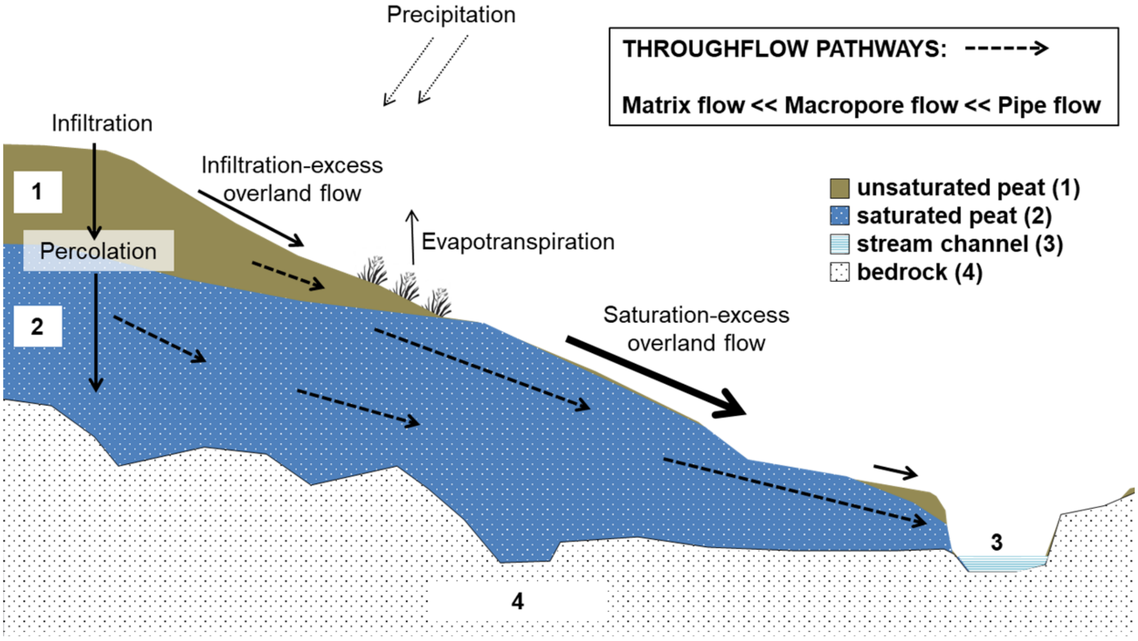

Figure 1.2 Schematic overview of hydrological pathways in blanket bog, detailing precipitation, infiltration, percolation, evapotranspiration, and infiltration-excess overland flow occurring over unsaturated peat, and saturation-excess overland flow occurring over saturated peat. The components of throughflow (pipeflow, macropore flow, and matrix flow) are ranked on the basis of the magnitude of their expected contribution to total drainage of the peat system to the stream channel.

1.3.1 Inputs – Precipitation

Blanket peatlands in the Northern Hemisphere are usually found in wet and humid geographical locations, normally with no sustained dry season. Within the bioclimatic envelope of boreal peatlands, blanket bog tends to form under the warmest and wettest conditions (Wieder *et al.*, 2006). For the UK, the number of days with rainfall is considered a key factor in explaining the distribution of blanket bog, even more than temperature (Lindsay *et al.*, 1988), with variation in annual rainfall mostly relating to altitude, with annual sums of > 2000 mm yr^{-1} at higher elevations (Holden and Rose, 2011). The net input of water to an ombrotrophic peatland is strongly linked to the balance between rainfall and evapotranspiration (evaporation of the peat + transpiration of vegetation), and therefore vegetation cover and species survival of peat-forming plants play a crucial role in determining water supply for blanket peatlands (Clark *et al.*, 2010).

1.3.2 Water storage – in the water table, unsaturated zone, and bog pools

Where the unsaturated and the saturated peat meet is referred to as the phreatic surface or the water table. The fluctuation of its depth below the surface may vary seasonally, depending on the local properties of peat, its structure and column depth, and the amount of preceding precipitation (Holden, 2009b). In intact blanket bog, the water table is either above or within 5 cm of the peat surface for >80 % of the year (Evans *et al.*, 1999), indicating blanket peats retain large quantities of water (90-98 % water by mass in saturated zones, and up to 95 % above the water table), even during dry periods, leaving little room for storage of fresh rainfall (Holden and Burt, 2003). Hence when it rains there is little space for water storage and so for intact systems perhaps as much as 80 % of rainfall will leave the system by saturation-excess overland flow, and its chemistry is characterised by a mixture of fresh rainwater and water that has been briefly inside the peat (Holden and Burt, 2003). Once the water-table depth drops more than a few centimetres below the surface, the peat appears able to retain its water without allowing any further free drainage. This means that during dry periods in pristine peatlands, water-table depth is controlled by clear diurnal patterns in evapotranspiration with very little change during night time hours (Evans *et al.*, 1999; Gilman, 1994). Water that cannot readily infiltrate may pond in small depressions and form larger bog pools. Bog pools represent a key interface between a C rich terrestrial system and an aquatic system and represent a potential hotspot for organic matter processing. Yet data that enable the extent of this process to be quantified are sparse (Pelletier *et al.*, 2015).

1.3.3 Outputs – Overland flow, Throughflow, and Evapotranspiration

Due to the limited water storage capacity of blanket bogs, water leaves the system predominantly via atmospheric, surface and subsurface pathways. Climatological parameters, the terrain, water-table position and vegetation (composition and cover) control water losses to the atmosphere via evapotranspiration. Any given soil has a maximum rate at which the soil can absorb falling rain when it is in a specified condition (infiltration capacity). As peat soils become saturated, with continued precipitation input, infiltration capacity reduces to a minimum, constant level. When the rainfall intensity is greater than the infiltration capacity (volume infiltrated per time unit), infiltration-excess overland flow may occur (Horton, 1945). When the soil profile is completely saturated, rainwater cannot be accommodated anymore, which results in 'saturation-excess overland flow' (Kirkby and Chorley, 1967). At the foot of hillslopes saturation-excess overland flow can also occur when it is not raining, by infiltrated water from upslope that returns to the surface or lateral soil water movement, causing the soil to become saturated. Any extra water is then forced out onto the surface to become saturation-excess overland flow. The main difference between the two overland flow types is related to their water flow paths. For infiltration-excess overland flow, all the water is fresh rainwater that has not been able to infiltrate in the soil, whereas saturation-excess overland flow is often a mixture of water that has been inside the soil (return flow) and fresh rainwater reaching the hillslope surface. As a result, differences in water chemistry may occur between the two types of overland flow, but for blanket peats this is not typical due to its ombrotrophic nature and soil contributions to surface runoff orginate mostly from the first 5 cm of the peat matrix (Holden and Burt, 2003). With the water table level sitting frequenlty close to the surface, storm runoff in blanket bogs is dominated by saturation-excess overland, even at very low rainfall intensities (Holden and Burt, 2003).

There are three different ways in which water can move through the peat body (throughflow) and this affects the timing of the water delivery to the river channel: matrix flow, macropore flow, and pipeflow. Whereas matrix flow is a relatively slow and even movement of water and solutes through the remaining open pores between soil particles, macropore flow refers to an uneven and often rapid movement of water and solutes that bypasses the soil matrix through soil cavities above capillary size (>1 mm in diameter). Pipeflow is an advanced from of macropore flow and has been found to occur in continuous connected voids with diameters > 10 mm. The mechanism that controls pipeflow and determines the extent, continuity and expansion of the conduits it flows through is generally referred to as piping (Jones, 1981).

Thresholds with regard to macropore flow are thought to exist with regard to rainfall intensity and antecedent soil moisture. That means: if the soil is too dry, or rainfall too light, then any flow which finds its way into macropores is rapidly absorbed into the soil peds (see, for example, Jones *et al.*

(1993)). Macropore flow measured in northern UK blanket bogs accounted for approximately 36 % of flow in *Sphagnum*-covered peat (Holden *et al.*, 2001), and at least half of the macropore flow occurred in the first 5 cm of soil, which proportion decreased to a minimum of 13-22 % at 20 cm below the surface. Infiltration tests on bare, *Calluna*-, *Sphagnum*-, and *Eriophorum*-covered blanket peats demonstrated that macropore flow decreases with increasing distance from the surface (Holden, 2009a). Where peat becomes cracked because of root growth and desiccation (Burt and Gardiner, 1984), and in combination with frost-heave it is hypothesised that hotspots may form for macropore flow. The expanse of erosion and increase of local flow as a result of it may lead to sapping, and internal erosion, allowing macropores to grow to more permanent and physically stable constructs as soil pipes, that provide continuous lateral and vertical connection in the peat for transport of water and solutes. Natural soil pipes have been shown to contribute 9 % to 36 % of streamflow in near-intact blanket peat (Holden and Burt, 2002b; Holden *et al.*, 2006; Smart *et al.*, 2013).

On an annual basis, for upland blanket peatlands in the UK, the proportion of rainfall that is converted into runoff (runoff coefficient) is often in the range of 50 – 80 % (Acreman and Holden, 2013; Evans *et al.*, 1999; Holden *et al.*, 2017). Thus, evapotranspiration represents between 20 and 50 % of total annual rainfall. While the evapotranspiration component is thought to be the dominant control on water-table drawdown in intact systems, this is less certain in degraded systems (Holden *et al.*, 2011).

1.3.4 Water budget of blanket bogs

In summary, the water budget of a blanket bog can be characterised by the following formula:

$$\boldsymbol{Inputs(P) = Change\ of\ Storage(G, U, R) + \ Outputs(OLF, TF, E)} \qquad 1$$

where *P* is precipitation, *G* the change of storage in the saturated peat (below the water table), *U* the change of storage in the unsaturated peat, *R* the change of surface storage in bog pools, *OLF* is overland flow (infiltration-excess and saturation-excess), *TF* is throughflow (matrix flow, macropore flow, and piping), and *E* the evapotranspiration by vegetation and the peat.

1.4 Piping

Piping is a common soil process which interacts with surface soil erosion processes (i.e. sheet, rill, ephemeral gully erosion and gully erosion) and has been recognised as an important factor in the formation of channel networks and slope instability (Bernatek-Jakiel and Poesen, 2018). Piping occurs in natural environments, e.g. in hillslopes (Verachtert *et al.*, 2012), in gully networks (Frankl *et al.*, 2012), and in alluvial plains and fans (Zhang and Wilson, 2013), but also in anthropogenic environments at the interface of subsurface structures of road drainage systems (Parker and Jenne, 1967), in and around earth dams (Richards and Reddy, 2007), in levees along rivers (Beek *et al.*, 2010), and in agricultural terraces (Tarolli *et al.*, 2014). In a recent review, Bernatek-Jakiel and Poesen (2018) determined that soil piping occurs in 69 % of all soil types recognised by the FAO (IUSS Working Group, 2007), with three soils being particularly prone to piping in Europe: Xerosols (Calcisols), Luvisols, and Histosols (i.e. peatlands).

Parker (1963) suggested piping occurred in the presence of four main factors: (i) enough water to saturate some part of the soil or bedrock above base level; (ii) sufficient hydraulic head to move the water through a subterranean route; (iii) the presence of a permeable, erodible soil or bedrock above base level; and (iv) an outlet. Jones (1981) later described the occurrence of soil pipes as the result of mechanical rather than solutional erosion, and denoted it as ‘pseudokarst’. While initiating factors tend to vary in different locations (Jones, 1981), the prevalence of soil pipes often reflects the critical interaction of local climatic conditions, soil characteristics, and hydraulic gradients (Bryan and Jones, 1997).

Beyond the requirement for sufficient availability of water in the soil matrix, be it from rainfall, temporal surface storage in pools, or ground water, Jones (1981) stated that for piping to occur both periods of desiccation and intense rainfall are needed. Wetting and drying cycles both play an important role in structural collapse of soil exposed to evaporative drying and the formation of shrinkage cracks (Faulkner, 2006). Once shrinkage cracks have established, subsequent turbulent flow within the cracks may enlarge them. For areas without steep slopes, Jones (1981) suggested that piping initiation would still be possible if a plentiful supply of water is available, possibly seasonally, and steep hydraulic gradients can develop at adjacent free-faces or gully walls.

Soil pipes are often reported to develop at significant subsurface textural discontinuities in ‘duplex’ soils or horizons of contrasting texture, where differences in swell and shrinkage capacity limit throughflow and pipe development to specific horizons (Wilson *et al.*, 2017). Additionally, the occurrence of a permeable stratum underlain by impermeable strata is often reported as a requirement for piping (Hagerty, 1991). Certain topographical settings also limit infiltration towards the pipe, i.e. limiting the surface of the pipe radius at which infiltration takes place, via the soil matrix or via macropores (Cunliffe *et al.*, 2013). Due to the covert nature of piping, considerable emphasis has been placed upon conceptualization of piping development in the literature (Hagerty, 1991; Jones, 1981; Parker, 1963), which has resulted in three different concepts being proposed, which may link to each other, but their occurrence may vary in different environments.

A first concept involves sediment entrainment through liquefaction promoted by seepage forces sufficiently large to overcome drag force in porous soils (Hagerty, 1991), resulting in backward erosion forming a subsurface conduit that works back from an outflow point of concentrated seepage (Fox and Wilson, 2010). However, the source of the seepage water need not be constant since the mechanism can operate intermittently, and the seepage water may vary in origin.

A second concept describes the expansion of established seepage paths, in which, under a sufficient hydraulic head, initial water flow causes further failure of the soil matrix along the channel walls. As a result, the conduit grows to a cylindrical shaped “pipe” and its increased radius allows for increase in discharge and transport of entrained soil particles to a distinct exit point in the seepage zone (internal erosion). Established pipes can form complex, branching, three-dimensional networks (Holden and Burt, 2002b), but may vary in hydrological connectivity due to temporal blockages (Zhu, 1997). As long as a pipe outlet exists, mobilised sediment can continue to be removed from the pipe network, and the high suspended sediment load in pipe water may be transported to local water courses, or can form a local sedimentation zone (pipe fan) downslope of the pipe outlet due to settling of the eroded material on the peat surface (See Figure 1.3a and c).

The third concept details, what Heede (1976) described as the final stage of piping, the ultimate collapse of the pipe roof under its own weight, leading to subsidence of the soil body above the pipe, which in cases of complete failure, opens up the interior of the pipe so that its walls are fully exposed. The latter would allow influx of surface runoff which increases the propensity of internal erosion to further widen the intact pipe sections downslope of the collapse (See Figure 1.3 b and d).

Various attempts to characterise natural pipeflow by using classic fluid dynamics and sediment transport models for pipeflow such as Bernoulli’s principle (pressure differential), Chézy’s formula (channel dimensions), and the Darcy-Weisbach equation (friction), evidence the complexity of their dynamics (Wilson *et al.*, 2017). Natural soil pipes deviate from the classic model pipes as pipe walls are considered pervious, and acting seepage forces may form a factor in particle detachment inside the pipe. However, assuming velocity in pipes is the product of an infinite supply of water, the velocity in a pipe is the driving force of wall shear stress, and therefore any increase in flow velocity as result of descending pipe bends, may lead to pipe wall erosion, and thus pipe enlargement. Where such conditions are met, albeit temporal,the radius of a macropore / pipe would become directly related to the velocity it may convey. Based on this theory, Wilson *et al.* (2017) stated that the degree to which pipeflow increases as pipes enlarge depends upon the water source, i.e. whether flux-controlled (e.g. runoff is intercepted by pipe collapse) or head-controlled (e.g. pipe enlarges through hydraulic gradient). If the boundary conditions are such that the flow in the pipe does increase, it would result in an increase in mean velocity, leading to an increase in erosion rate and rate of pipe enlargement, which in turn would allow larger volumes of water to pass through the pipe network. In general little is known about wetting patterns in soil pipes during stormflow in relation to their diameter, but for pipes in blanket peats links do exist between the location of pipes in the peat profile and the origin of pipe water (Cunliffe *et al.*, 2013; Holden and Burt, 2002b).

Figure 1.3 Surface expressions of soil pipes in peatlands: a. vent hole in vegetated area with sediment fan, b. pipe roof collapse under bare peat surface (pipe at substrate interface, notice rock fragments in pipe channel), c. pipe outlet within peat with sediment fan, d. pipe collapse under vegetated surface (1 m deep).

Given the complexity of piping and interlinked processes involved, the term “piping” is often used to refer collectively to the related processes, including suffusion (translocation of fines through the soil matrix without the soil volume changing), sapping (concentrated seepage erosion), heave and subsidence, backward erosion, and internal erosion (Bernatek-Jakiel and Poesen, 2018; Bryan and Jones, 1997; Wilson *et al.*, 2013; Wilson *et al.*, 2017). A common feature in those processes is the transport of water and/or solids in the subsurface causing the formation of linear voids (pipes) sufficiently large for water to further sculpt its form in soils or in unconsolidated or poorly consolidated sediments (Jones, 2010). The expanse of such voids and their connectivity drive subterranean erosion (Mears, 1968). It should be noted that piping involves not only water erosion processes driven by excess shear forces, but similar to gully erosion it also interacts with mass movement processes (e.g.

wall and roof collapses driven by gravity) (Heede, 1976). Because failure of soil pipes is usually undetected, its legacy in gully formation is often overlooked, but the number of studies reporting piping being involved in gully formation is increasingly recognised (Archibold *et al.*, 2003; Faulkner, 2013; Swanson *et al.*, 1989; Verachtert *et al.*, 2010). It has been shown that subsurface flow can contribute to tension failure due to the seepage force exceeding the soil shear strength or undercutting by seepage erosion, thereby promoting soil instability in earthen embankments (Fox and Felice, 2014). Occurrences of natural soil pipes in streambanks has been noted particularly in alluvial soil deposits where the natural layering associated with alluvium favours concentration of flow in more pervious strata, and more cohesive layers tend to bridge over cavities, allowing conduits to form (Hagerty, 1991).

1.5 Piping in peatlands

In peat deposits, pipes have been shown to occur at a variety of depths within the peat profile, connecting shallow and deep sources of water, and conveying gases, solids, and solutes (Billett *et al.*, 2012; Chapman *et al.*, 1993; Dinsmore *et al.*, 2011; Holden and Burt, 2002b; Holden *et al.*, 2012a, 2012b; Jones, 1997). The following sub-sections will detail piping processes in peat, before describing the type of pipes that occur and how these pipes form complex networks through the peat profile. Finally, I will describe how pipes can be identified from the surface, with a focus on pipe outlets.

1.5.1 Piping processes in peat

The mechanism that governs pipeflow is complex, especially in a deposit as peat, where transport of water in the subsurface is foremost a function of the deposit itself rather than rainfall characteristics only. As such, water movement in peat is governed by the availability of pore space. Pores in peat are pockets filled with water and air, trapped between decomposing organic matter and resistant organic matter (humus). The total volume of these pore spaces is therefore dynamic, but forms the primary porosity of the peat. The water fraction in the pores forms a soil solution. The velocity at which the soil solution moves through pores is governed by the geometry and continuity of these pore system, and the influence of gravity and differences in pressure between neighbouring pores. Initiation and continuity of flow of the soil solution (macropore flow) requires a supply of water exceeding all losses of energy to the soil matrix (Beven and Germann, 1982). The flux of this flow phenomenon can be expressed as the hydraulic conductivity K.

Where peat is saturated, hydraulic conductivity is at its potential maximum, Ks. However, above the water table, aeration of the peat promotes peat humification, which may lead to a decline in pore sizes as spaces between larger fragments of plant material decrease when broken down into amorphous peat (Rezanezhad *et al.*, 2016). In turn, a reduction in the inter-particle pore spaces increases the mass of dry material per volume of peat (Bragazza *et al.*, 2013; Moore *et al.*, 2005) and therefore the bulk density also increases. As a result, increased bulk density may reduce hydraulic conductivity as pores collapse (Holden *et al.*, 2014b; Rycroft *et al.*, 1975). Conversely, desiccation cracks and enlargement of macropores as a result of shrinkage allow for increased flow (Mustamo *et al.*, 2016) increasing the potential of hydraulic conductivity.

Due to ongoing biological processes and water-table fluctuations the volume of connected pores that support effective transport, in other words the effective porosity, changes continuously both spatially and through time. With increasing depth, peat density may increase from < 0.03 g cm^{-3} near the ground surface to > 0.15 g cm^{-3} at a depth of 35 cm (Quinton *et al.*, 2000). Links between macroporosity and hydraulic parameters, do not only depend on bulk density, but also on botanical composition of the peat (Liu and Lennartz, 2019). Wang *et al.* (2021) concluded that bulk density and soil organic matter in peat are spatially dependent for both intact bog and degraded fens, whereas *K*s and macroporosity are spatially independent if the peat is severely degraded.

Although the primary porosity of peat is generally stable, the effective porosity of peat will continue to decrease in time without the formation of a 'secondary porosity'. Secondary porosity is produced by fractures, fissures, or other soil deformations, and compensates for loss of the effective porosity. The most common processes involved in secondary porosity are piping, subsurface water storage, and ebullition of gasses (Chen and Slater, 2015). The variability of secondary porosity with depth in peat inspired a widely discussed theorem that peat also behaves as a duplex system, with two distinctive layers with contrasting hydraulic properties. One layer, the acrotelm, would include a network through which water, solutes, and colloids move relatively easily in large pores (Hayward and Clymo, 1982), while the other, the catotelm, consists of an immobile body with negligible fluid flow velocity in smaller open pores (Hoag and Price, 1997). However, unlike duplex soils, peat is a heterogenous deposit, and as result deeper peat layers can be as highly permeable as near-surface peat (Baird *et al.*, 2016). Despite the demonstrated presence of pipes in peat deposit, connecting shallow and deep peat layers hydrologically (Holden, 2004; Holden and Burt, 2002b), inclusion of piping in flow theory of peatland systems seems still limited and requires further attention, particularly where pipe networks are active contributors to discharge and erosion.

Weathering processes such as desiccation during summer months and frost action during winter months play an important role in supplying erodible peat particles for fluvial transport (Evans *et al.*, 1999; Francis, 1990; Holden and Burt, 2002a; Li *et al.*, 2018a; Li *et al.*, 2018b; Shuttleworth *et al.*, 2017). Taring of the surface by desiccation cracking may enhance water percolation to deeper peat layers, and in turn diversity humification processes influencing the effective porosity. Francis (1990) noted that frost heave preferentially affects previously loosened peat; so any peat that has already been affected by desiccation may be at further risk of erosion. However, little is known about how these processes play a role in pipe formation, or interlink with pipe erosion in peatlands.

1.5.2 Pipe types in peatlands

In peatlands, two end-member types of pipes are recognised as shown in Figure 1.4: 1) pipes that form at the base of the peat profile, sometimes in bedrock channels; or 2) pipes that occur within the peat profile itself. Pipes at the bedrock interfacemay be up to 1-m diameter (Beven and Germann, 1982) and are hypothesised to develop after peat has overgrown existing surface runoff channels sufficiently in time to cover the channel. Pipes within the peat profile itself are thought to form as a result of desiccation cracking during uncommon dry summers (Gilman and Newson, 1980), or from plant roots such as Calluna (Holden, 2005b).

Heede (1976) proposed that pipes may disconnect from the surface at a young age, but resurface when they have grown old. As a result of their growth, their diameter would not sustain the full support of their roof, with roof collapse occurring as a result, and then possibly leading to gully formation (Bower, 1961). Pipes that sit at the bedrock interface have been shown to survive over long periods of time and to conduct considerable amounts of runoff during storms (Gilman and Newson, 1980). Pipes within the peat profile often form complex and irregular network connections across hillslopes (Holden and Burt, 2002b). Another way of classifying pipes is in relation to their flow regime: (i) perennial flowing (continuous) or (ii) ephemeral flowing (responds only to storm events and therefore discontinuous) (Jones, 1981). Carling (1986) described gullies at the blanket peat slopes of Noon Hill, in the northern Pennines of England, to be associated with active head-cutting into large perennial pipes up to 1 m diameter, and smaller ephemeral pipes occurring alongside mass movement features such as terracing, flush-filled cracks and seepage scarps. The pipes showed surface expressions similar to pseudokarst, such as blow holes and extensive collapses.

Figure 1.4 Typical examples of the outlets of two types of pipes: a) pipes that sit at interface of peat and bedrock and b) pipes that sit within the peat .

1.5.3 Pipe networks in peatlands

Piping has been reported in peats across the world, including subarctic continental peats of Canada (e.g. Price (1992), Gibson *et al.* (1993), Carey and Woo (2000)), New Zealand peat (e.g. Mark *et al.* (1995), and Rapson *et al.* (2006)), and in oceanic boreal peats of Norway (Norrström and Jacks, 1996), Ireland (Thorp and Glanville, 2003), and the UK (Holden, 2005a). Sites that are conducive for piping may differ topographically but are generally characterised by either a high gradient for water flow, or soil characteristics that promote water flow in defined paths (Jones, 1981).

In blanket bog, pipes were found within the peat itself (36 %), but also at the interface between the peat and the underlying substrate (56 %), or within the substrate itself (8 %) (Holden, 2005a). Spatial variability of pipe prevalence is supported by findings of more pipes in deep peat top- and foot slopes than in shallow but uniform structured peats on mid-slope areas (Holden, 2005a). In blanket bog, some soil pipes are over 150 m long (Holden *et al.*, 2002).

Transects across 160 blanket peatland catchments in the UK showed that pipes occurred at a mean density of 69.2 per km of Ground Penetrating Radar transect (Holden, 2005a), but their extent, and frequency may vary with the degradation state of the peatland (Holden, 2004; Holden and Burt, 2002b; Holden *et al.*, 2002). Holden (2005a) found that ditched hillslopes (n = 171; 127.4 km^{-1}; standard error 6.2) had markedly higher pipe frequency per km (about twofold), than non-ditched sites (n = 789; 56.6 km^{-1}; standard error 2.0), independent of slope position context. Also, piping frequencies (pipes km^{-1}) on drained land across the UK increased linearly with the age of the drainage system (Holden, 2006). Furthermore, in the same study mean pipe diameter on undrained slopes (11.6 cm; standard error 0.6 cm) was significantly lower than that on drained slopes (15.9 cm; standard error 0.8 cm). However, it is not known whether the greater pipe frequency in drained peatland results in an increase in river flows, or associated aquatic carbon fluxes.

Pipe networks often form at points where stress is exerted on the peat (Gilman and Newson, 1980) by desiccation (Evans *et al.*, 1999), or from plant roots. For instance, piping has been found to be more common where *Calluna species* were present compared to sedges and mosses (Holden, 2005b). Both desiccation cracking and remnant burrows of roots may promote forms of secondary porosity, and therefore support bypass flow in the subsurface, providing conditions for pipe formation. As a result, large proportions of organic and mineral material may be transported from the underlying substrate throughout the peat profile. It is thought pipes form direct links between bog pools, draining and feeding them via seepage zones (Holden and Burt, 2002b), providing a heterogenous biogeochemistry of the otherwise ombrotrophic peat, leading to varying water qualities across the moor, and in streams draining them (Holden, 2012).

1.5.4 Pipe outlets in peatlands

Another way of quantifying the presence of pipe networks in peatlands is by studying the number, shape and position of pipe outlets, which are predominantly observed on the peat margin, streambanks and/or close to the stream head / source. Pipe outlets form the drainage point of the pipe network, at which pipeflow is discharged back to the surface (Smart *et al.*, 2013), suspended sediments are deposited (Holden *et al.*, 2012b), and trapped air and gasses originating from infiltration and degradation processes can volatilise (Dinsmore *et al.*, 2011).

Pipe outlets can vary in size, shape and position in the peat profile and be either perennial (water runs from the outlet all the time) or ephemeral (water flows in response to storm events) in nature, and their characteristics may evolve over time (Holden *et al.*, 2012a). In intact blanket bog, Holden and Burt (2002b) reported pipe outlet diameters ranging from 3 to 70 cm. Pipe outlets with vertically-elongated cross-sections may be associated with active down-cutting, whereas horizontally-elongated outlets may demonstrate inhibited pipe floor erosion due to the presence of a less erodible soil horizon (Holden *et al.*, 2012a; Jones and Cottrell, 2007). In deep upland blanket peat in the Pennine Hills of northern England, pipe outlets were found throughout the profile of streambanks ranging from the interface with the underlying substrate at ~3 m depth to pipes which sat within a few centimetres of the streambank edge (Holden and Burt, 2002b). Whereas these results originate from studies on intact blanket bog, little is known about pipe outlet morphology in more disturbed peat, and whether similar processes account for similar pipe outlet characteristics.

Counting the total number of outlets over a set length of streambank is a measurement often used to indicate pipe outlet prevalence. The first study to pioneer this method reported on pipe outlets at streambanks of Burbage Brook, draining peaty podzols, in the Peak District. In that study, Jones and Cottrell (2007) found 184 pipe outlets km^{-1} over 3 km in 1968. A resurvey of a section of the same stream in 2003 reported 134 pipe outlet km^{-1} over 500 m of the streambank (Jones and Cottrell, 2007). Using this method, Holden (2005a) reported a pipe outlet frequency of 19.7 km^{-1} of streambank across 160 blanket bog sites in the UK. Other studies on piping frequency, reported values from Welsh catchments of 36 km^{-1} and 56 km^{-1}, respectively, for Cerrig yr Wyn and Nant Gerig (Gilman and Newson, 1980) and 80 km^{-1} for Afon Cerist (Jones, 1975). The Welsh studies showed pipe outlets were commonly disconnected from the stream and were found at breaks of slope on the hillside often coinciding with changes in soil type (Jones and Crane, 1984), and at the base of the organic soil horizon (Chapman *et al.*, 1993). Pipe prevalence on streambanks in deep peat catchments in the north Pennines include, 9.5 km^{-1} at Little Dodgen Pot Sike (Holden and Burt, 2002b), and 36.6 km^{-1} (August 2007) and 31.7 km^{-1} (April 2010) at Cottage Hill Sike (Holden et al., 2012a). However, the reported values for frequency of piping at streambanks in Welsh and North Pennines uplands were often based on sample extrapolation, rather than elaborate field surveys covering the full length of the respective streambank length. Standard methods for the assessment of pipe frequency across piped landscapes seems poorly developed, and require further research.

1.6 The functioning of pipe networks in blanket peatland catchments

1.6.1 The contribution of pipeflow to streamflow in blanket peatland

Pipe networks can contribute markedly to streams in terms of flow. For histic podzols of the Maesnant catchment in mid-Wales, 49 % of streamflow was produced by soil pipes (Jones and Crane, 1984). Research in a 4 ha headwater catchment of the River Wye in mid-Wales, showed that pipes could contribute 3.3 to 32.2 % to the maximum stream discharge during rainfall events, with a mean of 10 % (Chapman, 1994). It was suggested by Jones (1997) that in some catchments the pipe network can drain an area 10 - 20 times greater than that of surface runoff and near-surface flow pathways. Pipes therefore have the potential to deliver water, solutes, dissolved gases and sediment directly to the stream network from more remote areas of the peatland, which would be considered disconnected under the traditional view of peatland hydrology.

At Cottage Hill Sike, a 17.4 haintact blanket bog catchment of the northern Pennines of England, pipes have been found to contribute between 10 – 30 % to streamflow (Holden and Burt, 2002b; Smart *et al.*, 2013) and provide good connectivity between deep and shallow peat layers (Billett *et al.*, 2012). However, little is known about feedback mechanisms that control continuity of pipeflow, and how and when pipes may interconnect different parts of the peat, or connect to each other.

Work on the Maesnant catchments (Wales, UK) in the early 1980s reported pipes to respond at different times during the same storm event and these different times also varied from event to event, depending on antecedent wetness and the intensity patterns of storm rainfall, on average the pipe ensemble responds in sync with the stream (Jones, 2010). Smart *et al.* (2013) monitored discharge of eight pipe outlets at Cottage Hill Sike and found that pipeflow hydrographs had characteristic steep rising and falling limbs, but varied in peak lag times. On average, flow from pipes peaked later than that observed in the stream, but often had longer recession limbs. . Smart *et al.* (2013) concluded that pipeflow mainly accounted for inter-storm flows at Cottage Hill Sike. These findings suggest that pipe-to-stream connectivity differs between wet and dry periods. While soil pipes may contribute significantly to streamflow, little is known about the interaction between piping as a process, pipeflow generation, and the water table in blanket peatlands, providing new avenues for further research.

1.6.2 Aquatic carbon transport from pipe networks in blanket peatland

Estimates of fluvial organic carbon fluxes for streams draining peatlands can differ markedly between sites with different degradation state (Shuttleworth *et al.*, 2015), but mechanisms to explain this variation is lacking. It is thought that the majority of fluvial carbon removed by streams orginates from degraded surfaces, but the pipe network as a source of carbon removal is often not considered in peatland erosion budgets.

Pipe networks are often considered dynamic systems with a varying extent over time. That means, if the flow through it ceases for a certain reason, the affected section may become prone to clogging, due to sedimentation in the pipe channel (Wilson et al., 2017). In blanket peatland, pipe surveys by Holden et al. (2012a) have shown that pipe outlets can change in shape, become dead ends and disappear, or new outlets appear over time. The contribution of pipe networks to the export of organic and inorganic sediments to blanket bog streams should therefore also be considered dynamic in nature. In addition, isotopic measurements in DOC and POC uncovered that the age and source of carbon released from peat pipes into the drainage network, in particular from POC is highly dynamic in space and time (Billett et al., 2012). Provided that decomposition rates differ across the depth profile of a peat deposit due to its wetted nature, it is expected that pipes transport an array of concentrations of DOC and POC, but few studies included monitoring on both forms at the same time, and none of them included degraded blanket bog sites.

The only publication to date that has analysed the DOC and POC concentratrations of pipe water and quantified the DOC and POC flux from pipes for a blanket bog stream is written by Holden *et al.* (2012b). For a near-intact blanket bog in the Northern Pennines of England they found that both DOC and POC concentrations displayed a wide range of concentrations; ranging between 5.3 and 180.6 mg L^{-1} for DOC and 0.08 and 220 mg L^{-1} for POC. They also found that the contribution of pipe water DOC and POC flux to the stream C flux varied between pipes; from between 80.0 % and 91.2 % for DOC and between 3.6 % to 17.1 % for POC. They also showed, when pooling data from four ephemeral and four perennial pipes, that mean DOC concentrations were similar between the two pipe types (30.5 and 27.9 mg L^{-1}, respectively), whereas the mean POC concentration of the ephemeral pipe water was more than twice that of the perennial pipes (5.4 and 2.2 mg L^{-1}, respectively). Together the eight monitored pipe outlets accounted for 2.1 % of the stream DOC flux and 5.2 % of the stream POC flux at the catchment outlet, but with larger annual fluxes for DOC (51.8 - 63.4 g m^{-2} yr^{-1}) than for POC (2.4 - 3.0 g m^{-2} yr^{-1}) (Holden et al., 2012b). For the year 2010, Holden et al. (2012b) estimated that, when scaling up to the 84 pipe outlets (60 ephemeral and 24 perennial) observed across the Cottage Hill Sike catchment, the pipes could be responsible for an estimated 20 % of the DOC flux and 56 % of the POC flux that leaves the catchment in streamflow, provided there was no storage in the stream bed and banks or loss to the atmosphere. Similar assessments have not been carried out on more degraded blanket bog sites. In that context, more work needs to be done to understand when and how pipes transmit DOC and POC to streams in degraded blanket peatland.

1.6.3 Blanket peatland degradation and restoration

Human activity in peatlands has introduced increasing pressure on their ability to deliver multiple ecosystem services. For example, in the UK, a large fraction of the blanket peatlands has been artificially drained to lower water tables in response to increased demand for livestock grazing, the management of grouse shooting estates (Holden *et al.*, 2006), and more recent infrastructural projects and windfarms (Holden, 2005a). However, drainage of peatlands is known to increase aerobic decomposition of peat as a result of lowered water table (Holden *et al.*, 2011) resulting in an increase in CO_2 loss to the atmosphere as well as increased leaching of nutrients (Evans *et al.*, 2021; Holden *et al.*, 2004), changes in the peat structure (Holden *et al.*, 2006), and changes to vegetation composition (Bellamy *et al.*, 2012; Ward *et al.*, 2007). Burning, grazing, and atmospheric pollution are associated with changes to peatland vegetation composition and reduced cover of key species, including *Sphagnum* (Bragg and Tallis, 2001; Noble *et al.*, 2018; Parry *et al.*, 2014; Smart *et al.*, 2010).

The major impacts of fire are destruction of living biomass, plant litter and surface peat, leaving bare peat patches behind, but this also causes hydrological change (Holden *et al.*, 2015; Holden *et al.*, 2014b). Where vegetation cover is lost, exposure to wind, rain, and water flow pose a serious threat to maintain the accumulated carbon stock (Pawson *et al.*, 2012; Roulet *et al.*, 2007). With an increase of bare surface area, peatlands lose their function as a filter to adjacent aquatic ecosystems leading to a release of stored carbon and trapped pollutants, such as heavy metals (Rothwell *et al.*, 2005). Also, without the protective vegetation cover, desiccation and subsequent rewetting events form new hazards for carbon loss from peat (Armstrong *et al.*, 2010; Wallage *et al.*, 2006). In an attempt to recover the ecosystem services provided by peatlands, restoration projects have increased since the 1990s (Bonn *et al.*, 2016).

1.7 Restoration of degraded blanket peatlands

1.7.1 Common restoration methods

Increasingly, peatland restoration projects aim to deliver multiple benefits, such as the stabilisation of eroding peat, enhancing carbon sequestration, reduced downstream flood risk, and remediation of poor water quality downstream of peatlands (Parry et al., 2014). Typically blanket bog restoration techniques target both geomorphic (e.g. peat pans and gullies) and more direct human intervention features of degradation (e.g. ditches), but most studies assessing their impact mainly focus on one at a time.

Shuttleworth *et al.* (2019) presented the first experimental assessment of the impact of blanket peat restoration on catchment runoff using revegetation and gully blocking in the South Pennines (UK). Storm hydrographs derived from the outlets of three micro-catchments showed revegetation treatments can increase lag times (106 % increase relative to the control) and reduce peak flows (27 % decrease relative to the control). With the addition of gully blocking the effect almost doubled; lag times increased by a further 94 % and peak flows reduced by an additional 24 % relative to the control (Shuttleworth et al., 2019).

Many different techniques are used for ditch blocking, including permeable (e.g. peat turves, heather bales, stone piles) and impermeable blocks (plastic piling, corrugated Perspex, plywood dams). Whereas impermeable blocks aim to retain water upstream of the block as much as possible, permeable blocks allow flow to seep through and aim to decrease flow velocities, trap sediment and eventually result in drain infilling (Armstrong et al., 2009). Factors that can impact the success of ditch blocking included amongst others the drain geometry, drain slope, and alignment of dam on the drain floor. Sometimes ditches are “reprofiled” by moving peat from ditch sides into ditch channels to reduce the sidewall gradient, the result being a much shallower channel on which vegetation cover can develop (Parry et al., 2014). Holden et al. (2017) suggest that dam failure due to subsidence or high seepage forces associated with the large hydraulic gradient in repacked peat dams, promoted cracking and piping, and so provided new routes for water to bypass and enhance subsurface pipe connectivity associated with ponding in ditches.

1.7.2 Options to reduce pipeflow in peatlands

Although pipe outlet blocking is mentioned as a potential restoration technology by Parry *et al.* (2014), there have been limited trials (Holden *et al.*, 2014a). Therefore, in the following section, I first draw on examples from the literature that use a variety of methods to moderate pipeflow in the laboratory and field for other soil types, before discussing options used in peatland environments.

The influence of piping and pipe clogging on slope stability has been tested in various laboratory settings. For instance, small-scale Hele-Shaw simulations by Pierson (1983) have shown pipe clogging to produce bulges downslope of the pipe-end that lifted the water table. It was previously thought that soil pipes could contribute to slope stability by increasing the rate of soil drainage and limiting the development of perched groundwater condition (Pierson, 1983). When generalizing to field conditions, bulge formation downslope of pipe clogs was expected to form a marked risk for pipe-induced landsliding on steep natural saturated deforested slopes, with pipes parallel or sub-parallel to the fall line. Later laboratory experiments based on the same principle, showed higher flume-bed pore water pressures in the presence of pipes, compared to no pipes (Kosugi *et al.*, 2004). Pore-water pressures tend to increase mostly near the location of the clog in the pipe (Midgley *et al.*, 2013), and decrease gradually to the pipe outlet (Kosugi *et al.*, 2004). Similar processes were found in natural clay pipes. Uchida *et al.* (2001) observed an increase of pore-water pressure in the surrounding matrix when matrix saturation was higher than the pipeflow transmission capacity.

Various measures have been trialled to restore piping erosion in agricultural and urbanised settings. Areas with piping are often resurfaced with a humus rich topsoil after the eroded areas are infilled with compacted soil (Bernatek-Jakiel and Poesen, 2018), but the impact of this approach on hydrological and erosional processes both up- and downstream of the intervention area have not been well monitored. For instance, Frankl *et al.* (2016) reported on the successes of a subsurface geomembrane dam, placed across a dry Ethiopian gully, to reduce subsurface flow in soil pipes in the gully wall. They showed that the wetness of areas upslope of the dam increased, and the subsurface dam can be used to stabilise gully heads, but any effects of this intervention on downstream hydrology were not looked into.

As far as I am aware, only one grey literature report exists that reports on interventions to impede pipeflow in peatlands, which was summarised by Holden *et al.* (2014a). To investigate the contribution of pipeflow to water discolouration and dissolved organic carbon (DOC) release into streams, water quality was monitored around blocked and un-blocked pipes on Keighley Moor in northern England between June 2012 and October 2013. Pipes were blocked by inserting plastic piling perpendicular to the expected pipe course. DOC, water colour, conductivity and pH were not significantly different between un-blocked pipes and water flowing from areas where pipe blocking had occurred (Holden *et al.*, 2014a). In the same report, results of a before-after control-treatment experiment were presented for the Trout Beck catchment, a blanket peat site within the Moor House National Nature Reserve in northern England. Here, the areas around six pipes were monitored for water quality, pipe discharge, overland flow, and changes in the water table. Two pipe blocking methods were trialled: 1) vertical insertion of impermeable plastic piling, and 2) vertical insertion of perforated plastic piling. The perforated design had multiple 10 mm diameter drill holes, spaced at approximately 10 cm intervals across the entire face of the piling sheet. The perforations were developed to allow pipe water to pass through, but retard flow in such a way that sediment would slowly be trapped, infilling the pipe slowly. At four pipes out of six, blocks were placed perpendicular to the expected pipe course 8.5 months after the start of monitoring while monitoring continued on all six pipes for a further 3.5 months. Three pipes were blocked with impermeable plastic piling, while one pipe was blocked with the perforated design. Two pipes remained unblocked and acted as a control. Results showed that blocking of pipes did not cease flow from pipes. In fact, flow records from the pipe outlets showed that flow continued to occur from the area around the pipe outlet for all blocked pipes after blocking. The Moor House investigation indicated that the overall effects of pipe outlet blocking on water colour and DOC in the following summer were small (5 - 7 % decrease in absorbance between 254 and 400 nm, and 2 % decrease in DOC relative to unblocked pipes). There were large (40 - 117 %) local increases in colour and DOC in overland flow but decreases in soil water (7 - 10 %) relative to the areas around unblocked pipes. The water table upslope of one pipe blocked with impermeable piling sat markedly closer to the surface post blocking compared to that of unblocked pipes. It was suggested that any water quality benefits gained from this rise in water table upslope of the blocked pipe, was counterbalanced by lowered water-table depth downslope of the pipe blocks (Holden *et al.*, 2014a). While both studies monitored effects of blocking over short periods of time, there is a lack of studies addressing the impact of pipe blocking on peatland hydrology, streamflow and carbon export over the longer-term.

1.8 Main knowledge gaps

Piping and pipe networks have been demonstrated to form an important component in hydrological and erosional processes of blanket peatlands, but to date the majority of studies on piping in blanket bog originate from near-intact sites. In the wider context of the conservation of degraded blanket bog for its regulatory and provisional ecosystem services, including carbon sequestration, biodiversity, and water supply, it is essential to understand the potential role of pipe networks in restoration practice. While the link between gully formation and pipe outlet prevalence is increasingly confirmed in clay and loess soils (Archibold *et al.*, 2003; Faulkner, 2013; Swanson *et al.*, 1989; Verachtert *et al.*, 2010), evidence for such interlinkage is lacking in blanket peatlands studies. Most approaches to attenuate flood risk and restore water tables in degraded blanket peatlands involve gully blocking and or re-vegetation treatments but do not consider attenuation of pipeflow. Within this context, peatland restoration practitioners are keen to understand how flow and erosion from soil pipe networks impact on common peatland restoration techniques, and whether flow and erosion from pipe networks can be attenuated by direct interventions. However, current methods to measure pipe outlet prevalence are poorly developed, as they are often based on sample extraction rather than elaborate surveys. Therefore, any future assessment of pipe prevalence in blanket bog needs further development to arrive at transparent and comparable outcomes. Also, there is a clear lack of information on pipe prevalence in more degraded blanket bog, and whether controls on pipe outlet prevalence and pipe outlet morphology in intact blanket peat work similarly in more degraded blanket peatland.

While recent advances in pipeflow monitoring have given an appreciation of the hydrological and erosional responses of pipeflow in intact blanket bog and how pipe networks contribute to DOC and POC exports at the catchment scale, little is known about controls on soil pipe development, pipeflow and associated erosion processes, or its linkage to the surface drainage network in more degraded blanket peatlands. Although pipe outlet blocking has been proposed as a technique to attenuate flow and sediment output to peatland streams (Parry *et al.*, 2014), little is known about how best to block pipe outlets, or the impact of pipe outlet blocking on storm responses and related aquatic carbon fluxes at the catchment scale (Holden *et al.*, 2017; Lindsay and Clough, 2016; O'Brien *et al.*, 2007; Parry *et al.*, 2014). In addition, no direct measurements of POC loss from pipes have been reported in severely degraded peatlands, and so there is limited understanding of how the hydrological function of pipe networks might link to fluvial carbon export in peatland streams. Currently there is less information known about pipe prevalence, formation and dynamics in degraded systems compared to intact blanket peatlands and limited information about how to best attenuate the flow of water from pipe outlets as part of peatland restoration projects.

1.9 Research questions and objectives

1.9.1 Key questions

The overall aim of this thesis is to assess the role of piping and pipe blocking in attenuating streamflow and aquatic carbon fluxes in streams draining a heavily degraded blanket bog. As such, the thesis is based on a series of three main research questions and one cross-cutting question, as follows:

1. Where do pipe outlets occur in degraded peatland systems that are heavily gullied and how do their characteristics vary spatially?
2. What is the effectiveness of impeding pipeflow by pipe outlet blocking on the discharge hydrograph of pipe and streamflow?
3. What is the effectiveness of impeding pipeflow by pipe outlet blocking on the export of fluvial organic carbon at the pipe and catchment scale?
4. What are the implications of the findings for peatland restoration?

The three main research questions are addressed in separate Chapters 2 – 4, respectively, and discussed further in a final synthesis of the findings (Chapter 5). Question 4 is considered in each of the main research chapters and the final synthesis chapter.

It is expected that outcomes of this work would provide indications for whether impeding pipeflow by blocking pipe outlets is practicable and whether it results in a reduction in runoff, erosion and carbon export during peatland restoration programmes. It is also expected that the information made available in this thesis will provide an evidence base to support the development of model parameters for the piping process in hydrological and erosional prediction models for blanket peatlands.

1.9.2 Research approach

This research will complement earlier monitoring of the atmospheric, hydrological and sediment fluxes of a heavily degraded blanket bog, by providing new monitoring insights of the impact of piping and pipe outlet blocking on hydrology and water quality at the sub-catchment scale. Together with the MFFP (co-sponsor of the project) an observational approach was used to address the research questions by taking measurements and samples from the Upper North Grain (UNG) catchment, situated in the Peak District National Park in the south Pennines of UK (Figure 1.5). In preparation for instrumenting the monitoring site, all gully sections of the catchment were visited to identify the location of pipe outlets and possible locations for the installation of stream weirs. Question 1 was addressed by carrying out a transect survey to determine the location and characteristics of pipe outlets in the gully network of the catchment. Statistical analyses determined whether differences occurred within groups of spatial indicators derived from the collected data. Question 1 used a spatial dataset obtained from the pipe surveys in the catchment, which was coupled to spatial data derived from LiDAR data and aerial photographs of the catchment. In this way, the spatial links were drawn on pipe outlet characteristics, including outlet shape, aspect, stream bank slope, depth to the pipe roof, streambank height, relative position in gully, flow contribution area, and surface cover. Pipe outlet frequency was determined using a combination of the collected dataset and geometric analyses of LiDAR data.

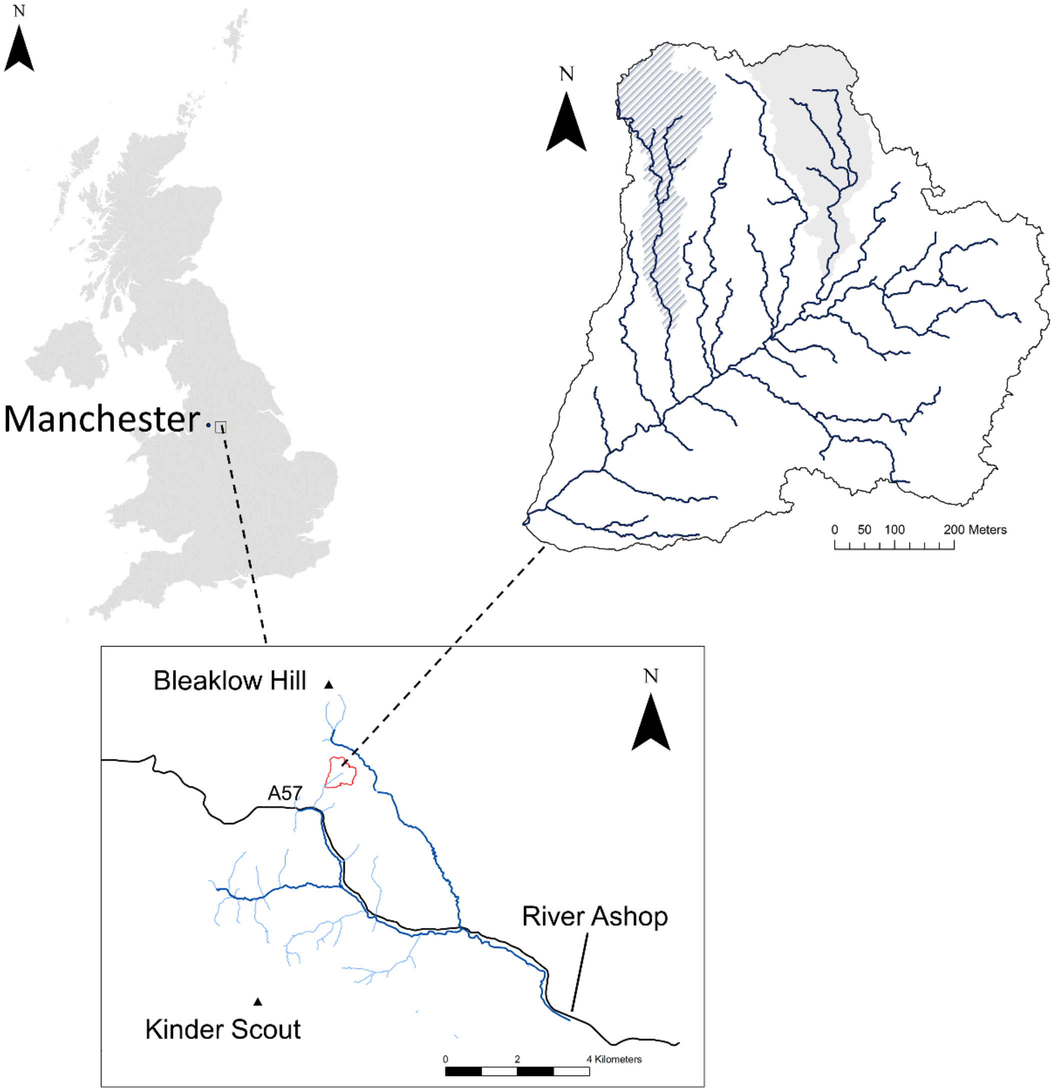

Figure 1.5 Location of study: top left – study catchment east of Manchester; bottom - the study catchment drains into the river Ashop, feeding into Lady Bower Reservoir; top right: catchment Upper North Grain, draining towards the south west.

Questions 2 – 3 were addressed by a 23-month before-after-control-intervention experiment that continuously monitored rainfall, stream discharge and aquatic carbon flux at regular intervals in two sub-catchments of UNG. One sub-catchment (the treatment catchment) had half of the identified pipe outlets blocked after 17 months of monitoring and the other sub-catchment had no pipe outlets blocked (the control catchment). In the treatment catchment, four pipes were monitored for discharge and water table, and one of these pipes was monitored for aquatic carbon flux.

Question 2 was addressed by sampling the storm responses obtained from rainfall, discharge in the treatment catchment and the control catchment, and discharge and water table from the four pipe outlets characterised the impact of pipe outlet blocking on the hydrological response of pipes, differences and similarities in pipe and stream response to storm events, and between sub-catchments. Question 2 was addressed by sampling characteristics of rainfall-driven and single peaked hydrographs observed at outlets of the two sub-catchments and four pipe outlets before and after pipe outlets were blocked. For each monitored pipe and stream outlet a stage-discharge curve was derived from manual discharge measurements, while, in addition, for streams, discharge was also estimated using salt dilution gauging. Pipe outlets were blocked using two different methods: 1) plugging pipe outlets with on-site available materials (jute bags filled with peat or a mixture of peat and stone), or 2) placing a vertical screen perpendicular to the projected pipe course (wooden planks or plastic piling). The impact of pipe outlet blocking was measured by observations of seepage around blocked pipe outlets, or by estimating effect sizes of hydrograph characteristics. For each hydrograph a selection of indices was determined, including information on the shape of the hydrograph, storm rainfall, storm discharge, peak lag, peak discharge, duration of storm discharge, (dynamic) contribution area, water-table recession rates. Statistical analyses was performed on the distribution of hydrograph indices across pipe outlets and between sub-catchments.

Question 3 was addressed by summarizing continuous rainfall, discharge and aquatic carbon data of the treatment catchment and the control catchment, and one pipe to assess the impact of pipe outlet blocking on both particulate and dissolved fluvial carbon export at pipe and sub-catchment scale. Water samples were collected by automatic water samplers installed at the outlet of the two sub-catchments and one pipe outlet. Water samples were analysed at the University of Leeds laboratories for POC, DOC, and indices of spectral absorbance, including specific ultra-violet absorbance (SUVA), and ratios of absorbances at 254 nm, 400 nm, and 665 nm. The relationship between absorbance at 254 nm and DOC was determined using linear interpolation. The product of the function was used to predict DOC concentrations and fluxes for analyses. The impact of blocking pipe outlets on aquatic carbon was determined by comparing POC and DOC concentrations and fluxes, and indices of spectral absorbance between pipe and sub-catchment and between sub-catchment outlets.

1.9.3 Thesis outline

The remainder of this thesis focuses on the results from the field-based research that yielded three journal manuscripts, followed by a synthesis discussing how the main findings can guide future research and best practice on piping in peatland restoration.

Chapter 2: Controls on the spatial distribution of natural pipe outlets in heavily degraded blanket peat.

Spatial distribution of natural pipe outlets and their characteristics were compared to aspect and surface cover of streambanks in the gully network. Spatial statistics were applied to determine the pipe outlet frequency and hotspots for pipe outlets in the catchment.

Chapter 3: Effects of pipe outlet blocking on hydrological functioning in a degraded blanket peatland.

The effectiveness of two different methods of blocking pipe outlets was compared by categorizing field observations recorded over six months since time of blocking. The effect of pipe outlet blocking on pipe scale was assessed for pipe outlets at two head and two edge locations, by comparing hydrograph indices between pipes and between pipes and streams, and comparing temporal changes in the water table around pipe outlets. The effect of pipe outlet blocking on stream scale was assessed by comparing hydrograph indices between streams.

Chapter 4: Aquatic carbon concentrations and fluxes in a degraded blanket peatland with piping and pipe outlet blocking.

The concentration and flux of POC and DOC, and spectral absorbance in discharge, from one head pipe and the two streams were compared between the period before and after pipe outlets were blocked. Additional temperature and discharge data were used to assess seasonality of DOC and POC concentrations and fluxes.

Chapter 5: Critical discussion and conclusions

Chapter 5 is a synthesis of the main findings presented in this thesis, drawing together the main findings from Chapters 2 – 4 and discussing their wider implications. The limitations of the study and directions for future work are also discussed. The chapter ends with a summary of the conclusions from the thesis.

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Chapter 2: Controls on the spatial distribution of natural pipe outlets in heavily degraded blanket peat

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

[1]water@leeds, School of Geography, University of Leeds, Leeds, LS2 9JT, UK
[2]Moors for the Future Partnership, The Moorland Centre, Edale, S33 7ZA, UK
[3]School of Environment, Education, and Development, The University of Manchester, Oxford Road, Manchester, M13 9PL, UK

Abstract

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

2.1 Introduction

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

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

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

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

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

This paper reports on a survey of pipe outlets in a heavily degraded blanket peatland in the southern Pennines of England. It aims to:

1. determine the extent and size of soil pipe outlets found along gullies;
2. examine the relative roles of topographic position and stream bank aspect on pipe outlet frequency and pipe outlet characteristics;
3. suggest process mechanisms associated with controls on pipe outlet frequency that can be examined by further research; and
4. discuss the implications of findings for peatland restoration management.

2.2 Methods

2.2.1 Study site

This research was conducted within the southern Pennines, on part of the National Trust High Peak Estate in the Peak District National Park, in northern England. The study catchment, Upper North Grain (UNG), is a small (0.49 km^2) headwater catchment of the River Ashop which drains the slopes of both Bleaklow and Kinder Scout (Figure 2.1).

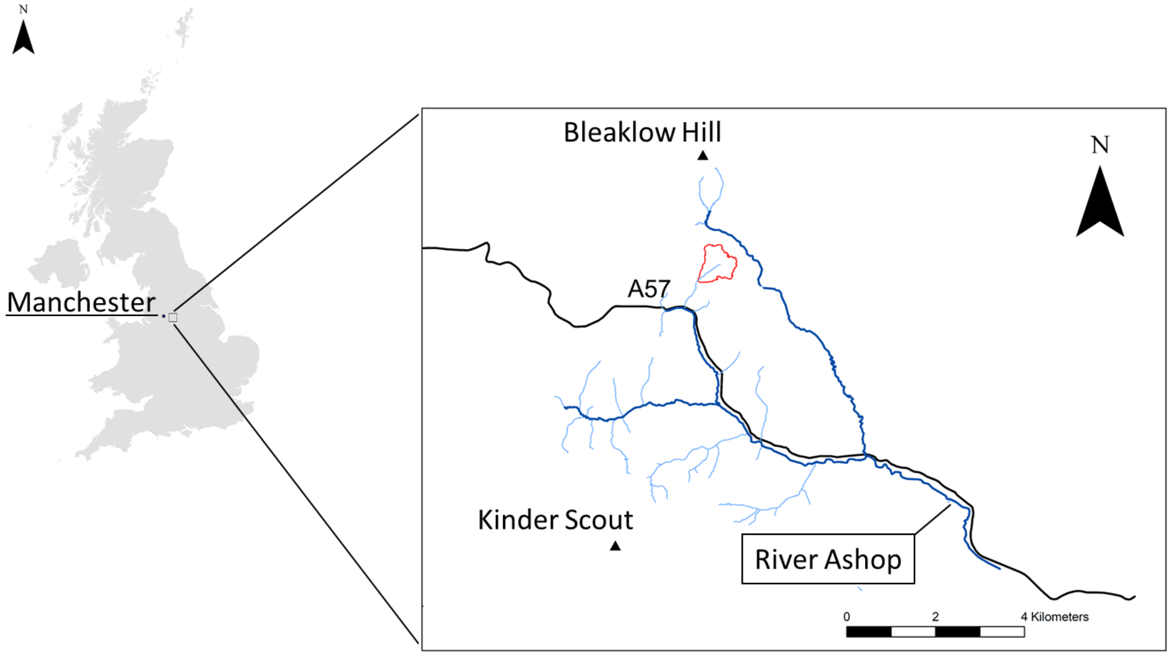

Figure 2.1 Location of Upper North Grain catchment (red boundary) east of Manchester. The catchment drains into the river Ashop, along which the A57 road runs.

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

2.2.2 Data collection

The primary goal of the survey was to assess the distribution of pipe outlets across the catchment and to collect data to determine spatial distributions of pipe outlet characteristics. Surveyors walked in pairs along the streambed of each gully in the upslope direction and identified pipe outlets by eye on streambanks, and recorded the geographical location of each pipe outlet using a hand-held GPS (e.g. Garmin Etrex10). Pipe outlets were recorded 1) in gullies, which had two clear banks (left- and right-hand side), and 2) at exposed edges of the peat margin, that faced the main drainage stem of the catchment (Figure 2.2 and 2.3). Both locations will hereafter be referred to as ‘streambank’. At each streambank the location of a pipe outlet was characterised as either occurring at: (1) the ‘edge’ where the streambank was broadly linear, without perpendicular headward incisions or (2) the ‘head’ where the streambank showed signs of headward retreat at the pipe outlet (Figure 2.2). For each pipe outlet four main characteristics were recorded: 1) the pipe outlet dimensions, 2) the distance from the roof of the pipe outlet to the top of the streambank, 3) the slope of the streambank adjacent to the pipe outlet, and 4) the sloping length of the streambank. The latter was measured as the distance along the slope of the streambank between the highest and the lowest point at the streambank adjacent to the pipe outlet. Pipe outlet dimensions were defined by the vertical (VL) and horizontal (HL) diameters, which were measured using a steel tape measure to the nearest 5 mm. Macropores smaller than 5 mm were ignored following the method of Holden *et al.* (2012a). The distance from pipe outlet roof to the top of the streambank was measured from the pipe roof to the boundary between the visible peat surface of the gully edge and the vegetation line, and was recorded to the nearest 5 mm. The slope of the streambank was measured by placing an inclinometer on its surface, measuring in the perpendicular direction of the stream. To further determine the relative position of each pipe outlet on the streambank, photographs were taken of each pipe outlet location (Figure 2.2). Twelve pipe outlet surveys were carried out at UNG over a 22-month period between December 2017 and

September 2019. In order to sample different parts of the catchment, the survey was conducted on different days during the year, which may have resulted in some inconsistencies in the number of pipe outlets found in certain areas of the catchment due to daylight limitations, flooding in streams, or adverse weather conditions.

2.2.3 Data processing

Table 2.1 describes the organization of the dataset used for analysis. Data preparation and processing was performed in ESRI ArcGIS Software suite 10.6. High-resolution LiDAR data recorded at a ground resolution of 0.5 m was used to produce a detailed digital terrain model (MFFP, 2014), which was used to delineate hydrological functions and terrain characteristics, including slope, aspect, flow direction, flow accumulation, stream raster, and the catchment boundary.

To determine the actual depth of a pipe outlet at the gully bank, bank slope and the distance from the pipe roof to the gully edge were converted into a parameter describing the depth to pipe roof relative to the edge of the gully (Figure 2.3), which was derived as follows:

$$\boldsymbol{D_V = sin\left(\frac{S_b \cdot \pi}{180}\right) \cdot D_0} \qquad \mathbf{2}$$

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

$$\boldsymbol{D_S = sin\left(\frac{S_b \cdot \pi}{180}\right) \cdot SL} \qquad \mathbf{3}$$

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

$$\boldsymbol{cross\ sectional\ area = \pi \cdot VL \cdot HL} \qquad \mathbf{4}$$

where VL is the vertical length of the pipe outlet (cm), and HL is the horizontal length of the pipe outlet (cm).

Table 2.1 Data frame showing selected parameters used in the analyses.

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

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

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

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

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

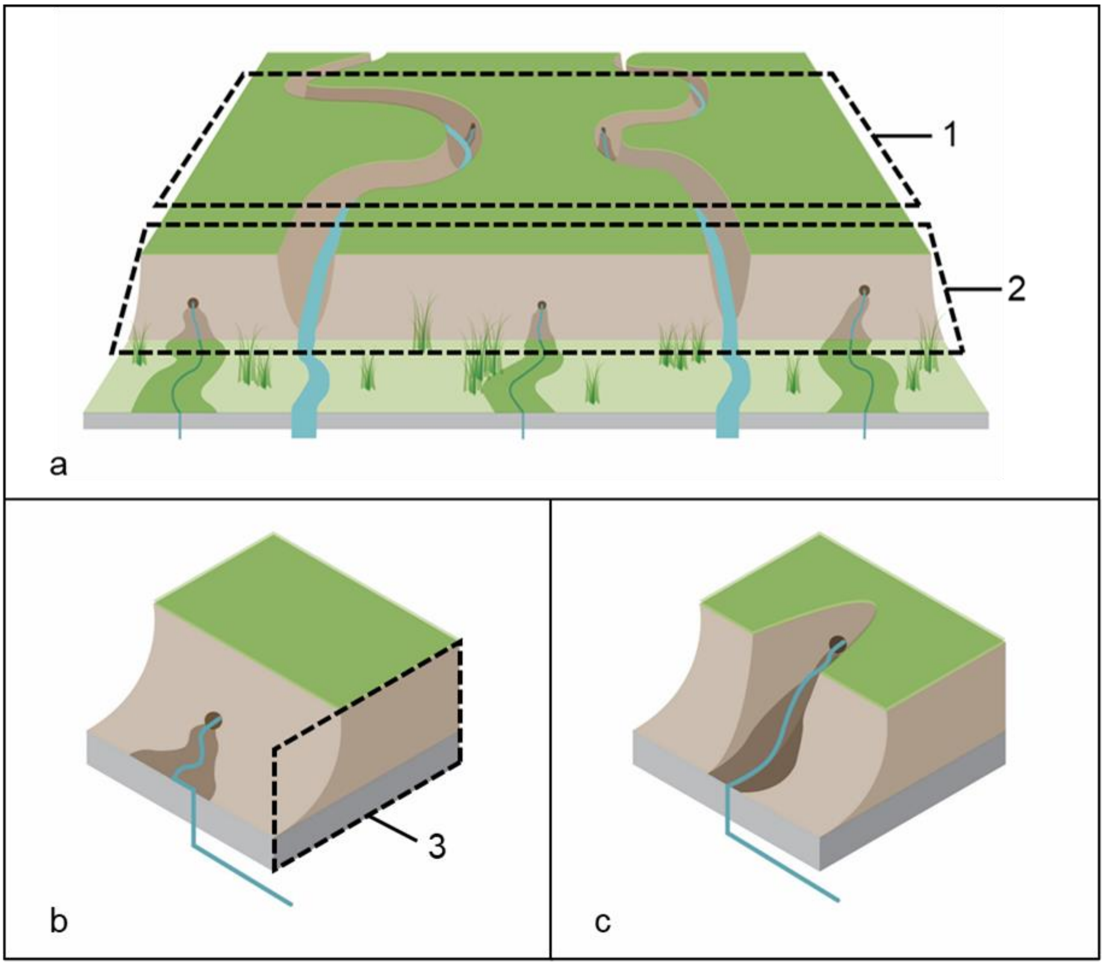

Figure 2.2 Diagram showing schematic representation of survey locations and pipe outlet locations: a. locations at which pipe outlets have been surveyed; in gullies (1) and along the peat margin (2); b. edge locations and c. head locations. Streambanks were defined as the area covering one gully wall 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 2.3 the sample polygon with the highest value of pipe outlet frequency is indicated with a red line. This area depicts the maximum pipe outlet frequency in the catchment recorded over at least 200 m of streambank, denoted as pipe outlets per km streambank.

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

2.3 Results

2.3.1 Frequency of piping

A total of 346 pipe outlets were identified, of which 336 pipe outlets occurred at streambanks in gullies, while 10 pipe outlets occurred on the peat margin. A total of 88 pipe outlets were found at head locations, and 258 pipe outlets were found at edge locations. The mean pipe outlet frequency was 22.8 per km streambank. Sampling in areas with a high kernel density for pipe outlets resulted in a maximum pipe outlet frequency of 91 per km streambank (Figure 2.3), located in the middle part of the catchment in a wide and deeply eroded gully.

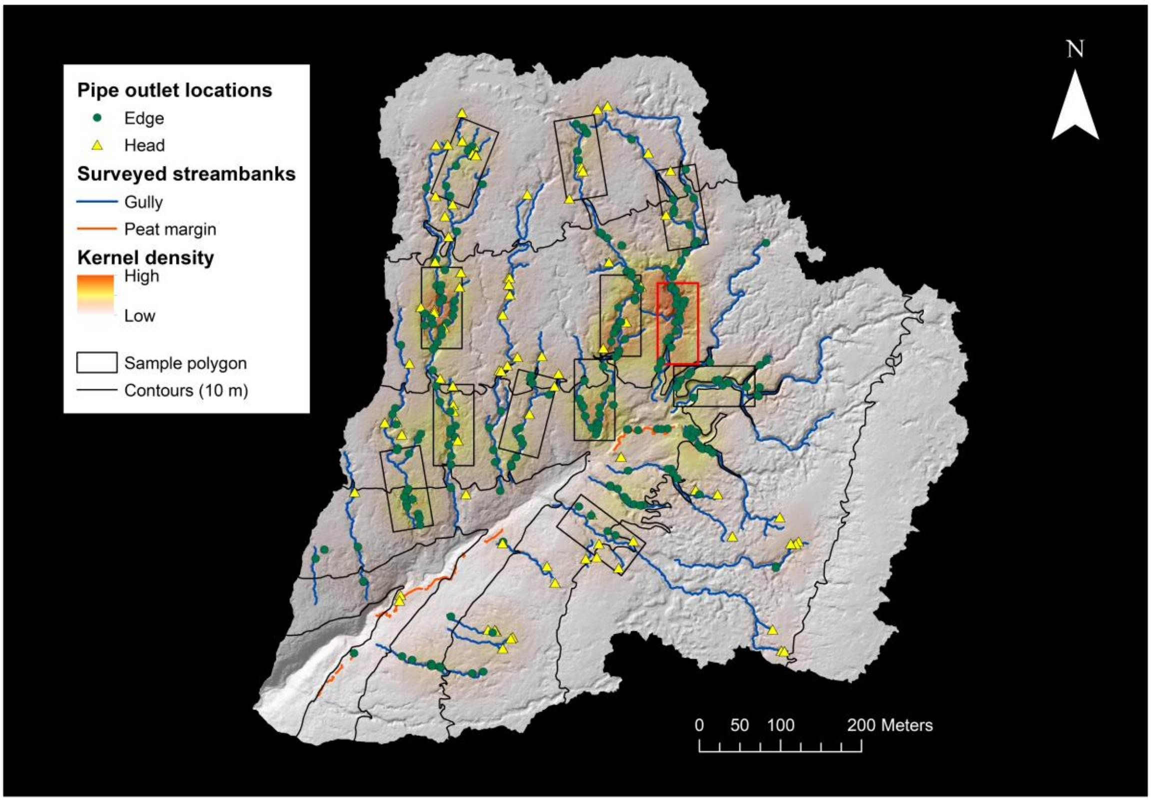

Figure 2.3 Map showing surveyed streambanks with identified pipe outlets, superimposed on a hillshade map of the catchment. A kernel density map was produced to indicate hotspots of pipe outlet frequency across the catchment, ranging from low to high (indicative). Rectangular polygons indicate areas of interest to determine the maximum pipe outlet frequency in the catchment. The polygon that is outlined in red indicates the location with the highest estimated pipe outlet frequency. Contour lines run between 490 and 530 m, with 10 m interval. The highest point in the catchment is at 539.9 m above mean sea level.

2.3.2 Pipe outlet locations

More than half of the pipe outlets were identified at elevations between 515 m and 525 m (Figure 2.4), which covers an area with wide and deep gullies (Figure 2.3). Edge and head locations were significantly different across elevation (U = 15143.5, $p < 0.001$), with median elevation of 519.5 m (edge) and 523.6 m (head) respectively (Figure 2.4). The pipe outlets that were identified at streambanks on the peat margin were mostly found at the interface of the organic layer and the mineral bedrock, whereas the pipe outlets at streambanks in gullies were generally found in the peat profile (Figure 2.2 and 2.5).

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

The streambank height (D_S) was determined for 190 edge locations and 22 head locations. There was no difference in streambank height between edge locations and head locations (U= 1781.5, $p = 0.257$) but the relative position of pipe outlets was different across location (U=3419, p < 0.001), with a median of 0.80 for edge locations compared to a median of 0.95 for head locations. A Spearman's rank-order correlation showed that depth to pipe roof and streambank height had a positive correlation at edge locations at $p < 0.001$ ($r_s(188) = 0.350$), whereas no significant correlation was found at head locations ($r_s(20) = 0.307$, $p = 0.165$) (Figure 2.5).

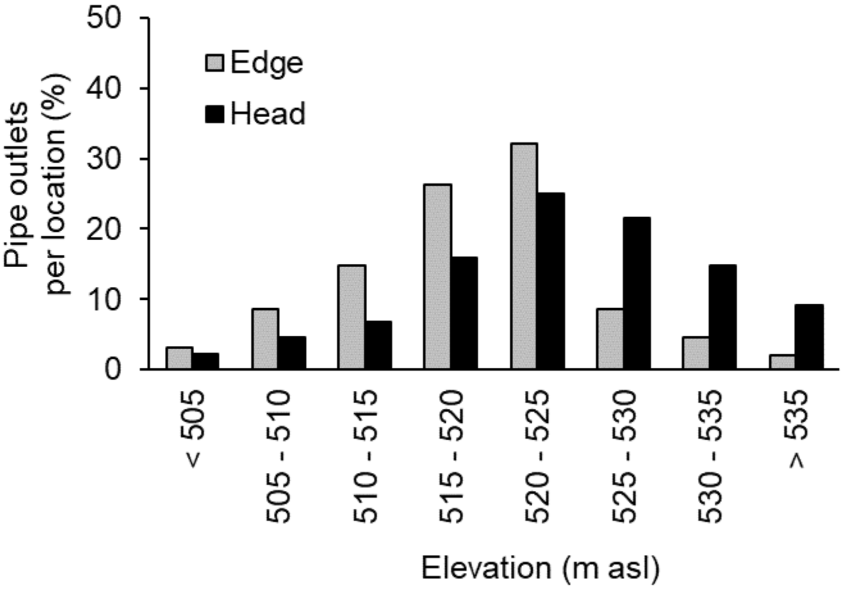

Figure 2.4 Bar diagram showing the distribution of pipe outlets by elevation in the catchment.

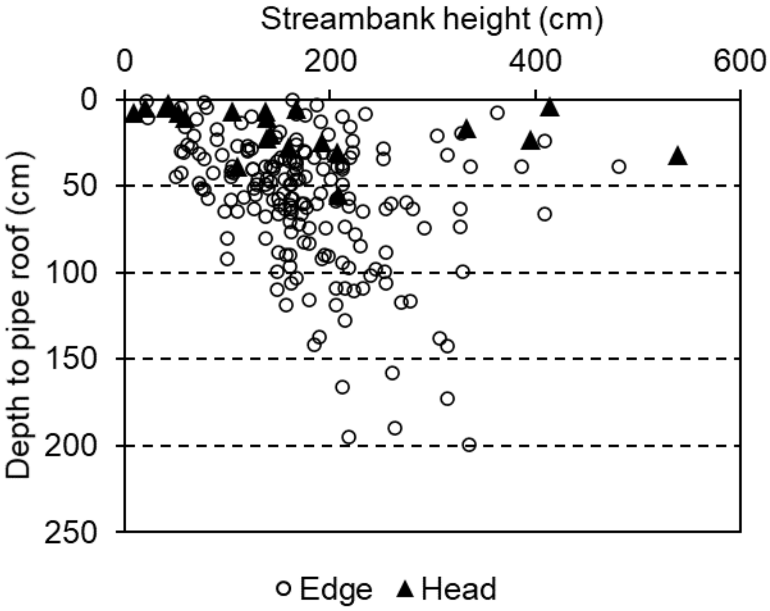

Figure 2.5 Scatter plot showing depth to pipe roof against streambank height for pipe outlets at edge and head locations.

2.3.3 Pipe outlet shape and size

There were 227 circular pipe outlets (c) (185 edge, 42 head), 10 horizontally lenticular pipe outlets (h)(5 at each location), 79 vertically lenticular pipe outlets (v)(52 edge, 27 head). Vertical length ranged from 1 to 90 cm, with a median of 8 cm. The horizontal length ranged 1 to 60 cm and had a median of 5 cm. Cross-sectional area of pipe outlets ranged from 3 cm^2 to 7539 cm^2, with a median of 119 cm^2. The total cross-sectional area of pipe outlets in the catchment was 110,477 cm^2, which translates to a density of piping along streambanks of 0.73 m^2 km^{-1}. Figure 2.5 shows that pipe outlets at head locations are particularly concentrated near the surface. Within head locations pipe outlets issuing at the head of gullies occurred significantly closer to the surface compared to pipe outlets at head locations elsewhere in the catchment, with medians of 5.1 cm and 22.9 cm respectively (Mann-Whitney U = 68, $p = 0.020$). Such differences were not found for cross-sectional area.

Values for streambank slope and depth to pipe roof were determined for 175 circular pipe outlets (154 edge, 21 head), 9 horizontally lenticular pipe outlets (4 edge, 5 head), and 53 vertically lenticular pipe outlets (39 edge, 14 head). Figure 2.6a shows the distribution of streambank slope for pipe outlets by location and shape type, with median values of streambank slope per shape type at edge locations (Ec = 40 ˚, Eh = 40 ˚, and Ev = 42 ˚) and head locations (Hc = 35 ˚, Hh = 25 ˚, Hv = 27.5 ˚). Vertically lenticular pipe outlets had significantly different distributions of streambank slope across categories of location (U = 147.5, $p = 0.011$). Distributions of streambank slope for circular (U = 1532.5, $p = 0.695$) and horizontally lenticular (U=8, $p = 0.730$) pipe outlets did not differ between locations. On edge locations there was no difference in the distributions of streambank slope across shape types: Ec versus Ev (U = 3494.5, $p = 0.111$), Ec versus Eh (U = 282.5, $p = 0.775$) and Eh versus Ev (U = 101, $p = 0.361$). At head locations the difference in streambank slope between Hc and Hv had a weak significance at $p < 0.1$ (U = 97.5, $p = 0.096$), but streambank slopes did not differ between Hc and Hh (U = 38, $p = 0.374$), and Hh and Hv (U = 29.5, $p = 0.622$) (Figure 2.6a).

Figure 2.6b shows the distribution of depth to pipe roof for pipe outlets by location and shape type, with median values of depth to pipe roof per shape type at edge locations (Ec = 51.6 cm, Eh = 59.1 cm, and Ev = 39.8 cm) and at head locations (Hc = 20.0 cm, Hh = 31.7 cm, Hv = 7.3 cm). The distribution of depth to pipe roof of circular pipe outlets was significantly different across categories of location (U = 540.5, $p < 0.001$). The distribution of depth to pipe roof of vertically lenticular pipe outlets was significantly different across categories of location (U = 108.5, $p = 0.001$) (Figure 2.6b).

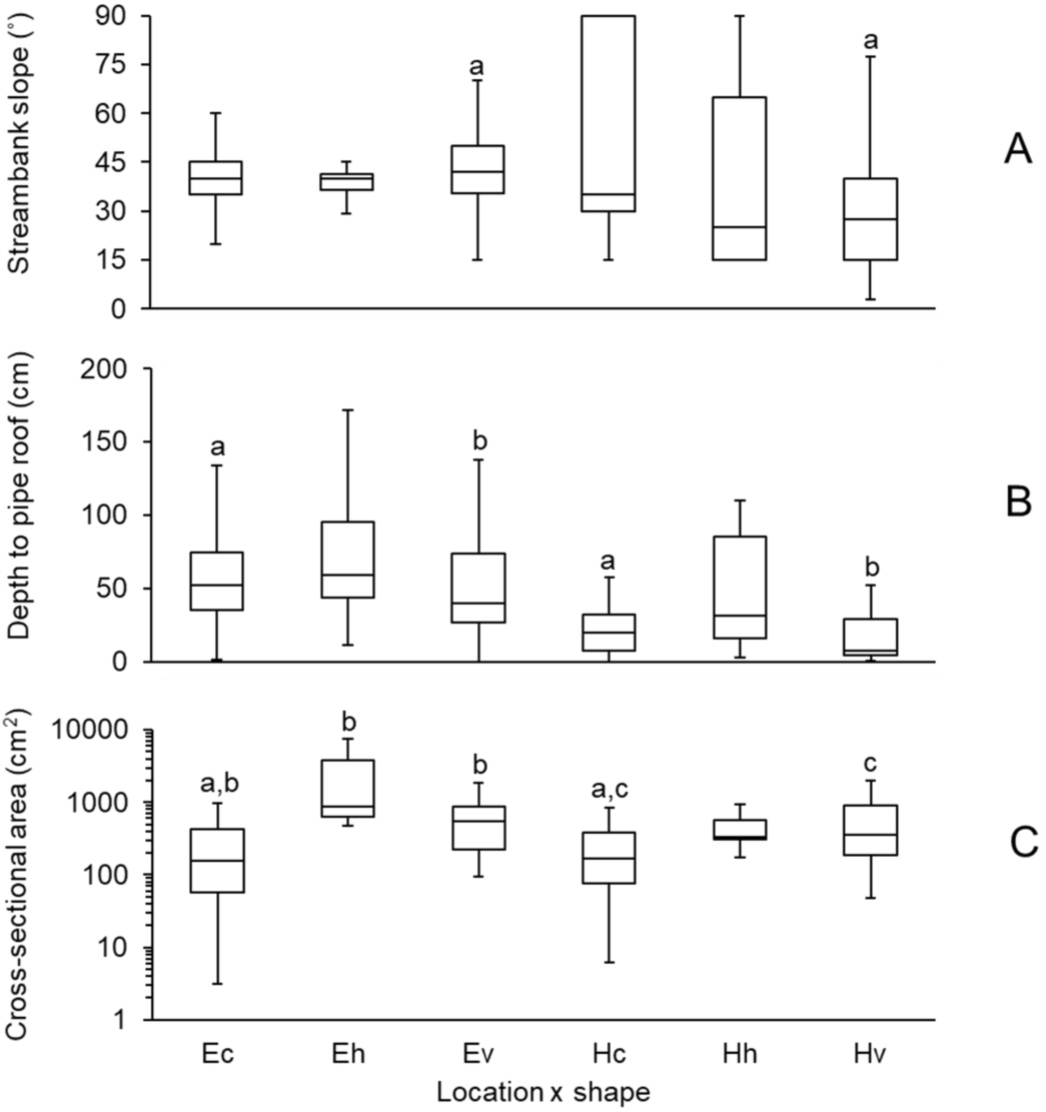

*Figure 2.6 Box plots showing the effects of location in the gully on: A) bank slope (degrees), B) depth to pipe roof (cm) and C) cross-sectional area of pipe outlets (cm^2), for location (E: edge; H: head) and shape type (c: circular; h: horizontally lenticular; v: vertically lenticular). The boxes show the interquartile range between Q1 and Q3, with the median indicated within the boxes as a black horizontal line. The whiskers indicate the lowest and highest values that are still within the range: [Q1 - 1.5 * (Q3 - Q1)] and [Q3 + 1.5 * (Q3 - Q1)]. Different superscript letters indicate significant difference (p < 0.05) compared with the other location and shape combinations.*

The distributions of depth to pipe roof of horizontally lenticular pipe outlets did not differ across location (U = 8, *p* = 0.730) (Figure 2.6). At head locations there was no difference in the distributions of depth to pipe roof across shape types: Hc versus Hv (U = 112.5, *p* = 0.249), Hc versus Hh (U = 67, *p* = 0.374) and Hh versus Hv (U =20.5, *p* = 0.186) (Figure 2.6b). At edge locations the difference in depth to pipe roof between Ec and Ev had a weak significance at $p < 0.1$ (U = 2408.5, *p* = 0.056). Depth to pipe roof did not differ between Ec and Eh (U = 345.5, *p* = 0.678), and Eh and Ev (U = 60, *p* = 0.479) (Figure 2.6b).

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

Figure 2.6c shows the distribution of cross-sectional area of pipe outlets by location and shape type, with median values per shape type at edge locations (Ec = 66.0 cm^2, Eh = 867.1 cm^2, and Ev = 340.9 cm^2) and head locations (Hc = 157.1 cm^2, Hh = 326.7 cm^2, Hv = 351.9 cm^2). The distribution of cross-sectional area of circular pipe outlets was significantly different between categories of location (U = 5425, $p < 0.001$). No difference was found in distribution of cross-sectional area between locations for horizontally lenticular (U = 5, *p* = 0.151) and vertically lenticular (U = 708, *p* = 0.951) pipe outlets. The distribution of cross-sectional area of circular and vertically lenticular pipe outlets were significantly different from each other at edge locations (*U*= 8395.5, $p < 0.001$) and at head locations (U=804.5, *p* = 0.003). The distribution of cross-sectional area of circular and horizontally lenticular pipe outlets were significantly different from each other at edge locations (U=895, $p < 0.001$), and at head locations, but only at $p < 0.1$ (U=160, *p* = 0.058). The distribution of cross-sectional area of vertically and horizontally lenticular pipe outlets was significantly different from each other at edge locations (U=50.5, *p* = 0.021), but not at head locations (U=66, *p* = 0.960).

2.3.4 Relationship between pipe outlets and surface contributing area

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

2.3.5 Relationship between pipe outlets and aspect

Aspect was determined for 346 pipe outlets. A *chi* square goodness of fit test showed that aspect was a significant factor controlling the distribution of pipe outlets ($\chi^2(8) = 141.7$, $p < 0.001$). For each of eight aspect categories, 38.4 pipe outlets were expected, but the observed count was larger for streambanks facing southwest (n = 76) and west (n = 76), which in total account for 43.9 % of the pipe outlets. The rest of the pipe outlets faced north (n = 11), northeast (n = 16), east (n = 40) and south east (n = 41), south (n = 44), and northwest (n = 40). Two pipe outlets were found on flat surfaces (Figure 2.7). On streambanks with southerly, southwestly and westerly aspects, pipe outlets at edge locations were found significantly deeper compared to pipe outlets at head locations with the same aspect, at $p < 0.05$ (Table 2.2). On streambanks facing south, southwest and west, the cross-sectional area of pipe outlets at edge locations was significantly smaller compared to pipe outlets at head locations with the same aspect, at $p < 0.05$ (Table 2.2).

2.3.6 Surface cover and pipe outlets

A total of 202 pipe outlets occurred where there was a bare surface (edge = 177, head = 25) with 144 pipe outlets where there was vegetation (edge = 81, head = 63). The distribution of depth to pipe roof was the same across classes of surface cover in both edge locations (U = 3538.5, n = 197, p = 0.056) and head locations (U = 126.5, n = 40, p = 0.159) (Figure 2.8). On bare surfaces, the distribution of depth to pipe roof was significantly different across categories of location (U = 433.0, n = 146, p = 0.003), with a median of 51.6 cm for edge locations and 22.9 cm for head locations (Figure 2.8). On vegetated surfaces, the distribution of depth to pipe roof was significantly different across categories of location (U = 330.5, n = 91, $p < 0.001$), with a median of 42.4 cm for edge locations and 10.0 cm for head locations (Figure 2.8).

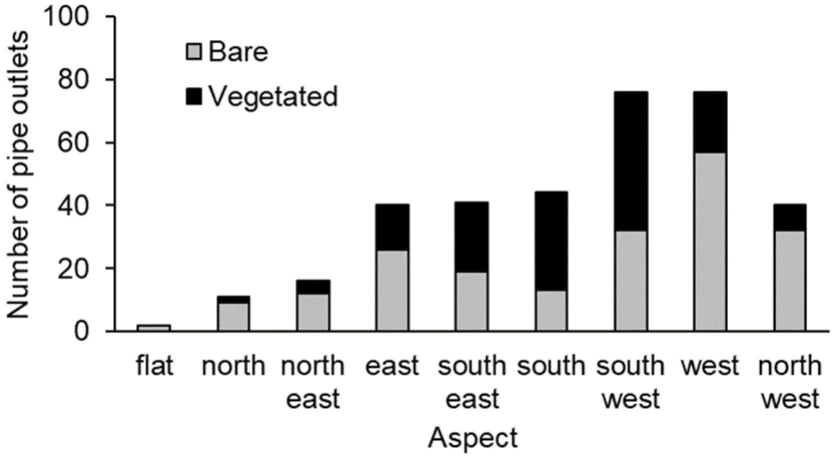

Figure 2.7 Stacked bar chart showing number of pipe outlets against aspect, stacked by cover type.
Post hoc pair wise chi square comparison showed that the number of pipe outlets was significantly different for north versus south ($\chi^2(1)= 19.8, p < 0.001$), north east versus south west ($\chi^2(1) = 39.1, p < 0.001$), and east versus west ($\chi^2(1) = 11.2, p = 0.001$). The distribution of pipe outlets was assumed to be the same between south east and north west facing streambanks ($\chi^2(1) = 0.012, p = 0.912$).

Table 2.2 Results of Mann-Whitney U independent sample tests on the distributions of depth to pipe roof (D_V) and cross-sectional area across categories of location for classes of aspect. Fields marked with a dash indicate missing data in either edge or head locations, hence comparisons were not performed.

Differences between edge and head locations

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

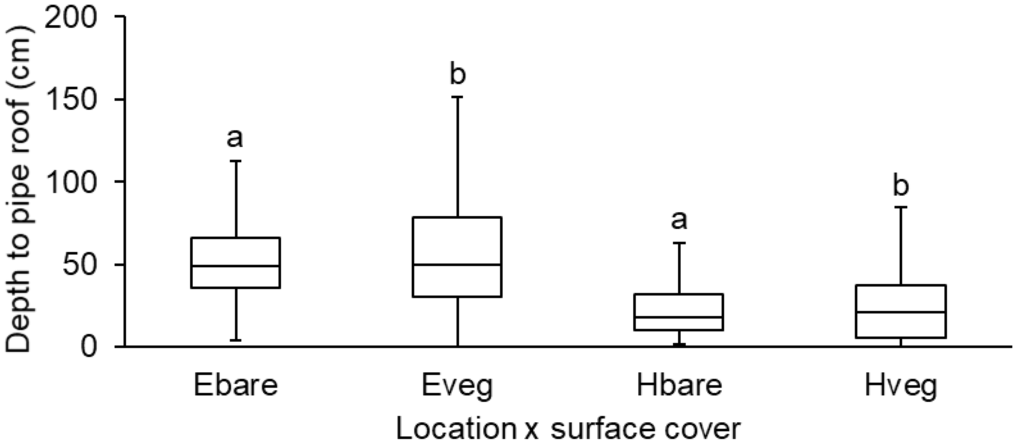

*Figure 2.8 Box plots showing the distribution of depth to pipe roof (cm), grouped by location (E: edge; H: head) and surface cover (bare; vegetated). The boxes show the interquartile range between Q1 and Q3, with the median indicated within the boxes as a black horizontal line. The whiskers indicate the lowest and highest values that are still within the range: [Q1 - 1.5 * (Q3 - Q1)] and [Q3 + 1.5 * (Q3 - Q1)]. Different superscript letters indicate significant difference (p < 0.05) compared with the other location and surface cover class combinations.*

The distribution of cross-sectional area across categories of surface cover type was assumed to be the same in both edge locations (U = 7081.0, n = 248, *p* = 0.213) and head locations (U = 626, *p* = 0.523). Cross-sectional area was significantly different across categories of location in both classes of surface cover. In bare surface areas (U = 2374.5, n = 190, *p* = 0.030) edge pipes had a median cross-sectional area of 88.0 cm^2 (edge) which was significantly smaller in size compared to pipe outlets in head locations (219.9 cm^2). A similar pattern was observed for pipe outlets at vegetated surfaces (U = 2570.0, n = 126, *p* = 0.001), with median values of 94.2 cm^2 for edge locations and 304.7 cm^2 for head locations. A *Chi* square goodness of fit test indicated that the occurrence of pipe outlets was significantly different across classes of aspect for areas with a bare surface (χ^2 (8) = 97.9, *p* < 0.001) and areas with a vegetated surface (χ^2 (7) = 79.4, *p* < 0.001) (Figure 2.7). Bare surfaces that were facing west (n = 57) had markedly more pipe outlets than bare surfaces at other aspects. Vegetated surfaces that were facing south (n = 31) and southwest (n = 44) had markedly more pipe outlets than vegetated surfaces at other aspects.

2.4 Discussion

2.4.1 Pipe outlet frequency

The pipe outlet frequency in UNG (22.8 km^{-1} streambank) was slightly larger in comparison to the average pipe outlet frequency of 19.7 km^{-1} streambank across 160 blanket bog sites reported in Holden (2005). Table 2.3 shows that UNG has a relatively high pipe outlet frequency when compared to other blanket peat study catchments. One of the first surveys that looked specifically at the frequency of pipes in streambanks was conducted on the streambanks of Burbage Brook in the Peak District (podzol site) with 184 km^{-1} over 3 km of streambank in 1968 (Jones, 1975), and a resurvey in 2003 resulted in 134 km^{-1} over 500 m streambank (Jones and Cottrell, 2007). Other studies on piping reported values from Welsh catchments of 36 km^{-1} and 56 km^{-1}, respectively, for Cerrig yr Wyn and Nant Gerig (Gilman and Newson, 1980) and 80 km^{-1} for Afon Cerist (Jones, 1975). It should be noted that pipe outlets found in UNG were not like those in the Welsh studies where pipes were commonly disconnected from the stream and were found at breaks of slope on the hillside often coinciding with changes in soil type. The Welsh pipe systems were also characterised by pipes found at the base of the organic soil horizon. More recent examples in deep peat catchments in the north Pennines include 9.5 km^{-1} at Little Dodgen Pot Sike (Holden and Burt, 2002), and 36.6 km^{-1} (August 2007) and 31.7 km^{-1} (April 2010) at Cottage Hill Sike (Holden *et al.*, 2012a). However, none of the above studies in Welsh and North Pennine uplands mentioned the total length of their survey transects, nor the methods that were used for calculating the pipe outlet frequency per length of streambank, and so a fair comparison between studies is difficult to undertake.

Table 2.3 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).

Catchments	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 (Jones and Crane, 1984)	histic podzols	14.5	0.656	10[a]	2200	541	8.1	9.5
Cerrig yr Wyn, Cambria (Gilman and Newson, 1980)		56		5	2200	472	10.3	9
Nant Gerrig, Cambria (Gilman and Newson, 1980)		36		10	2200	495	4.4	9
Burbage Brook, Peak District (Jones, 1975)	humo-ferric podzols	89	0.554	9	983.6[b]	150	2	10.2

[a] *10 cm (ephemeral), 24 cm (perennial)*

[b] *as presented in Jones and Cottrell (2007)*

***** *only observations included of survey in 2010*

2.4.2 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 2.3 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 characterised 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 2.5). 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 2.3). Daniels *et al.* (2008) showed that water-table levels in UNG drop to larger depths and more frequently at gully sides than in intact bog further away from the gully. Where water tables are lowered in consecutive years permanent cracks may form in the peat, that provide new routes for bypass flow, thus leading to pipeflow and piping (Holden, 2006). Examples from drylands suggest that when gullies incise deeper than the pipe outlet, increases of the hydraulic gradient can occur, which then promotes the development of more soil pipes upslope (Swanson *et al.*, 1989). We found pipe outlets predominantly on streambanks that face towards the sun and prevailing wind direction (west southwest – (Clay and Evans, 2017)), though these differences in pipe outlet frequency across gully banks may also relate to the orientation of the catchment itself, as UNG is draining towards the south west. However, such streambanks hosted more pipe outlets at edge locations, which sat deeper in the profile and were smaller than pipe outlets at head locations with the same aspect. Moreover, edge locations in unvegetated (bare) areas hosted more and smaller pipe outlets than pipe outlets on head locations in bare areas. Over the summer of 2018 prolonged drought caused peat to crack open to depths of 40 cm at places across UNG. Cracks that were observed at south, southwest and west-facing streambanks had not fully filled in by September 2019 as many of these cracks were still visible. Desiccation-stress cracking can induce a form of piping called sapping (Parker and Jenne, 1967), which refers to the mass failure or slumping resulting from undercutting of an embankment by seepage erosion (Fox and Wilson, 2010), followed by mass movement in the subsurface (subsidence) (Baillie, 1975). This evidence supports the idea that the occurrence of soil piping at edge locations is associated with the incidence of desiccation cracking as is observed on gully sides (Gilman and Newson, 1980; Holden, 2006).

2.4.3 Size and shape of pipe outlets

Table 2.3 summarises, for a number of selected studies, the cross-sectional area per length of streambank. With 0.73 m^2 km^{-1} streambank UNG had a markedly greater surface occupied by pipe outlets than the average of 0.556 m^2 km^{-1} observed across 160 UK blanket bog sites (Holden, 2005). UNG ranks also higher than deep peat sites in the North Pennines, e.g. 0.026 m^2 km^{-1} at Little Dodgen Pot Sike (Holden and Burt, 2002) and 0.35 m^2 km^{-1} at Cottage Sike Hill (Holden *et al.*, 2012a), which were both recorded in catchments that have naturally revegetated with slope-channel decoupling as a result (Evans *et al.*, 2006; Holden and Burt, 2002; Holden *et al.*, 2012a). UNG is considered to be still in an active eroding phase (Evans *et al.*, 2006).

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

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

2.5 Implications for peatland restoration

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

2.6 Conclusions

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

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

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

2.7 Acknowledgements

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2.8 Data availability

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

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Chapter 3: Effects of pipe outlet blocking on hydrological functioning in a degraded blanket peatland

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

[1]water@leeds, School of Geography, University of Leeds, Leeds, LS2 9JT, UK
[2]Moors for the Future Partnership, The Moorland Centre, Edale, S33 7ZA, UK
[3]School of Environment, Education, and Development, The University of Manchester, Oxford Road, Manchester, M13 9PL, UK

Abstract

Peatland restoration practitioners are keen to understand the role of drainage via natural soil pipes, especially where erosion has released large quantities of fluvial carbon in stream waters. However, little is known about pipe-to-stream connectivity and whether blocking methods used to impede flow in open ditch networks and gullies also work on pipe networks. Two streams in a heavily degraded blanket bog (southern Pennines, UK) were used to assess whether impeding drainage from pipe networks alters the streamflow responses to storm events, and how such intervention affects the hydrological functioning of the pipe network and the surrounding peat. Pipeflow was impeded in half of the pipe outlets in one stream, either by inserting a plug-like structure in the pipe-end or by the insertion of a vertical screen at the pipe outlet perpendicular to the direction of the predicted pipe course. Statistical response variable η^2 showed the overall effects of pipe outlet blocking on stream responses were small with $\eta^2 = 0.022$ for total storm runoff, $\eta^2 = 0.097$ for peak discharge, $\eta^2 = 0.014$ for peak lag, and $\eta^2 = 0.207$ for response index. Both trialled blocking methods either led to new pipe outlets appearing or seepage occurring around blocks within 90 days of blocking. Discharge from four individual pipe outlets was monitored for 17 months before blocking and contributed 11.3 % of streamflow. Pipe outlets on streambanks with headward retreat produced significantly larger peak flows and storm contributions to streamflow compared to pipe outlets that issued onto straight streambank sections. We found a distinctive distance-decay effect of the water table around pipe outlets, with deeper water tables around pipe outlets that issued onto straight streambanks sections. We suggest that impeding pipeflow at pipe outlets would exacerbate pipe development in the gully edge zone, and propose that future pipe blocking efforts in peatlands prioritise increasing the residence time of pipe water by forming surface storage higher up the pipe network.

3.1 Introduction

Soil piping has been reported in all regions of the world (Bernatek-Jakiel and Poesen, 2018), but most commonly in tropical forests (Chappell, 2010), loess soils (Verachtert *et al.*, 2010; Zhu *et al.*, 2002), subarctic hillslopes (Carey and Woo, 2002), dispersive semi-arid soils (Faulkner, 2013), boreal forests (Roberge and Plamondon, 1987), steep temperate hillslopes (Anderson *et al.*, 2009), and peatlands (Anderson and Burt, 1982; Rapson *et al.*, 2006). Pipes can act as important hydrological and geomorphological agents (Bryan and Yair, 1982; Gilman and Newson, 1980; Jones, 1971). Soil piping is increasingly recognised as a significant factor in soil degradation in many natural and anthropogenic landscapes (Bernatek-Jakiel and Poesen, 2018). Pipes often erode to form gullies (Wilson, 2011; Xu *et al.*, 2020) and can be a common feature of degraded landscapes. Piping has been widely reported in British upland regions (e.g. Jones *et al.* (1997)), and is particularly prevalent in sloping blanket peat (Holden, 2005). Peatlands are important global carbon stores and in some regions, including the British Isles, are source areas for significant proportions of potable water (Xu *et al.*, 2018). Headwater peatlands can often also be source areas for flooding (Acreman and Holden, 2013). Given these ecosystem service drivers, there has been increasing attention paid to the degraded state of some headwater peatlands and whether active management of pipe networks and pipeflows in peatlands might be important for managers to consider as part of peatland restoration projects.

Peatlands cover around 10 % of the British Isles but many of these have been subject to damage from peat abstraction, drainage, overgrazing, burning and atmospheric pollution (Evans and Warburton, 2007; Smart *et al.*, 2010; Ward *et al.*, 2007). In the southern Pennines of England, widespread peat erosion is most commonly ascribed to atmospheric deposition of acidic pollutants which, since the Industrial Revolution, has severely damaged peat forming mosses (Yeloff *et al.*, 2006). The erosion is severe including much gullying (Evans *et al.*, 2006), and causes problems downstream including reservoir sedimentation (Labadz *et al.*, 1991) and enhanced water discolouration, increasing treatment costs for potable supplies (Bonn *et al.*, 2010; Fearing *et al.*, 2004; Van der Wal *et al.*, 2011). In that context, downstream flooding is a major concern and recent work has suggested that peatland restoration could contribute to reduced flood peaks and delayed peak flow times through slowing flow accumulation in headwaters (Gao *et al.*, 2016; Grayson *et al.*, 2010; Holden *et al.*, 2008; Shuttleworth *et al.*, 2019).

Pipe outlets are observed at the head and on banks of gullies in degraded blanket peatlands (Regensburg et al., 2020). The role of pipeflow in flood generation from peatlands remains unclear, but pipeflow can be an important contributor to flow in peatland streams (e.g. Gilman and Newson (1980); Jones (1982); Jones and Crane (1984); Jones (1997a); Chapman *et al.* (1993); Chapman (1994); Chapman *et al.* (1997); Holden and Burt (2002); Smart *et al.* (2013)). For a histic podzol system in

Wales, Jones (1997b) reported pipes to respond at different times during the same storm event and these lag times varied between events, depending on antecedent wetness and rainfall intensity. However, there is a lack of pipeflow studies in heavily degraded peatland systems where water tables can be deep adjacent to gullies (Daniels *et al.*, 2008) and interactions between water tables and pipeflow in peatlands are not well studied.

Keeping peatlands saturated is an important target of restoration work since shallow water tables are required to reduce peat decomposition and maintain net C uptake. Gully banks are accessible to practitioners who are keen to know whether impeding flow at pipe outlets on gully banks is a viable component of peatland restoration. Plugging of pipe outlets in mineral soils showed soil pore saturation to increase upslope of the plugs (Wilson and Fox, 2013), and it was hypothesised that with time after pipe plugging new pipes may form (Midgley *et al.*, 2013). Frankl *et al.* (2016) showed impediment of subsurface flows by use of geo-membranes perpendicular to the flow direction could increase wetness of areas upslope of the subsurface screen and stabilise gully heads, but downstream impacts of impeding pipeflow have not been studied. Here we report on an experiment investigating the impact of pipe outlet blocking on streamflow in a heavily degraded blanket bog. This paper aims to:

1. investigate whether impeding pipeflow at pipe outlets in degraded blanket peat alters the stormflow response of streams, and
2. explore how pipe outlet blocking affects the hydrological functioning of soil pipes and the water table in the surrounding peat.

3.2 Study site and experimental design

3.2.1 Field area

The study was conducted in the Upper North Grain (UNG) catchment on the southern flank of the Bleaklow plateau in the Peak District National Park in northern England. The system drains an area of 0.49 km^2 and enters the Ashop, a river flowing in a southeastly direction (Figure 3.1a). The catchment has an altitudinal range of 467-540 m and a south-south-west aspect (Figure 3.1b). The site has a sub-Arctic oceanic climate with a mean annual temperature of 6.9 °C and an annual precipitation of 1313 mm (2004-2013) (Clay and Evans, 2017). The pedology of UNG is characterised by blanket peat, being 4 m thick in places, with an active vegetation layer consisting of *Eriophorum vaginatum*, *Eriophorum augustifolium*, *Calluna vulgaris*, *Erica tetralix*, *Vaccinium myrtillus*, *Empetrum nigrum* and patches of *Sphagnum spp*. Peat is deposited on a thin, discontinuous periglacial head deposit covering solid sandstones of the carboniferous age Millstone Grit Series (Wolverson Cope, 1998). Slopes in the catchment vary between 0 and 15 ^{o}, with the majority of the catchment (>80%) being between 0 and 7^{o}. The peat cover on UNG is regarded as degraded and characterised by an extensive network of deep gullies which, in the lower reaches, cut into the underlying bedrock. Further details on the erosion history of the catchment can be found in Regensburg *et al.* (2020). They found 346 pipe outlets throughout the UNG catchment, and linked their occurrence to desiccation processes in straight streambank sections (`edge location'), and places where headward erosion occurred around the pipe outlet (`head location'). Unless differences between pipe outlets at these two locations are discussed, hereafter, further references to the identity of pipes with outlets at these two locations will be made by using the terms "edge pipes" or "head pipes" respectively. The majority of pipe outlets were observed in the upper meter of the peat deposit (Regensburg *et al.*, 2020). As part of ongoing peatland restoration works in the area, the National Trust had carried out gully blocking in a number of tributaries at UNG between 2013 and April 2018 which consisted of: 1) placing tree trunks in the streambed (2013) on the southern flanks of the catchment, and 2) wooden planks and stone boulders (2018) in the northern flanks of the catchment (Figure 3.1c). All gully blocks were installed before monitoring of stream- and pipeflow commenced.

3.2.2 Experimental design

To determine the impact of impeding pipeflow on streamflow, a before-after-control-intervention (BACI) study design was implemented, comparing hydrological responses of two sub-catchments before and after pipe outlets were blocked in one of them. The two sub-catchments, “Control” and “Treatment”, were selected based on comparable geometry, orientation and frequency of pipe outlets (Regensburg *et al.*, 2020), using DEMs (0.5 m resolution LiDAR) and field verification (Table 3.1, Figure 3.1b). The experiment commenced in April 2018, and covered a pre-blocking period of 17 months (“pre”), and a post-blocking period of 6 months (Sept 2019 – February 2020) (“post”). In the treatment catchment, pipe outlets were blocked in autumn 2019, whereas pipe outlets in the control site were left unaltered. Pipeflow was ephemeral and responses to storm events were studied by monitoring pipe discharge and water-table depth at four pipe outlets in the intervention catchment, which all had a mean outlet diameter larger than 10 cm. Two pipes were monitored at head locations (pipe H1 and pipe H2), and two pipes monitored at edge locations (pipe E1 and pipe E2) (Figure 3.1c).

3.2.3 Pipe outlet blocking

Pipe outlets were blocked using two methods: 1) the insertion of a plug-like structure in the pipe-end, and 2) the insertion of a vertical screen at the pipe outlet perpendicular to the direction of the predicted pipe course. Materials used involved jute bags filled with peat, a mixture of peat and stones, wooden planks, and plastic piling (Figure 3.3), within practical labour costs and sustainable resource use constraints. Plugging pipe outlets with on-site available materials was considered to be less destructive to the peat and would only affect the direct surroundings of a pipe outlet, whereas screens would form an impermeable barrier to both pipe water and throughflow of the surrounding peat. Therefore, prior to field trials, a laboratory test was performed to investigate the sealing strength of peat as a blocking medium (for design see Appendix A-Fig 1). Results showed that peat plugs sealed themselves under a constant pressure head. To verify whether a similar result could be achieved *in situ*, blocking trials were carried out at UNG on four pipe outlets that were not within either of the two monitored sub-catchments, between May and August 2019. The first attempts involved constructing a plug-like structure consisting of a jute bag filled with locally sourced peat (Figure 3.2a), which was inserted up to 30 cm into the pipe outlet. Time-lapse cameras captured any surface changes of the newly blocked pipe outlets and any seepage of water over a two week period after blocking. The footage showed water was observed emanating either side of the plug. In a second attempt, the same outlets were filled over the same length with a mixture of peat and stones, sourced from the nearest stream bed (Figure 3.2b), which resulted in a more varied seepage pattern, with at least one blocked pipe outlet being occasionally dry whilst others still showed active seepage around the plug.

Table 3.1 Details of the two sub-catchments monitored in Upper North Grain

	Control catchment	**Treatment catchment**
Catchment outlet	53°26’31”N , 001°50’16”W	53°26’28”N , 001°50’30”W
Elevation of outlet (m asl)	519.1	511.8
Area (m^2)	43,178	37,506
Mean slope (degrees)	6.11	7.68
Flow direction of main channel	south west to south east	south
Number of pipe outlets [a]	41 (5 head; 39 edge)	65 (25 head; 40 edge)
Number of blocked pipe outlets	0	31

[a] identified in 2018-2019 pipe outlet survey (Regensburg, 2020).

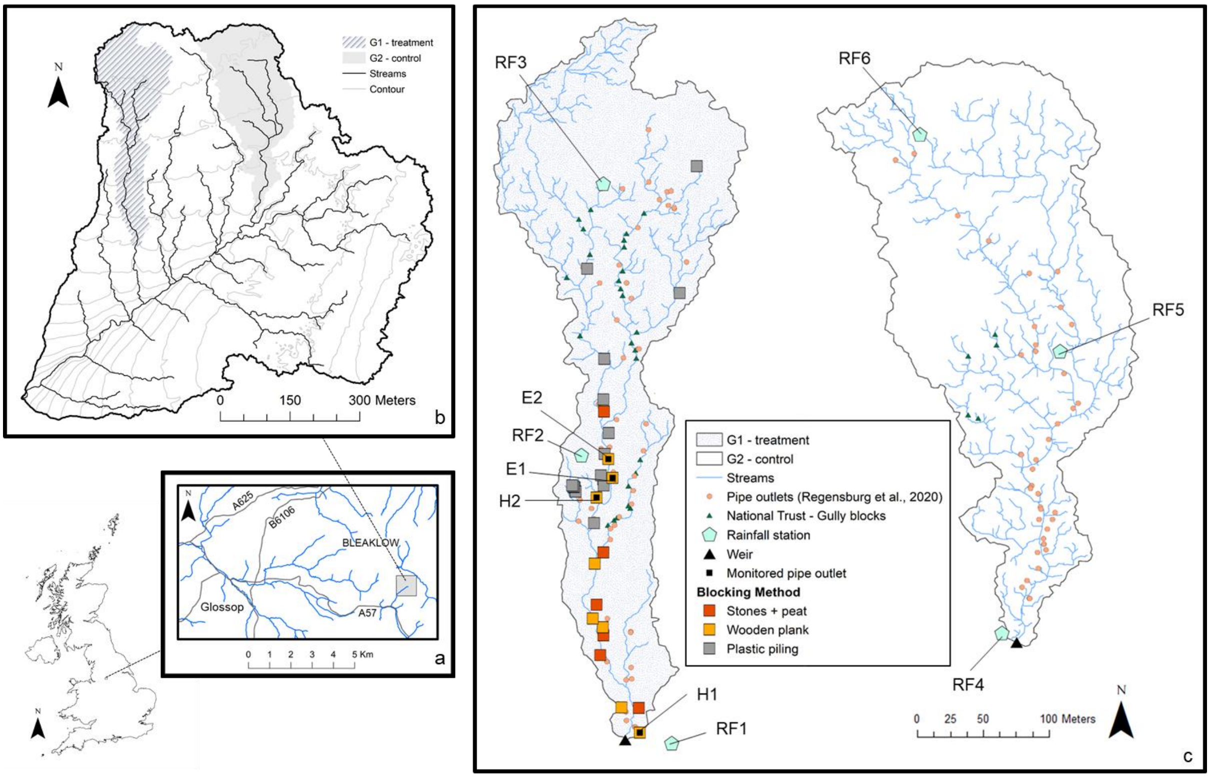

Figure 3.1 Map overview showing a) the location of Upper North Grain study catchment; b) the location of the selected sub-catchments in the stream network, with contour intervals of 5 meters from 535 m to 480 m above sea level; c) monitoring setup for the sub-catchments showing the location of pipeflow gauges at head locations (pipe H1 and pipe H2) and edge locations (pipe E1 and pipe E2), rainfall stations (RF1 – 6), and weirs (black large triangle) at catchment outlets. Materials used to block pipe outlets: 1. Mixture of peat and stones (red), 2. Wooden plank (orange), and 3. Plastic piling (grey). Identified pipe outlets in both catchments (beige circles) are added for reference. Note that the area of tributaries affected by gully blocks (small triangles – green) is larger for the treatment catchment compared to the control catchment.

Between 20 August and 24 September 2019, pipe outlets with clear evidence of recent pipeflow were blocked in the treatment catchment. Initially, ten pipe outlets were blocked by inserting a plug-like structure involving a mixture of peat and stones, but water was observed percolating around and through all of them within 7 days of blocking. Therefore, further blocking focused on the insertion of vertical screens of marine plywood (‘wooden planks’) (Figure 3.2c) and later plastic piling (Figure 3.2d). Screen widths ranged between 0.3 and 1 m. The four pipe outlets with a pipeflow gauge were each blocked with a wooden plank of 1 m width, which was inserted up to at least twice the depth of the pipe outlet relative to the peat surface. Where feasible, pipe outlets initially blocked with a mixture of peat and stones received either a wooden or a plastic screen. By 24 September 2019, a total of 31 pipe outlets had been blocked in the treatment catchment resulting in six blocks with a mixture of peat and stones, eight with wooden planks, and 17 with plastic piling. These 31 blocked outlets represented 68 % of the total identified pipe outlets across the treatment catchment at that time (Regensburg, 2020). On 27 September 2019 a further 20 pipe outlets were identified in two tributaries of the treatment catchment, which both had gully blocks in them (Regensburg, 2020). Between August 2019 and February 2020, the 31 blocked pipe outlets in the treatment catchment were assessed for leakiness through the observation of seepage from photos taken at biweekly intervals. When seepage was observed, its most dominant flow route was determined using the following classification: 1) unidentifiable, 2) from the old outlet only, 3) from new outlets only, and 4) a combination of old and new outlets. For each observation of seepage the rate of flow was visually estimated, using pipe discharge measurements before blocking (see below).

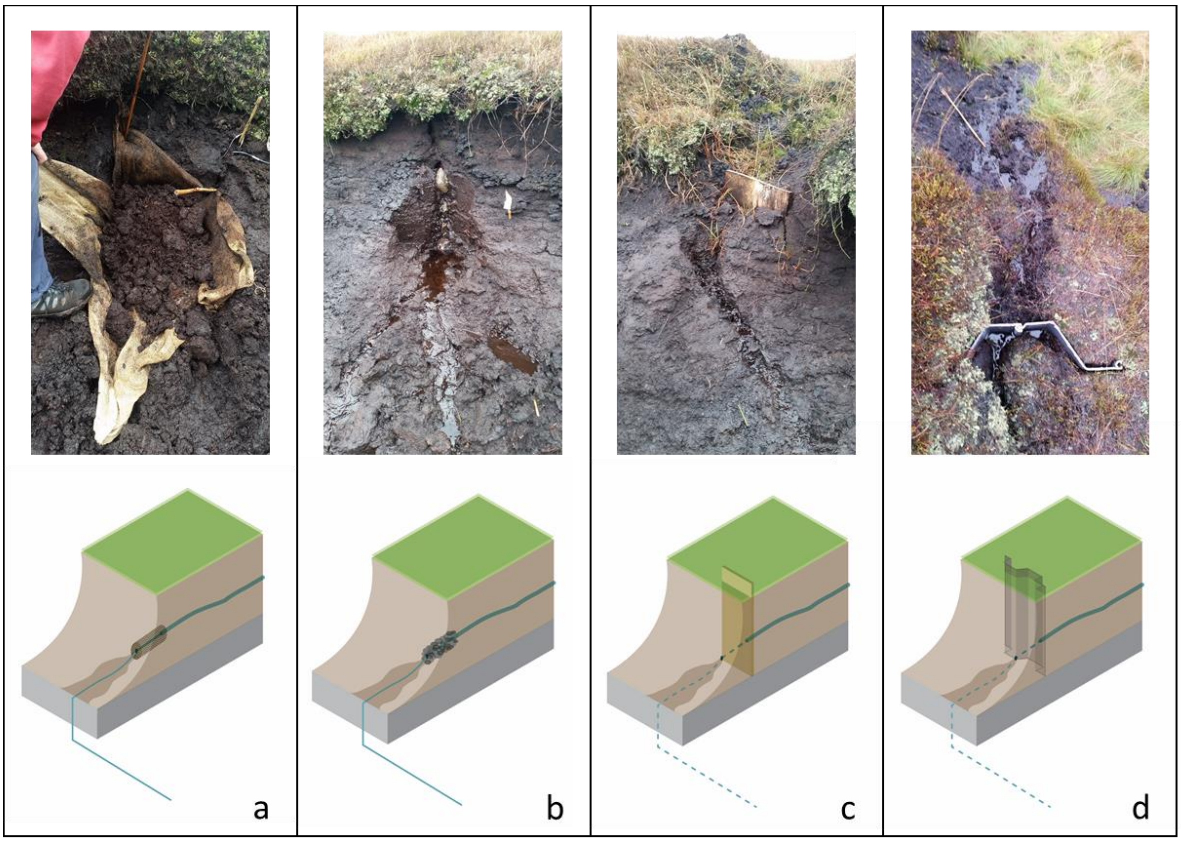

Figure 3.2 Schematic showing the design and in-field application of plug-like structures and vertical screens to block pipe outlets: a) jute bag filled with peat, b) mixture of peat and stones, c) wooden plank, and d) plastic piling. Illustrations produced by Philippa Lewis.

3.3 Monitoring

3.3.1 Precipitation

Rainfall stations were installed at three locations within each sub-catchment, equidistantly spaced between the stream outlet and the head of the respective stream network. Each rainfall station comprised of a tipping bucket (DAVIS AeroCone with 0.2 mm resolution) recording at 5-minute intervals, and a storage gauge to measure accumulated rainfall between field visits (approximately every two weeks). One rainfall station (RF2) was placed next to pipe E2 in April 2018, with the other five being installed in December 2018 (Figure 3.1c).

3.3.2 Stream discharge

Stream discharge was gauged at the outlet of each catchment by insertion of a weir plate using a calibrated V-notch. Water head above the notch was recorded using a vented pressure transducer (In-Situ Troll 500) that was placed in a stilling well ~1 metre upstream of the weir crest. Stage was recorded at 5-minute intervals. At low flows, up to 0.5 litre per second, a stage discharge relationship was determined by measuring the volume of water per unit of time using a measuring cylinder and stopwatch. At higher flows, salt dilution gauging was carried out in a 10 m straight section downstream of the weir. A stage-discharge relationship for each stream was constructed by combining the results from the two methods. Streamflow monitoring commenced in October 2018 for the treatment catchment and in December 2018 for the control catchment.

3.3.3 Pipe discharge

Pipe discharge was monitored at four pipe outlets in the treatment catchment: pipe H1 (May 2018 to February 2020), pipe H2 (May 2018 to December 2019), pipe E1 (October 2018 to August 2019), and pipe E2 (May 2018 to February 2020). At each pipe outlet, water was channelled via guttering into a rectangular plastic box of 140 mm x 340 mm x 220 mm with a 22.5° V-shaped opening, hereafter referred to as “pipeflow gauge”. Each pipeflow gauge was instrumented with a vented pressure transducer (In-Situ Troll 500), which recorded water level above the sensor head in the box at a 5-minute interval. Gutters from the pipe outlet to the pipeflow gauge were shielded from rainfall using waterproof tape or polyethylene plastic sheeting. After blocking pipe outlets in August 2019, any water that appeared around or close to the blocked outlets that were monitored, was redirected to the respective pipeflow gauge, where possible, using guttering, to quantify the amount of water escaping from the blocked pipe. During field visits, when water was flowing over the notch of the V, discharge from the pipeflow gauges was measured using a measuring cylinder and a stopwatch, to derive a stage-discharge relation. The seepage around other blocked pipe outlets observed during field visits was visually estimated as No Flow, Low (< 0.05 L s^{-1}), Medium (0.05 – 0.50 L s^{-1}), and High (> 0.5 L s^{-1}).

3.3.4 Water-table depth

Water table was measured around each of the four pipe outlets, using a network of 12 dipwells, that was set up in three transects, of which one was parallel to the projected pipe course (α) and two perpendicular to it (β and γ). Transect α had four dipwells at 1, 3, 5, and 9 m from the pipe outlet (Figure 3.3a). Transects β and γ each had five dipwells spaced equidistantly every 1 m with the middle dipwell on transect α, at 1 and 3 meters from the pipe outlet respectively (Figure 3.3a). Each dipwell comprised a 1 m length of polypropylene pipe (internal diameter 30 mm) with perforations at 50 mm intervals, with four holes at a 90 ° spacing per interval. Dipwells were driven into pre-prepared boreholes. A removable cap was placed on top of each dipwell to prevent water ingress by rainfall or animal disturbance (Figure 3.3b). The dipwell closest to the pipe outlet was instrumented with an automated water-level logger (In-situ Troll 500), recording at 5-min intervals. At the other 11 dipwells, water-table depth was measured manually every two weeks by inserting a sounding dip-meter. Continuous water-table records for the automated dipwells were available for all four pipe locations, but spanning different periods: pipe H1 May 2018 – January 2020, pipe H2 May 2018 – December 2019, pipe E1 May 2018 - December 2019, and pipe E2 May 2018 – December 2019. Between April and August 2019 water-table data were not available for pipe H2 and pipe E1 due to equipment failure.

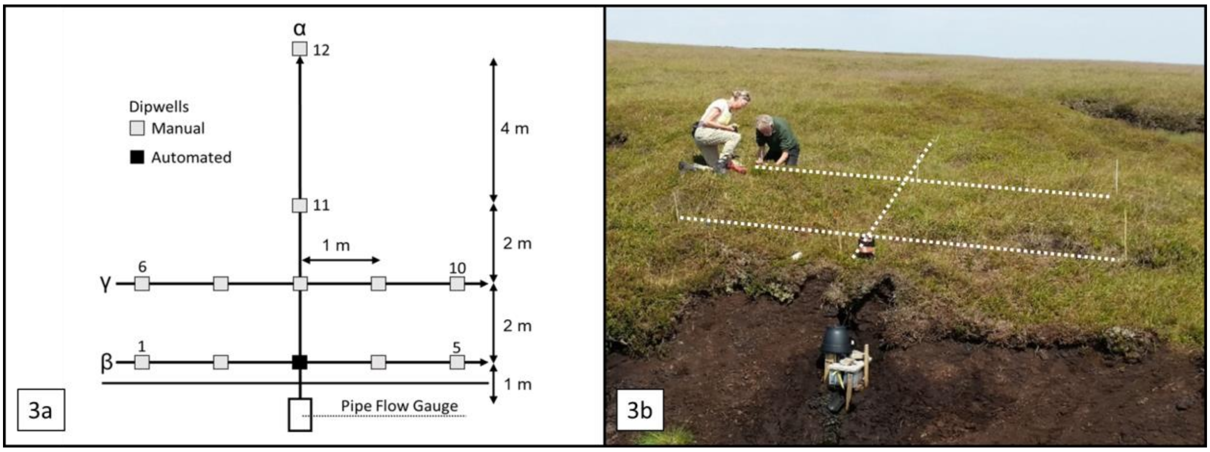

Figure 3.3 Monitoring of water table at each gauged pipe outlet location: a) schematic of dipwell set up around gauged pipe outlets. Dipwells were placed along transect lines α, β, and γ. Transect lines β and γ were used to characterise the lateral water-table interactions from the projected pipe course, and α to determine water table parallel to the projected pipe course. Transect β and γ run parallel to the gully edge; b) volunteers measuring water-table depth at pipe E1 on 16 July 2019. White dotted lines indicates approximate position of the dipwell transects (β and γ parallel to gully edge, and α perpendicular to it).

3.4 Data processing

Operational issues led to occasional periods where no data were available for some locations.

3.4.1 Precipitation

Gaps in rainfall timeseries were referenced to nearby stations (for details see Appendix A). An antecedent precipitation index (API) was derived for the catchment preceding storm events using a universal API equation after Kohler and Linsley (1951):

$$\boldsymbol{API_t = API_{t-1}\,k + \,P_{\Delta t}} \qquad \textbf{6}$$

where API_t is API at time t, $P_{\Delta t}$ is the precipitation occurring between times t-1 and t, and k is the recession coefficient. API was calculated for a period of three consecutive days prior to each storm event, using daily precipitation totals for $P_{\Delta t}$. As blanket peats have generally little capacity for extra water uptake, it was assumed that per new day half of the indexed precipitation from the previous three days would dissipate via evapotranspiration and runoff. To account for this, the contribution of previous wetting events to runoff was discounted by 50 % (k = 0.5). API was used to study whether antecedent rainfall could explain seepage from blocked pipe outlets during field visits.

3.4.2 Storm responses

Hydrological responses were derived from rainfall time series from April 2018 to February 2020, at time steps of 5 minutes. Stream and pipe discharge series were screened for responses to rainfall events in excess of 1 mm over at least three consecutive time steps. A total of 141 storms were identified, covering 93 events in the pre-blocking period and 48 events post-blocking. The response of stream- and pipeflow to each individual storm was quantified as long as the following criteria were met:

1. The event was rainfall-driven and not associated with snowmelt.
2. Storm responses were single peaked, but minor secondary peaks with peak discharge of less than 20 % of the total storm peak discharge were allowed to help achieve temporal representativeness across stream- and pipeflow.
3. Storm responses were not included when data gaps occurred around the projected discharge peak.

This resulted in different numbers of hydrographs being analysed for pre- and post-blocking at each catchment and pipe outlet (Table 3.2).

Hydrograph response was quantified using four metrics: 1) storm discharge – the total volume (in mm or L) of water leaving the weir during an event; 2) peak lag – the time (in hours) between peak rainfall and peak discharge; 3) peak discharge – the highest discharge (L s^{-1}) reached during the storm; 4) duration of storm discharge – the total time for which the measured discharge was larger than baseflow (Appendix A-Fig 2). To account for the impact of catchment area on stream discharge, storm discharge was divided by topographic drainage area, providing specific discharge, expressed in mm; the runoff coefficient was also calculated as a function of total storm rainfall. Because the topographic drainage area of pipe outlets is not known, a theoretical dynamic contributing area was calculated by dividing total pipe discharge by total rainfall, assuming a rainfall-to-runoff conversion of 100 %. To characterise hydrograph shape, a response index was calculated by dividing storm peak discharge by the time duration that storm discharge was larger than baseflow. For events with peak discharges outside the confidence window of the stage-discharge curves, the raw stage data of each respective sensor was used to determine the time of peak discharge. Recession rates for water table were derived from the gauged dipwell closest to each pipe outlet, and calculated as a mean over 6 and 12 hours after rainfall cessation (Appendix A-Fig 2).

Table 3.2 The number of hydrographs per gauge that met the required criteria for analyses.

	Pre-blocking period	**Post-blocking period**	**Total per gauge**
Control catchment	61	35	96
Treatment catchment	59	36	95
Pipe outlet H1	73	34	107
Pipe outlet H2	80	16	96
Pipe outlet E1	64	-	64
Pipe outlet E2	45	17	62

Most variables did not follow a normal distribution, therefore non-parametric tests of difference were employed. When groups of data violated assumptions for homogeneity of variance, differences between groups were explained in terms of their distributions, otherwise median differences were reported. The combined effect of blocking 31 individual pipe outlets on streamflow was determined by calculating a statistical response variable (η^2) for storm events to which both sub-catchments responded. Data on runoff coefficients and peak lag were both ratio data, therefore standardizing was not applied, and difference was calculated by subtracting control from treatment. For metrics depending on peak discharge, data were scaled before subtracting control from treatment data. The statistical response variable was calculated as follows:

$$\boldsymbol{\eta^2 = \frac{Z^2}{n-1}} \tag{7}$$

where Z is the standardised test statistic in the Mann Whitney U test performed on the difference between control and treatment, n is the number of samples involved. η^2 was used to explain the fraction of the variability in the ranks that can be accounted for by blocking of pipe outlets.

3.5 Results

3.5.1 Water budget

The first 12 months from 1 April 2018 were relatively dry, with 844 mm compared to the long-term mean of 1313 mm. Rainfall between 1 April 2019 and 29 February 2020, was more typical with a total of 1467 mm. Summer (JJA), autumn (SON) and winter (DJF) were all considerably wetter in 2019 compared to 2018, with 382, 546 and 376 mm in 2019 versus 121, 266 and 165 mm in 2018 respectively (Figure 3.4). Rainfall totals were comparable for the period April-May in 2018 and 2019, with 118 mm in 2018, compared to 112 mm in 2019, respectively. The maximum 15-minute rainfall intensity was 35.3 mm h^{-1}, recorded on 24 July 2019. Water budgets for the treatment and control catchments were similar to each other from month to month (Figure 3.4). Over the whole monitoring period, when both stream runoff records were available, the runoff coefficient was 85.9 % for the treatment catchment and 85.2 % for the control catchment. In winter periods, both sub-catchments show rainfall conversions larger than 100 %, which may be due to delayed snow melt events or surface catchment areas not aligning with subsurface catchment areas where piping is an ubiquitous process.

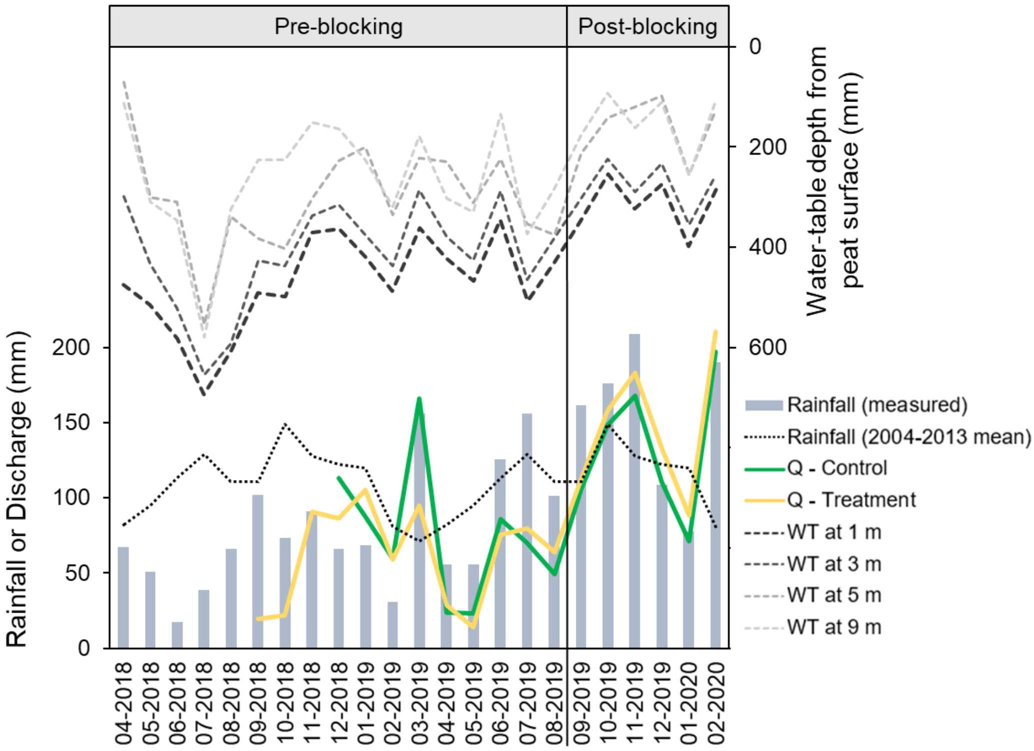

Figure 3.4 Monthly rainfall over the period April 2018 – February 2020. The mean rainfall between 2004-2013 is shown for reference (based on Clay and Evans (2017)). Total discharge for the control (Q – Control) and treatment catchment (Q – Treatment). Monthly median water-table depths from peat surface (WT) are specified for dipwell positions at 1 m, 3 m, 5 m and 9 m away from the pipe outlet following transect α (see Figure 3.3) (grey dashed lines, with increasing shading for increasing distance away from pipe outlet).

3.5.2 Success of pipe outlet blocking

Blocked pipe outlets were assessed for leakiness through observations of seepage on 12 occassions between August 2019 and February 2020. Not all pipe outlets could be assessed on each visit, but in total 86 observations were recorded. Seepage around blocked pipe outlets was recorded in 86 % of observations. After 25 September 2019, seepage was observed in more than half of the pipe outlets on visit days with an API > 10 mm. Seepage was observed at a median of 14 days since blocking. Seepage was observed within 26 days of blocking at pipe outlets plugged with a mixture of peat and stones, as early as 5 days since blocking at wooden plank screens, and as early as the day of blocking at plastic piling screens. Three quarters of all blocked outlets showed signs of seepage within 36 days of blocking. One pipe outlet blocked by a wooden plank only showed the first signs of seepage after 90 days since blocking. The occurrence of leaks was recorded 95 % for stone and peat blocks, 83.3 % for wooden planks, and 82.9 % for plastic piling (Table 3.3).

Seepage was observed via the old outlet (57 %), new outlets (15.1 %), or both (2.3 %) (Table 3.3). Flow from new pipe outlets was observed in 37.5 % of pipe outlets blocked by screens of wooden planks and 11.8 % of pipe outlets blocked by screens of plastic piling (Table 3). In the majority of the seepage observations, flow rates across blocked pipe outlets were < 0.5 L s^{-1}, with 36 % for < 0.05 L s^{-1} and 39.5 % for 0.05-0.5 L s^{-1} (Table 3.3). New outlets occurred within a range of 0.3 to 2.0 m from the original outlet, on both left and right hand sides, and both shallower and deeper than the blocked pipe outlet.

Table 3.3 Summary of the leakiness of blocked pipe outlets, detailing the number of observations on 1) flow rate of seepage, and 2) the dominant flow route of seepage (NI = not identifiable, old outlet only, new outlet only, both old and new pipe outlets). NF = no flow, Low = < 0.05 L s^{-1}, Med = 0.05 – 0.5 L s^{-1}, High = > 0.5 L s^{-1}.

	Flow rate of seepage (n)				**Flow route of seepage (n)**			
Blocking method	NF	Low	Med	High	NI	old only	new only	old + new
stone + peat (n = 6)	1	8	8	4	2	18	0	0
wooden plank (n = 8)	4	5	10	5	0	10	9	1
plastic piling (n = 17)	7	18	16	0	8	21	4	1

3.5.3 Storm analyses - Stream responses

The combined effect of pipe outlet blocking on stream responses ranged between 0.014 and 0.207, with medians being significantly different across intervention periods for peak discharge and response index (Figure 3.5).

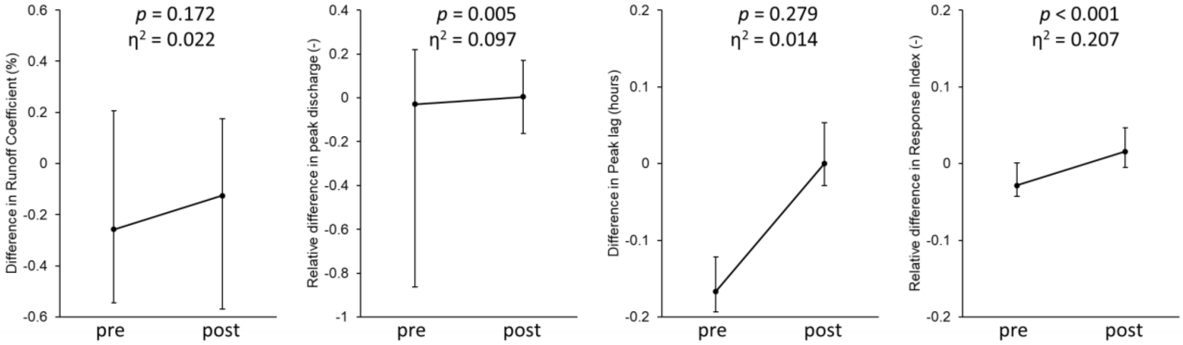

*Figure 3.5 Interaction plots for differences (treatment minus control) before and after pipe outlet blocking for runoff coefficient (%), standardised peak discharge (-), peak lag (hours), and standardised response index (-), calculated for 84 storm responses (pre: 49, post: 35). Positive values on the y-axis indicate that the metric of interest is larger in the treatment catchment than in the control catchment, while negative values indicate the opposite. The whiskers indicate the lowest and highest values that are still within the range: [Q1 – Q2 - 1.5 * (Q3 - Q1)] and [Q3 - Q2 + 1.5 * (Q3 - Q1)]. For each metric the difference of variation and the statistical response variable* $\boldsymbol{\eta^2}$ *was determined. Note that the y-axis of the plots may have different scales.*

The treatment catchment showed increased median runoff coefficients across intervention periods. The control had significantly different distributions of runoff across intervention periods (Table 3.4, Appendix A-Fig 3). In the post-blocking period, distributions of runoff coefficient were similar between catchments. Median runoff coefficients were significantly different in the pre-blocking period, with the treatment catchment producing much less discharge per mm rainfall compared to the control (Table 3.4, Appendix A-Fig 3). Peak flows ranged from 0.1 L s^{-1} to 16.8 L s^{-1} in the treatment catchment, and 0.1 L s^{-1} and 20.1 L s^{-1} in the control catchment. Pipe outlet blocking did not affect differences between treatment and control catchments for peak discharge and peak lag (Table 3.4). The treatment catchment produced significantly smaller median peak discharges compared to the control catchment in the period before blocking, but peak discharges were the same for both catchments in the post-blocking period (Table 3.4, Appendix A-Fig 3). Median peak discharges in the post-blocking period were significantly larger compared to those in the pre-blocking period for the treatment catchment, but were the same for the control catchment across intervention periods (Table 3.4, Appendix A-Fig 3). No significant differences were found between catchments or intervention periods for peak lag ($p < 0.05$) although the difference of median peak lag for the treatment catchment between intervention periods was marginally significant at $p = 0.066$ (Table 3.4). Flow duration was found to be the same in catchments and across intervention periods. Therefore, differences between response indices mimic those of the peak discharge. In the pre-blocking period, hydrograph shapes were significantly different between the treatment catchment and the control catchment, but in the post-blocking period their hydrograph shape was similar (Table 3.4, Appendix A-Fig 3).

Table 3.4 Statistical analyses of storm responses, providing Mann-Whitney U test results for differences across catchments and monitoring periods with medians for runoff coefficient, peak discharge, peak lag and response index.

		Differences across catchments		**Differences across monitoring periods**	
Parameter	Period	p - value	N samples	Control (n = 95)	Treatment (n = 94)
Runoff Coefficient (%)	Pre	0.005	118	50.7	30.4
	Post	0.709	71	68.0	66.5
				$p = 0.004$	$p < 0.001$
Peak discharge (L s^{-1})	Pre	0.018	118	5.4	3.3
	Post	0.159	71	7.7	6.7
				$p = 0.104$	$p = 0.012$
Peak lag (hr)	Pre	0.631	118	2.0	2.4
	Post	0.881	71	1.6	1.7
				$p = 0.211$	$p = 0.066$
Response Index (L s^{-2})	Pre	0.014	118	1111	548
	Post	0.218	71	1602	1127
				$p = 0.524$	$p = 0.039$

3.5.4 Storm analyses - Pipe response

Between 11 September 2018 and 1 September 2019, the four monitored pipe outlets, which were the largest in the treatment catchment, contributed 11.3 % to storm discharge, with the two head pipes contributing 9.3 % (pipe H1: 2.0 %, pipe H2: 7.3 %) and the two edge pipes 2.0 % (pipe E1: 0.7 % + pipe E2: 1.3 %). In the post-blocking period, 1 September 2019 to 1 March 2020, pipe water that escaped from the blocked pipes contributed 4.3 % to stream stormflow (pipe H1: 2.3 %, pipe H2: 1.8 %, pipe E2: 0.1 %). Pre-blocking, a clear differentiation was observed between discharge responses of pipe outlets at head and edge locations, especially when comparing contribution area to API and event rainfall (Appendix A-Fig 4a). Increased dynamic contribution area resulted in a larger peak discharge with a strong relationship for head locations in both intervention periods (Appendix A-Fig 4b). Peak lag was not dependent on dynamic contribution area for both head and edge locations (Appendix A-Fig 4b).

In the pre-blocking period, the distributions of storm discharge between head and edge locations were significantly different ($p < 0.001$, n = 262) (Table 3.5, Appendix A-Fig 4b). Pre-blocking, the distributions of storm discharge were significantly different between pipe outlets at head locations (pipe H1 and pipe H2)($p < 0.001$, n = 153) and pipe outlets at edge locations (pipe E1 and pipe E2) ($p < 0.001$, n = 109) (Table 3.5, Appendix A-Fig 5). No evidence indicated that storm discharge was different between pipe H1 and pipe H2 post blocking (Table 3.5). Median storm discharge increased across intervention periods for pipe H1 ($p = 0.009$, n = 107), whereas the opposite was observed for pipe H2 ($p = 0.028$, n = 96) (Table 5, Appendix A-Fig 5). No data were available for pipe E1 in the post-blocking period due to instrument failure. Pipe E2 only produced discharge during two of the seventeen storms after it was blocked. As a result, storm discharge distributions for pipe E2 were significantly different across intervention periods ($p < 0.001$, n = 62) (Table 3.5). Because pipe E2 rarely flowed in the post-blocking period, analyses of peak discharge and peak lag were omitted. As all pipes received a blocking treatment in August 2019, a subset of data comparing the same times of year pre and post blocking were compared (September 2018-February 2019; September 2019-February 2020). Due to limited edge pipe data post-blocking, comparisons between years were only performed for head pipes. Median storm discharge was 2.2 m^3 for 2018/19 (n = 47) and 1.7 m^3 for 2019/20 (n = 48). Total storm discharge was 177.9 m^3 for 2018/19 and 128.6 m^3 for 2019/20. Despite 2018/19 being 26.4 % wetter, no evidence was found to indicate that distributions of head pipe storm discharge differed significantly between 2018/19 and 2019/20 ($p = 0.364$, n = 95).

Table 3.5 Comparison of storm pipeflow responses in the pre- and post-blocking period, with median values per metric for each pipe outlet for storm discharge (L), peak lag (hr), peak discharge (L s^{-1}), dynamic contribution area (m^2) and response index (L s^{-2}). For each metric Mann-Whitney U test outputs (MWU) at 95 % significance interval are indicated for comparisons across intervention period and across pipe outlet location.

Storm discharge (L)

	Pre-blocking	n	Post-blocking	n	MWU
Pipe H1	714	73	1670	34	$p = 0.009$
Pipe H2	3528	80	1606	16	$p = 0.028$
MWU	$p < 0.001$		$p = 0.618$		
Pipe E1	247	64	No data	-	-
Pipe E2	943	45	0	17	$p < 0.001$
MWU	$p < 0.001$		-		

Peak discharge (L s^{-1})

	Pre-blocking	n	Post-blocking	n	MWU
Pipe H1	0.060	72	0.108	34	$p = 0.072$
Pipe H2	0.220	79	0.116	15	$p = 0.084$
MWU	$p < 0.001$		$p = 0.680$		
Pipe E1	0.018	64	No data	-	-
Pipe E2	0.069	45	0.028	2	$p = 0.204$
MWU	$p < 0.001$		-		

Peak lag (hr)

	Pre-blocking	n	Post-blocking	n	MWU
Pipe H1	2.9	72	2.3	34	$p = 0.164$
Pipe H2	2.5	79	3.2	15	$p = 0.287$
MWU	$p = 0.409$		$p = 0.051$		
Pipe E1	2.2	64	No data	-	-
Pipe E2	2.0	45	-0.1	2	$p = 0.204$
MWU	$p = 0.902$		-		

Dynamic contribution area (m^2)

	Pre-blocking	n	Post-blocking	n	MWU
Pipe H1	156	73	341	34	$p < 0.001$
Pipe H2	673	80	265	16	$p < 0.001$
MWU	$p < 0.001$		$p = 0.092$		
Pipe E1	48	64	No data	-	-
Pipe E2	144	45	0	17	$p < 0.001$
MWU	$p < 0.001$		-		

Table 3.5 continues next page

Response index (L s^{-2})

	Pre-blocking	n	Post-blocking	n	MWU
Pipe H1	16.620	72	13.196	34	*p* = 0.478
Pipe H2	9.569	79	15.191	15	*p* = 0.432
MWU	*p* = 0.037		*p* = 0.819		
Pipe E1	13.072	64	No Data	-	-
Pipe E2	11.209	45	20.423	2	*p* = 0.599
MWU	*p* = 0.968		-		

In the full pre-blocking period, peak storm discharge for the four monitored pipes ranged from 0.001 to 0.859 L s^{-1}. In the same period, distributions of storm peak discharge were significantly different between head and edge locations (p < 0.001, n = 260) (Table 3.5, Appendix A-Fig 4), between pipe outlets at head locations (pipe H1 and pipe H2) (*p* < 0.001, n = 151), and between pipe outlets at edge locations (pipe E1 and pipe E2) (*p* < 0.001, n = 109) (Table 3.5, Appendix A-Fig 5). Across intervention periods, median storm peak discharges were marginally significantly different for pipe H1 (*p* = 0.072, n = 106) and pipe H2 (*p* = 0.084, n = 94) (Table 3.5, Appendix A-Fig 5).

In the pre-blocking period, distributions of dynamic contribution area were significantly different for head and edge locations (p < 0.001, n = 262) (Table 3.5, Appendix A-Fig 4). In the pre-blocking period, distributions of dynamic contribution area for pipe H1 and pipe H2 were significantly different (*p* < 0.001, n = 153), and for pipe E1 and pipe E2 (*p* < 0.001, n = 109)(Table 3.5, Appendix A-Fig 5). Post-blocking, medians for dynamic contribution area of pipe H1 and pipe H2 were marginally significantly different to each other (*p* = 0.092, n = 50)(Table 3.5, Appendix A-Fig 5). Across intervention periods, a significant difference was found between median dynamic contribution area for pipe H1 (*p* < 0.001, n = 107), and distributions of dynamic contribution area for pipe H2 (*p* < 0.001, n = 96) (Table 3.5, Appendix A-Fig 5). Peak lag was not different between pipes in the pre-blocking period. Post-blocking, median peak lag differed marginally between pipe H1 and H2 (*p* = 0.051, n = 49) (Table 3.5). Peak lag and time from peak flow to baseflow for pipes was the same as for the stream in both intervention periods.

3.5.5 Water-table responses

Overall, average water table was at its deepest during JJA 2018 and its shallowest during DJF 2018-19 (Figure 3.4). Mean water-table depth across all monitored dipwells was 364 mm in the pre-blocking period and 247 mm post-blocking. Water-table recession rates over 6 hours were distributed significantly differently across intervention periods for pipe H1 (*p* = 0.013, n = 101), pipe H2 (*p* = 0.030, n = 82) and were marginally different for pipe E1 (*p* = 0.052, n = 74) (Appendix A-Fig 6). Distributions of water-table recession rates over 12 hours were significantly different across intervention periods for pipe H1 (*p* = 0.005, n = 94), pipe H2 (*p* = 0.008, n = 78), and pipe E2 (*p* = 0.006, n = 90) (Appendix A-Fig 6). In the post-blocking period, the lower boundary of the water-table depth at the automated dipwell at pipe H1 stabilised at around 400 mm, but such strong effects were not observed in other dipwells in the vicinity of pipe H1, nor in water-table timeseries at the other pipe outlets (Figure 3.6).

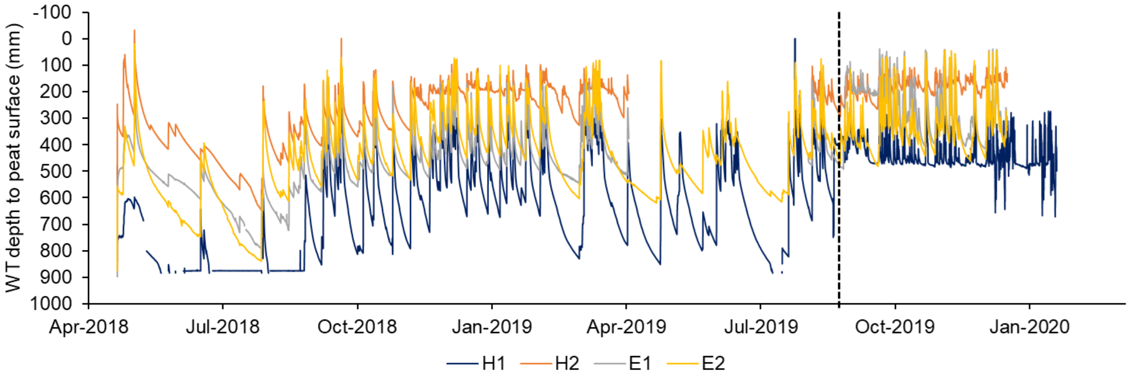

Figure 3.6 Timeseries of water-table depth at automated dipwell stations for pipes H1, H2, E1 and E2. Vertical dotted line indicated time of blocking pipe outlets.

In both transects β and γ at pipe H1 and pipe E2, median water-table depths were considerably lower and less varied over time at positions not directly above the projected pipe course compared to other pipe outlets (transect α) (Appendix A-Fig 7). At head locations, distributions of water-table depth were significantly different across intervention periods for dipwells at 1 m ($p < 0.001$) and 5 m ($p = 0.003$) from the pipe outlet (Table 3.6). At head locations, median water-table depth decreased across intervention periods at 3 m ($p = 0.001$) and 9 m ($p = 0.02$) from the pipe outlet (Table 3.6). At edge locations, median water-table depth decreased significantly across intervention periods at 1, 3 and 5 m from the pipe outlet (Table 3.6). Dipwells at 9 m from the pipe outlet at edge locations had similar distributions across intervention periods (Table 3.6). In the pre-blocking period, median water-table depths at dipwells 1 and 9 m from the pipe outlet were significantly shallower for head locations compared to edge locations. Distributions of water-table depths differed significantly between head and edge locations in the pre-blocking period at 3 m from the pipe outlet, and in the post-blocking period at 1, 3, and 9 m from the pipe outlet (Table 3.6). Water-table depth at 5 m from the pipe outlet was not significantly different between head and edge locations in both intervention periods (Table 3.6). Across the whole monitoring period a clear drawdown of the water table was observed along dipwell transect α, with increasing water-table depths towards the pipe outlet. Drawdowns ranged from 94 mm to 115 mm between 1 m and 3 m away from the pipe outlet, and 85 mm and 156 mm between 3 m and 5 m away from the pipe outlet (Figure 3.7). This distance-decay effect occurred up to 9 m from head pipe outlets and 5 m from edge pipe outlets (Figure 3.7).

Table 3.6 Differences in water-table depth relative to the peat surface (mm) at pipe outlet locations (head and edge) at 1, 3, 5, 9 m from the pipe outlet (following transects α, see figure 3.3), with median water-table depth for both intervention periods (pre and post), and tests of difference between intervention periods (pre- and post-blocking) and between head and edge locations.

		distance from pipe outlet (m)			
		1	3	5	9
head	pre	407.4	300.5	268.5	200
	post	279.4	193.1	131	94
	p-value (n = 68)	< 0.001	0.001	0.003	0.02
edge	Pre	537.4	452.8	294	475
	post	407.6	336.1	229	393.5
	p-value (n = 68)	< 0.001	< 0.001	0.016	0.381
pre-blocking head vs edge		*p* < 0.001, n = 100	*p* < 0.001, n = 100	*p* = 0.238, n = 81	*p* = 0.001, n = 78
post-blocking head vs edge		*p* = 0.011, n = 36	*p* < 0.001, n = 36	*p* = 0.126, n = 36	*p* = 0.012, n = 36

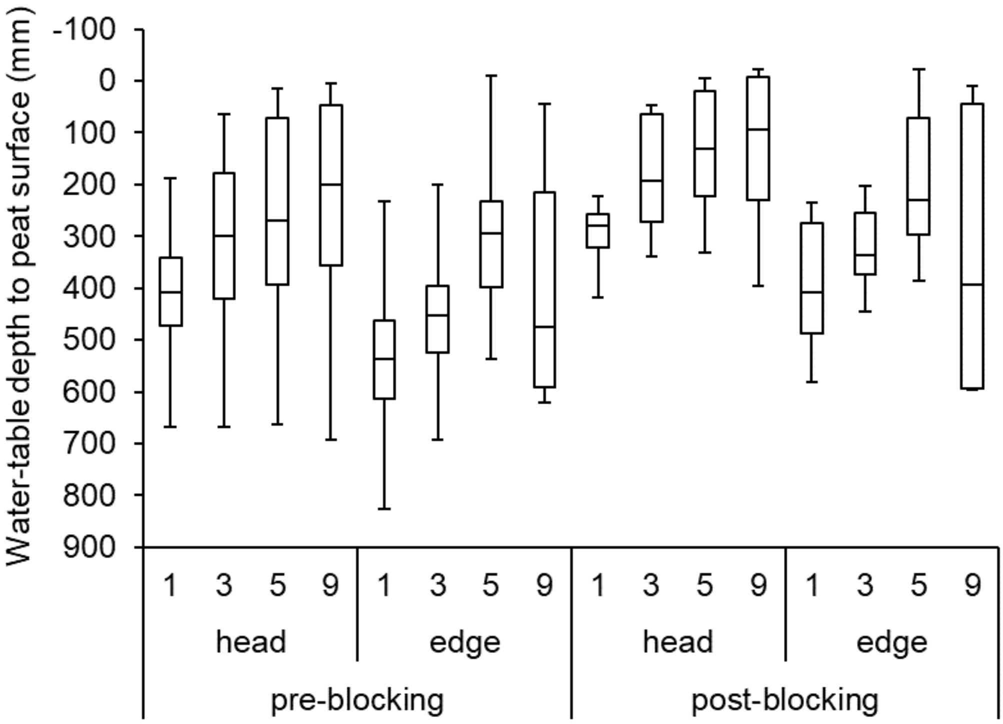

Figure 3.7 Boxplot of water-table distribution at head and edge locations, across intervention period (pre and post), at 1, 3, 5, and 9 m from the pipe outlet.

3.6 Discussion

3.6.1 Effect of pipe outlet blocking on streamflow

This study assessed, for the first time, the hydrological implications of pipe outlet blocking on streamflow in a heavily degraded blanket bog. Our results show that stormflow responses in two sub-catchments had similar distributions for runoff, peak discharge, peak lag and hydrograph shape after pipe outlets had been blocked in one of them. As shown in Figure 3.4, the pre-blocking period was drier than the post-blocking period. Storm runoff was the same in both catchments post-blocking, whereas pre-blocking storm runoff in the treatment catchment was 20.3 % less than in the control. A similar trend was observed for peak discharge between the two catchments across intervention periods. The increase in storm runoff in the treatment catchment post-blocking may be related to the increased rainfall over the course of the experimental period. A wetter peat profile may promote pipes to drain water from outside the topographic boundary of the catchment, resulting in increased pipe-to-stream runoff contributions in the treatment catchment compared to the control, where fewer pipes were present per catchment area. In addition, the build-up of pipe water behind blocks may have increased hydraulic pressures in the pipe, which has been observed in soil pipes that have clogged naturally (Mikayla *et al.*, 2015). In turn, this may have caused surcharging within the pipe network, helping to connect portions of the pipe network that are overflow dependent and that otherwise would not drain below such overflow thresholds (Gilman and Newson, 1980). Pre-blocking, the limited runoff production in the treatment catchment may result from gully blocks in the tributaries, whereas the control only had gully blocks in a small headwater section (see Figure 1c). Gully blocks can provide a reduction in streamflow (Shuttleworth *et al.*, 2019) with impacts most notable in drier conditions when runoff is buffered behind the blocks.

3.6.2 Success of the different pipe outlet blocking methods

Pipe outlets blocked by either method, insertion of plug-like structures in the pipe-end or the insertion of vertical screens at the pipe outlet perpendicular to the pipeflow direction, showed signs of leakiness. Given that at 75 % of the blocked pipes seepage occurred within 6 weeks of blocking, this highlights the challenge in trying to stop pipeflow by blocking outlets. The insertion of plug-like structures into pipe-ends did not result in any reductions of pipeflow as evidenced by flow emerging from pipe outlets post-blocking, but no new exits were observed around pipe outlets blocked by plug-like structures in contrast to pipe outlets blocked by vertical screens.

Laboratory tests by Wanger *et al.* (2019) showed plugs of compressed sand inserted into pipes mobilised regardless of the pressurised time, particularly when the plugs became saturated. However, the hydraulic conductivity of peat is often very low at depth within the peat profile and so in theory could provide a suitable plug substrate. Nevertheless exposed peat can desiccate and crack. Thus the peat in the trialled plug-like structures may have been exposed to air drying on gully edges, leading to leaks. Insertion and alignment of vertical screens perpendicular to pipe courses was difficult due to local differences in topography and lack of knowledge about the actual pipe course. The screens provided a smooth surface along which accumulated pipe water could flow. This may have increased the propensity to form new pipe outlets. This effect may have been larger for pipe outlets blocked with wooden planks as they were thicker than the plastic piling and bent more easily when inserted, thereby increasing the width of horizontal incision along which water could flow. However, it should be noted that new pipe outlets may also occur at random and existing ones may become blocked naturally and disappear over time, as the result of the ongoing development of the pipe network (Holden *et al.*, 2012).

3.6.3 Effect of blocking on pipeflow

Despite all four monitored pipe outlets being ephemeral, they contributed up to 11.3 % of streamflow. The largest contribution came from pipe H2 (7.3 %), which is relatively high for an individual pipe compared to other studies on ephemeral piping (Chapman *et al.*, 1997), but it should be noted that UNG is still in a phase of active erosion (Evans et al., 2006). Other peatland pipe studies (all northern England blanket peat) showed that the pipe network (both perennial and ephemeral) contributed 9 to 36 % of streamflow (Holden and Burt, 2002; Holden *et al.*, 2006; Smart *et al.*, 2013). The maximum peak discharge from a single peaked hydrograph event in our study was 0.859 L s^{-1} (pipe H1), an order of magnitude smaller than the 9.81 L s^{-1} reported on the largest pipe in the Wye headwaters of mid-Wales (Chapman *et al.*, 1997; Muscutt *et al.*, 1993), and 77 % lower than the maximum pipeflow reported from a peatland in northern England (Smart *et al.*, 2013).

Our results suggest that head pipes produced consistently larger contributions to streamflow compared to pipe outlets at edge locations. Given that head pipes make up 40 % of identified pipe outlets in the treatment catchment compared to ~12 % in the control (Regensburg, 2020), and 25 % of the total identified pipe outlets in the Upper North Grain catchment, the contribution of pipeflow to streamflow in the treatment catchment was probably much larger than that we were able to monitor in this study. This suggests that if practitioners seek to moderate pipe-to-stream connectivity, most effort should be made to impede flow from pipe outlets at head locations. However, the variability in the degree to which individual head pipes responded to blocking underlines the need for further research on factors that control pipeflow.

Despite differences in peak lag not being observed between pipes, volumes of runoff differed markedly across pipe locations and individual pipe outlets. Pipe H2 (head pipe) produced discharge and peak flows one order of magnitude larger than the other three pipes. Also, following pipe outlet blocking, head pipes (pipe H1 and pipe H2) displayed contrasting responses to blocking. For instance, at pipe H1, increases in both dynamic contribution area and peak discharge were observed post-blocking. Such change in flow behaviour may indicate increased connectivity upstream of the pipe outlet within the pipe network and adjacent to the block, due to better utilization of remnant pipe channels that were not previously as frequently connected to the main pipe course. Large dynamic contribution areas may indicate good connectivity between the surface and the pipe network, which may link drought cracks or segments of collapsed pipe roof, forming vent holes. However, such forms of surface-to-pipe network integration were only observed upstream of the outlet of pipe H2 where overland flow was actively infiltrating via vent-holes into the pipe network.

However, post-blocking, the lag time of pipe H2 increased, and its peak flows and dynamic contribution area decreased significantly. The blocking of pipe H2 may have resulted in a backwater effect that forced pipe water back into the pipe network. Return flow can naturally occur in pipes after clogging of the network and may exacerbate internal erosion (Gilman and Newson, 1980). Such return flow may promote the redistribution of pipe water. In turn, blocking pipe outlets may result in a larger spread of pipeflow on gully banks adjacent to the blocked pipe outlets, thereby increasing the propensity of existing pipe networks to further develop inwards (Hagerty, 1991; Parker and Jenne, 1967).

3.6.4 Water table

The water-table depths at head and edge locations were shallower following pipe outlet blocking across all dipwells. A similar pattern was observed in the water table after subsurface dams were placed perpendicular to an arid gully head, with strong effects locally directly upslope of the barrier (Frankl *et al.*, 2016). Our results showed the water table around pipe outlets to become shallower with increasing distance from the gully edge, but the extent differed between pipe outlet locations both pre- and post-blocking. The distance away from the outlet at which the distance-decay effect was observed appeared to be smaller for edge pipes compared to head pipes. In the same study catchment, Upper North Grain, Allott *et al.* (2009) observed water tables to drop when closer to the edge of deep gullies (up to 4.5 m), with an effect which extended up to 3.5 m away from the gully edge, measured over 0.5 – 1.0 m intervals perpendicular to the gully edge. The prevalence of this distance-decay effect was ascribed to the state of degradation of the peat at UNG. Despite streambanks in the treatment catchment only being incised to 2.5 m, they show very similar erosion patterns to those along streambanks investigated by Allott *et al.* (2009). Such distance-decay effects on the water table were also observed in arid gully systems by Frankl *et al.* (2016), but they did not report any interactions with pipes. While our water-table data were measured at a spacing of 2 m, the drawdown towards the gully edge was deeper around pipes at edge locations than around head pipes. Surveys of pipe outlets at UNG have shown pipe outlets at edge locations to be deeper in the profile compared to head pipe outlets, and mostly on drier south-facing streambanks (Regensburg *et al.*, 2020). As the hydraulic conductivity of peat decreases with depth in the profile, flow into deep pipe sections may be very small. Therefore, the water table may not be a good reference to pipe connectivity in the gully edge zone. Similar discrepancies between pipe activity and the water table were obtained by Wilson *et al.* (2017) on soils with fragipans, concluding connectivity based on spatial extent of perched water tables is not always a good indicator of hillslope pipeflow. Consistently deep water tables close to the pipe outlet at those locations would further increase the reach of desiccation and frost heave into deeper layers, which in turn would provide conditions to further promote pipe development by sapping (Parker and Jenne, 1967) and mass movements (Baillie, 1975). Panels E2-β and E2-γ (Appendix A-Fig 7) show that water table can vary by up to 0.5 m per 1 m lateral distance close to the pipe outlet, and even at 5 m away from the pipe outlet. An absence of water-table inflection across a transect perpendicular to a projected pipe course may be indicative of the difficulty of locating soil pipe position from surface indicators alone (Goulsbra, 2010; Regensburg *et al.*, 2020), which may complicate accurate *in-situ* blocking practices.

3.7 Conclusions and implications for managers

Impeding pipeflow by blocking pipe outlets by either plug-like structures in the pipe-end or insertion of a vertical screen at the pipe outlet did not completely prevent all pipeflow. Installing impermeable (wooden and plastic) screens caused new pipe outlets to form, particularly in the degraded gully edge zones where water tables are generally deep. The formation of new pipe outlets as a result of pipe outlet blocking should be considered as an undesirable side effect and therefore be prevented if peatland practitioners aim to overcome pipeflow contributions to the drainage network. Therefore we do not advocate blocking of pipes at the pipe outlet as part of peatland restoration. As blocking of pipe outlets is time consuming and labour intensive, and gullies are susceptible to increased pipe formation, peatland practitioners should consider control measures that reduce pipeflow further upslope of their outlets. Blocking pipes further upslope away from streambanks would generate a return flow which would spill onto the surface via existing desiccation cracks, before following a path through vegetated surfaces with a much lower flow velocity (Grayson *et al.*, 2010; Holden *et al.*, 2008), thereby potentially delivering greater flood benefits than pipe outlet blocking.

Overall, our study assessed the effects of pipe outlet blocking on streamflow, pipeflow, and the water table surrounding pipe outlets. We have shown that permanent blocking of peat pipes has had no direct impact on streamflow. When pipes were active, pipes at head locations contributed more to streamflow compared to pipes at edge locations. Thus, a primary focus should be on pipe outlets at head locations. Pipe blocking at the outlet had a measurable impact on water table but its extent was very localised. Water tables in gully edge zones showed a distance-decay effect, with significantly deeper water tables at edge locations compared to head locations, but a larger reach further away from the gully at head locations. Further work is required to test upslope pipe blocking impacts, away from outlets, to establish if this has greater impacts than the blocking of outlet locations alone. However, more precise mapping of pipe networks will be required, potentially using more recent advances in ground penetrating radar detection so that peat pipes < 10 cm in diameter can be mapped (Bernatek-Jakiel and Kondracka, 2019; Holden *et al.*, 2002).

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Chapter 4: Aquatic carbon concentrations and fluxes in a degraded blanket peatland with piping and pipe outlet blocking

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

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

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

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

Abstract

Soil piping is an important agent of erosion in many environments, including blanket peatlands. Peatland restoration that aims to reduce erosion has mainly focussed on revegetation and blocking ditches and gullies, rather than reducing erosion from natural soil pipes. However, little is known about the contribution of pipeflow to the fluvial carbon budget of degraded blanket peatlands and whether it is possible to moderate it. In a heavily degraded blanket bog, dissolved and particulate organic carbon (DOC and POC), and water colour, from two catchments were compared before and after half of the pipe outlets in one catchment were blocked. One blocked pipe was monitored for discharge and water quality both pre- and post-blocking as new pipe outlets had formed around the blocked outlet. Both pre- and post-blocking, maximum concentrations of DOC and POC were markedly higher in pipe-water than stream-water, with ratios of 1.2 (pre) and 1.3 (post) for DOC, and 4.8 (pre) and 8.8 (post) for POC, rendering pipe-to-stream transfer more effective for DOC than POC due to the deposition of POC close to pipe outlets. The increase in DOC and POC flux post-blocking in both catchments was near-identical, suggesting pipe outlet blocking was ineffective in reducing fluvial carbon export from pipe networks. Extrapolation of pipe fluxes to catchment scale showed pipes potentially contribute ~56 % of DOC exported by the stream, and that more POC was produced by pipes than was exported by the stream. Our work highlights that pipes need to be considered when seeking to reduce fluvial carbon export in degraded blanket peatlands.

4.1 Introduction

Piping is widely considered an important agent of subsoil erosion in both natural and modified landscapes (Bernatek-Jakiel and Poesen, 2018), especially where pipe roof collapse aids gully formation (Marzolff and Ries, 2011; Wilson, 2011; Xu *et al.*, 2020). Soil pipes provide a fast route for throughflow and facilitate transport of large quantities of water, eroding soil from the inside out whilst entraining solutes and nutrients along the way (e.g. in tropical forests (Baillie, 1975; Sayer *et al.*, 2006); dispersive semi-arid soils (Faulkner, 2013), loess soils (Verachtert *et al.*, 2011), and in temperate hillslopes (Anderson *et al.*, 2009; Anderson and Burt, 1982; Rapson *et al.*, 2006)). Piping in the temperate humid zone, including the British Isles (e.g. Jones *et al.* (1997)), is particularly prevalent in blanket peatlands (Holden, 2005). Where pipe density has been enhanced by management such as ditch drainage or burning of shrub cover for gun sports (Holden, 2005), there is concern about greater rates of sediment and carbon loss from the peatland system which may have negative impacts on downstream ecosystems (Brown *et al.*, 2019).

Peatland ecosystems are an important store of terrestrial carbon globally (Leifeld and Menichetti, 2018) and in some regionspeatlands are a major source of drinking water (Xu *et al.*, 2018). A key issue for water companies over the last ~30-40 years in northern Europe has been the rising trend in water colour (Chapman *et al.*, 2010; Watts *et al.*, 2001; Worrall *et al.*, 2003) as a result of increasing dissolved organic carbon (DOC) concentrations in streams draining organic soils (de Wit *et al.*, 2016; Evans *et al.*, 2006a). Deterioration in water colour complicates water purification for water companies (Bonn *et al.*, 2010; Fearing *et al.*, 2004; Van der Wal *et al.*, 2011) and also has health implications as the chlorination of highly coloured water can result in the production of carcinogenic disinfection-by-products such as trihalomethanes (Valdivia-Garcia *et al.*, 2016). In addition, the potential environmental implications of the increasing trend in DOC are wide ranging, from local effects on water transparency (Williamson *et al.*, 2015), acidity (Urban *et al.*, 1989), and metal toxicity (Rothwell *et al.*, 2007; Tipping *et al.*, 2003) through to effects on aquatic flora and fauna (Ramchunder *et al.*, 2012). Therefore, reducing DOC production and subsequent export is an important motivation for peatland restoration. However, blanket peatland restoration techniques have typically targeted ditches and gullies (Parry et al., 2014), rather than pipe networks. While previous work has shown that in intact peatland systems pipes contribute significantly to particulate organic carbon (POC) and DOC fluxes at the catchment scale (Holden *et al.*, 2012), to date, there has been little research on how blocking pipe outlets affects DOC and POC concentrations and fluxes in pipe- and / or stream-water, especially for highly eroded/degraded peatlands.

Peatlands, mainly in the form of sloping blanket bogs, cover about 10 % of the British Isles but a substantial proportion is severely degraded as a result of peat abstraction, drainage, overgrazing, burning, and atmospheric pollution (Evans and Warburton, 2007; Smart *et al.*, 2010; Ward *et al.*, 2007). In particular, the southern Pennines of England carry the scars of a legacy of atmospheric deposition of metals (Rothwell *et al.*, 2005), acidifying pollutants, and overgrazing which has resulted in highly degraded systems, where gully development has occurred as a result of damage to surface vegetation (Bower, 1961; Evans and Warburton, 2007; Yeloff *et al.*, 2006). The extent and severity of this peatland erosion indicates the rapid destabilisation of a major terrestrial carbon store, with the peatland acting as a net exporter of carbon rather than a sink (Evans *et al.*, 2006b). The erosion of these systems has led to rapid reservoir sedimentation downstream (Labadz *et al.*, 1991).

Recent blanket peatland research has examined processes controlling gully erosion (Evans and Lindsay, 2010), the production and loss of POC and DOC in runoff (Pawson *et al.*, 2012), fate of DOC/POC in runoff (Li *et al.*, 2019; Palmer *et al.*, 2016) and impacts of ditch and gully blocking and re-vegetation on DOC and POC concentrations and fluxes in stream-water (Evans *et al.*, 2016; Peacock *et al.*, 2018; Renou-Wilson *et al.*, 2019; Shuttleworth *et al.*, 2015). Previous work showed that soil piping is ubiquitous in degraded blanket bog (Regensburg *et al.*, 2020), yet controlling factors for pipe erosion in blanket peatlands have not been well studied. Preventing erosion from soil piping is an overlooked issue in soil erosion control (Bernatek-Jakiel and Poesen, 2018). While some data exist on the concentration and fluxes of DOC and POC in peatland pipe-water, it is predominantly from more intact peatland systems in the northern Pennines of England (Holden *et al.*, 2012) or organo-mineral soils in Wales (Chapman *et al.*, 1993), rather than highly eroded peatlands. One approach to tackling piping in degrading peatland systems is to reduce sediment flux by blocking pipe outlets. To date, the impacts of pipe outlet blocking have only been studied in the context of its effects on stream and pipe hydrology (Regensburg *et al.*, 2021). It remains unclear if pipes in more degraded blanket peatlands such as those found in the southern Pennines of England yield larger fluxes of aquatic carbon than observed in more intact blanket bog. Nevertheless, local peatland practitioners are keen to develop a better understanding about whether blocking pipe outlets provides wider benefits for preservation of ecosystem services through erosion control, including reduced discoloration of stream-water and sedimentation of downstream reservoirs. There is a need for further research to inform peatland practitioners as to whether pipe blocking should be included in future restoration initiatives in order to meet carbon export reduction objectives.

Here we report on an experiment investigating the impact of pipe outlet blocking on the concentrations and fluxes of DOC and POC in stream- and pipe-water in a heavily degraded blanket bog. Using a ‘before-after-control-intervention’ approach with paired catchments and routine sampling before and after pipe blocking this paper aims to:

1. determine how pipe concentrations and flux of POC and DOC compare to fluvial carbon output in streams;
2. investigate whether pipe blocking results in a decrease in POC / DOC concentration and flux in stream-water.

4.2 Materials and methods

4.2.1 Study site

For this study, two sub-catchments were monitored in Upper North Grain (UNG), which is a small headwater (49 ha, Figure 4.1) on the edge of the Bleaklow Plateau in the South Pennines of the UK, draining into the River Ashop. The River Ashop provides a major inflow to Ladybower Reservoir, which forms an important source of potable water in the region. UNG experiences a maritime temperate humid climate with a mean annual rainfall of 1313 mm (2006 - 2013) which is evenly distributed over the year and a mean annual temperature of 6.9 °C (Clay and Evans, 2017). Altitude ranges from 531 to 467 m above sea level at the catchment outlet. The topography is characterised by steep slopes up to 15 ° closer to the peat margin in the middle of the catchment, while most gullies occur on more gentle gradient hillslopes ranging from 0 to 7 °. The catchment is underlain by relatively soft shale grits with scattered exposed outcrops of the more resistant Millstone Grit (Wolverson Cope, 1998). The grits are overlain with a continuous cover of blanket peat of the Winter Hill Association (Jarvis *et al.*, 1984). Dissection of the blanket peat in UNG is characterised by shallow branching gullies and peat hags on the flat summits (Bower Type I), whereas the sloped terrain in the catchment is incised by a network of active, mostly unbranched gullies (Bower Type II) (Bower, 1961), exposing the underlying geology in the lower sections. The UNG catchment is dominated by a heather, bilberry and cotton grass vegetation assemblage, which is lightly grazed by sheep (Rothwell, 2006). The two sub-catchments included in this study run north-to-south (Figure 1), and include gullies with incision up to 4 m deep into the peat. The extensive dissection by gully erosion and consequent exposure of bare peat on gully walls means that rates of POC production by surface erosion are high. Measured POC fluxes from UNG vary from 74.0 to 95.7 g C m^{-2} yr^{-1} (Evans *et al.*, 2006a; Pawson *et al.*, 2008), and are on the high end of values measured across the South Pennine region (3.4 - 90 g C m^{-2} yr^{-1}) (Billett *et al.*, 2010), with strong connectivity of bare peat surfaces to the stream drainage network (Evans *et al.*, 2006b). Details about the onset of peat erosion and gullying at UNG were described by Regensburg et al. (2020).

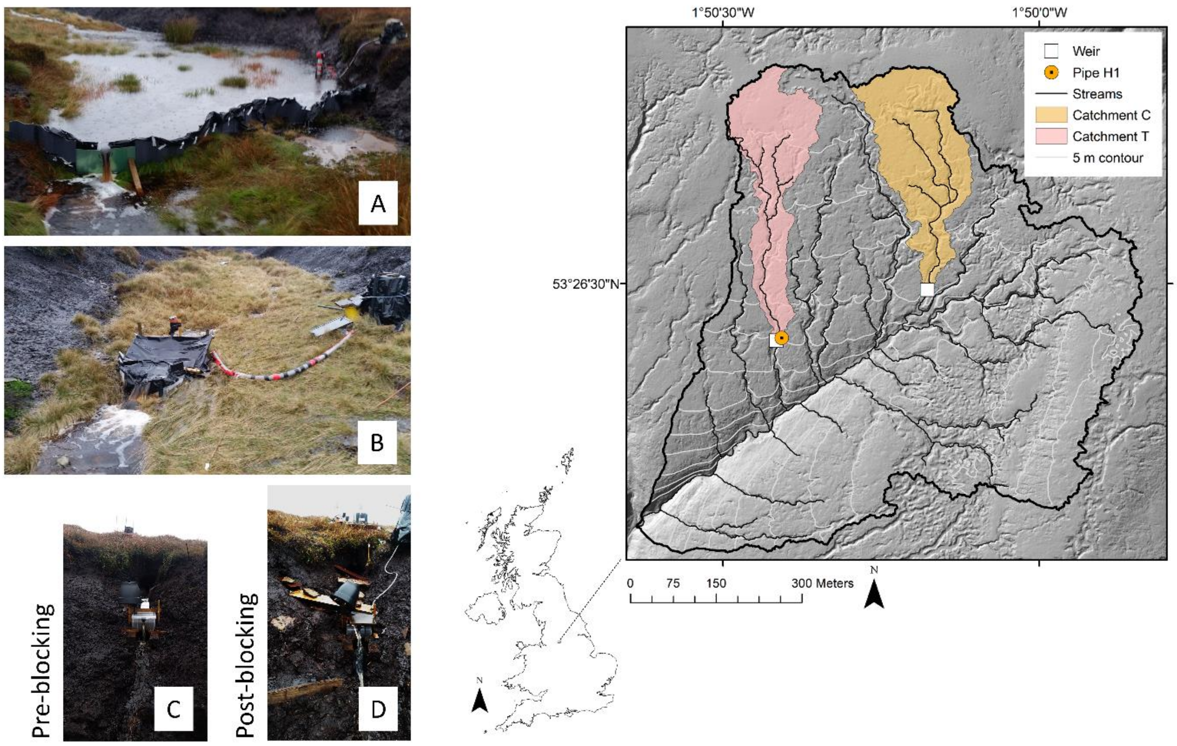

Figure 4.1 Left panel: A) outlet of catchment C, B) outlet of catchment T, C) outlet of pipe H1 pre-blocking, and D) outlet of pipe H1 post-blocking. Right panel: map of UK showing location of UNG, with inset of the monitored sub-catchments superimposed on a hillshade of the catchment, showing locations of each catchment weir (white rectangle) and pipeflow gauge at outlet of pipe H1 (orange circle).

4.2.2 Experimental design

To investigate the impact of pipe outlet blocking on fluvial carbon export, fluxes of POC and DOC from two streams were compared. Pipe outlet blocking treatments were installed in the catchment of one stream, hereafter called ‘catchment T’. The pipes in the catchment of the other stream were left untouched and the catchment functioned as a control, hereafter called ‘catchment C’. Suitable locations for weir placement were identified by walking upslope in the respective gully network, taking into account the possibility to perform salt dilution gauging immediately up or downstream of the weir. The area upslope of the weirs was estimated using a Digital Elevation Model obtained from LiDAR (MFFP, 2014), resulting in an estimated surface catchment of 4.32 ha for catchment C and 3.75 ha for catchment T.

Pipe surveys at UNG as reported by Regensburg *et al.* (2020) showed that the largest pipe outlets were usually found in gully sections with signs of headward retreat (referred to as head pipes: ‘H’) as opposed to smaller pipe outlets along the edge of straight gully sections (referred to as edge pipes: ‘E’). Considering the large diameter of head pipes, it was assumed such pipes would actively contribute to gully formation, and therefore, outflow from one head pipe in catchment T, hereafter referred to as pipe H1, was sampled to investigate the relative fluvial carbon contribution of pipe-water to stream-water. Based on storm responses, Regensburg *et al.* (2021) characterised pipe H1 as ephemeral. 68 % of the pipe outlets in catchment T were blocked between August and September 2019. This represented a total of 31 pipe outlets, which were blocked with either a plug-like structure (n = 6) or a vertical screen (n = 25, including pipe H1) (for details see Regensburg *et al.* (2021)). On 27 September 2019, a further 20 pipe outlets were identified in two tributaries of catchment T. The tributaries had stone and wooden dams in them as part of earlier restoration activity (Regensburg, 2020), but none of their pipe outlets were blocked. In this paper the results focus on the combined impact of pipe outlet blocking methods on POC and DOC loss from catchment T. Monitoring of the streams and pipe H1 ran from 1 December 2018 to 29 February 2020, but the data for analyses was divided into two periods: a pre-blocking period (1.12.18 – 31.08.19) and a post-blocking period (1.09.19-29.02.20).

4.2.3 Discharge monitoring

Rainfall data were collected at three locations within each sub-catchment using an automated tipping bucket gauge (DAVIS AeroCone) with 0.2 mm resolution and a bulk rain collector at each location. For the period between December 2018 and February 2020, at least three of the six rainfall gauges across UNG were active at the same time. Therefore precipitation levels were derived by averaging recorded data across any of the active rainfall stations at an interval resolution of 5 minutes (for details see Appendix A). Stream discharge was gauged at the outlet of each catchment by insertion of a weir plate using a calibrated V-notch. The water level above the notch was recorded using a vented pressure transducer (In-Situ Troll 500) that was placed in a stilling pool ~1 metre upstream of the weir plate. Stage was recorded at 5-minute intervals. When discharge was < 0.5 litre per second, a stage discharge relationship was determined by measuring the volume of water per unit of time using a measuring cylinder and stopwatch. At faster flows, discharge was estimated using salt dilution gauging in a 10 m straight section immediately downstream of the weir plate. Streamflow monitoring commenced in October 2018 for catchment T and in December 2018 for catchment C.

Pipe water from the outlet of H1 was channelled via guttering into a rectangular plastic box of 140 mm x 340 mm x 220 mm with a 22.5° V-shaped opening, hereafter referred to as the “pipeflow gauge”, which was instrumented with a vented pressure transducer (In-Situ Troll 500). Pressure readings above the sensor head in the box were recorded at a 5-minute interval. Gutters from the pipe outlet to the pipeflow gauge were shielded from rainfall using waterproof tape, polyethylene plastic sheeting, or wooden planks. During field visits, when water was flowing over the notch of the V, discharge from the pipeflow gauge was measured using a measuring cylinder and a stopwatch. A stage-discharge relationship for pipe H1 was derived by aggregating data from the calibration measurements on four pipeflow gauges in UNG (H1, H2, E1, and E2) (Regensburg *et al.*, 2021). For this study, discharge monitoring at pipe H1 covered the period between May 2018 and February 2020. After blocking the outlet of pipe H1, any water that appeared from newly formed outlets and the blocked outlet was redirected to its respective pipeflow gauge using guttering to quantify the amount of water escaping from the blocked pipe.

4.2.4 Water sampling

Water sampling started in December 2018, and covered a pre-blocking period of 8.5 months ("pre"), and a post-blocking period of 6 months (September 2019 – February 2020) ("post"). ISCO 3700 portable automatic water samplers (Teledyne Isco, Inc., Lincoln, NE, USA) were installed in the stilling pools located at straight stream sections of catchment C and catchment T, at least 1 m upstream of their respective weirs. The inlet for an ISCO 6712 portable automatic water sampler (Teledyne Isco, Inc., Lincoln, NE, USA) was installed in the pipeflow gauge at the outlet of pipe H1. Samples of pipe- and stream-water (500 mL) were collected using two different temporal resolutions: 1) storm events triggered the samplers to collect 24 water samples of 0.5 L at irregular intervals of maximum 30 minutes, or 2) at regular intervals of either 6 or 12 hours for a period of up to twelve consecutive days, with sampling being started manually during field visits. Storm sampling sequences were activated on nine occasions during the pre-blocking period until the end of May 2019, though not all automatic samplers were trigger simultaneously. Thereafter water samples were collected at regular set intervals. Water samples were collected from the field site on a fortnightly basis and stored in a dark, cold room at 4 ° C before analysis to minimise decomposition of the aquatic carbon.

4.2.5 Water sample analyses

POC was estimated by loss-on-ignition of the residue from 500 mL water samples. Samples were filtered through pre-ashed (550 °C, 5.5 h), pre-weighed 0.7 µm Whatman GF/F glass micro-fibre filters using suction filtration equipment. The filtrate was dried at 105 °C for 24 h, weighed, and then ignited at 375 °C for 16 h in a muffle furnace and re-weighed (Dawson *et al.*, 2002) to determine the suspended sediment in mg L^{-1}. All samples were weighed in grams with a five decimal place calibrated balance (Sartorius MSE125P-000-DU). The POC content of the suspended sediment was then calculated using a regression equation for non-calcareous soils (Ball, 1964).

Water colour was determined on all samples while DOC was determined on approximately one third of the total collected samples. Water colour and concentration of DOC were determined on 10-15 mL subsamples that were filtered through pre-washed 0.45 µm nylon syringe filters (Avonchem SF-3020) and stored in centrifuge tubes (Sarstedt) at 4 °C until analysed. Prior to analysis of DOC, the sub-samples were acidified and sparged with oxygen in order to stabilise the sample and to remove any inorganic carbon. DOC in water was then determined using a Multi N/C 2100 combustion analyser (Analytik Jena), which has a detection limit of 50 µg L^{-1} with the DOC concentration determined by a calibration curve created using the standard DOC calibration compound, potassium hydrogen phthalate (KHP) and standard DIC stock solution. Regular analysis of KHP standards and use of a certified reference material, VKI QC WW4A, were used to check instrument performance during each run of samples. Water colour was measured using a UV-VIS spectrophotometer (Jasco V-630), using deionised water as a blank control. For each sample the E2:E4 (absorbance at 254 nm/absorbance at 400 nm), E4:E6 (absorbance at 400 nm/absorbance at 665 nm) and E2:E6 (absorbance at 254 nm/absorbance at 665 nm) ratios were calculated to characterise the seasonality of the coloured portion of dissolved organic matter. Where samples were analysed in duplicate or triplicate the mean value was determined and used in all further data analyses.

4.2.6 Data processing

All water samples collected when the instantaneous discharge at the stream or pipeflow gauge was zero were omitted from data analyses. POC samples were then checked for inconsistencies in the weighing procedure using a four point quality control (see for details Supplementary Information Appendix B). Concentrations of DOC which were determined initially as described above, are referred to as cDOC. The Specific Ultraviolet Absorbance (SUVA) for water samples was determined by dividing absorbance at 254 nm by cDOC. Absorbances at wavelengths 254 nm and 400 nm were both tested as a predictor of DOC concentration using linear relationships. For catchment C, catchment T, and pipe H1, absorbance at 254 nm provided the best predictor of DOC concentration with R squared values of 0.97, 0.95 and 0.97, respectively. Conversion functions for absorbance at 254 nm and 400 nm to DOC concentration are provided in Appendix B-Table 1. Hereafter, the derived relationships for DOC using absorbance at 254 nm, referred to as DOC_{254}, were used to characterise the distribution of concentration and flux of DOC for each outlet. Daily mean fluxes of POC and DOC_{254} from pipe H1 and catchments C and T were calculated using the following equation (Walling and Webb, 1985):

$$\boldsymbol{Flux} = \frac{\boldsymbol{c} \cdot \sum_{\boldsymbol{i}=1}^{\boldsymbol{n}} (\boldsymbol{Q_i} \cdot \boldsymbol{C_i})}{\sum_{\boldsymbol{i}=1}^{\boldsymbol{n}} \boldsymbol{Q_i}} \cdot \boldsymbol{Q_r} \qquad \textbf{8}$$

where *c* is a conversion factor to scale measurement intervals to an hourly frequency, $Qi*C_i$ as the product of concentration Ci measured at an instantaneous discharge Qi forming the instantaneous flux in mg s^{-1}, and Q_r as the hourly mean discharge. Instantaneous discharge and instantaneous flux are both summed over n samples that were available for each hour, which may have varied during the monitoring period. Flux was expressed as an hourly mean export weight of dissolved or particulate organic carbon in kilograms. Then for each outlet the calculated hourly DOC and POC flux was plotted over the hourly mean discharge to derive a linear function of the form y = a x + b. All functions were forced through the origin for simplification. The relationships are depicted in Table 4.1. For each outlet, the functions were used to convert available discharge data to flux, which were then summed to obtain a total yield per outlet, for each season respectively.

Table 4.1 Overview of calibration functions for DOC and POC flux. The quality of line fit for slope a is indicated by the r squared value for each outlet and flux variable respectively.

	Flux as function of hourly discharge, *Qr*					
	Hourly DOC flux			Hourly POC flux		
	a	r^2	n samples	a	r^2	n samples
Catchment C	0.0667	0.7455	130	0.0497	0.4298	233
Catchment T	0.0611	0.8464	176	0.0172	0.4776	200
Pipe H1	0.0638	0.7827	116	0.0502	0.3092	86

The maximum discharge that was inferred from the stage-discharge calibration curve determined for each outlet, differed markedly between the three monitored outlets (catchment T: 16.8 L s^{-1}, catchment C: 20.1 L s^{-1}; pipe H1: 0.859 L s^{-1}), and runoff between streams, and pipes, varied across intervention periods (Regensburg *et al.*, 2021). To account for the differences in discharge range and runoff amount when scoping for variation in DOC and POC flux across outlets and across intervention periods, the exceedance probability of discharge for each outlet was determined for the period between 1 December 2018 and 29 February 2020 by standardising their hourly discharge respectively, using the following formula:

$$\boldsymbol{P_{exceed}} = \frac{\boldsymbol{average\ rank}}{\boldsymbol{n+1}} \tag{9}$$

with P_{exceed} expressing the percentage chance that a set discharge may be equalled or exceeded, using the $average\ rank$ of a discharge for a list of n number of recorded discharge intervals. The average rank was chosen here to correctly detect the prevalence of equally-sized discharges, particularly in low flow conditions. To investigate how the influence of discharge on concentrations and fluxes of fluvial carbon varies across outlets, for each outlet the discharge was categorised to either above or below its respective median. An exceedance probability equal or smaller than 50 % was categorised as above median discharge (“AMD”), and all else as below median discharge (“BMD”). Flow duration curves for both catchments and pipe H1 are provided in Appendix B-Fig 1. Discharge continuity was determined for each outlet for the periods March-April-May (MAM), June-July-August (JJA), September-October-November (SON), and December-January-February (DJF).

Datasets did not follow a normal distribution, even after transformation, and therefore non-parametric tests of association were employed. Due to varying water sampling intervals among all outlets, comparisons between sample pairs of variables or outlets were performed by association using Kendall's Tau (2-tailed, $\alpha = 0.01$).

4.3 Results

4.3.1 Water budget

Rainfall was 886 mm and 931 mm for the pre-blocking period and post-blocking period respectively (Figure 4.2). Runoff was 26 and 54% higher in the post blocking period (857 mm versus 935 mm) than the pre blocking (678 mm versus 607 mm) for catchment C and T respectively (Figure 4.2). Pipe H1 produced 452 m^3 of discharge in the pre-blocking period compared to 807 m^3 in the post-blocking period and contributed to 2.0 % and 2.3 % of stream discharge in catchment T in each intervention period, respectively (Table 4.2).

For all outlets, the duration for which flow over the weir was observed (AMD + BMD) was markedly longer in the post-blocking period with flow durations 1.91, 1.90, and 1.12 times longer for catchment C, catchment T, and pipe H1 respectively compared to the pre-blocking period (Table 4.2). In the pre and post-blocking period, the fraction of flow above and below median discharge was similar for both catchments (Table 4.2). Zero flow over the weir occured more often in catchment C than in catchment T during the whole monitoring period, with 37 % versus 23.4 % of the time respectively, with the largest difference (NF: C = 23 % vs T = 2.3 %) observed over September, October, November (SON)-2019 (Table 4.2). Periods with relative short flow duration in catchment C occurred in spring and summer; 35 % of the time in MAM-2019 and 38.4 % in JJA-2019 (Table 4.2). The period with the shortest flow duration for catchment T was observed in MAM-2019 with flow occurring 41.3 % of the time (Table 4.2).

Overall, pipeflow at the outlet of pipe H1 did not decrease after pipe outlet blocking, as pipeflow was produced 86.1 % of the time in the post-blocking period compared to 76.4 % in the pre-blocking period. The discharge distribution around the median was strongly skewed for pipe H1 in both intervention periods, with a smaller percentage of flow pre-blocking being above the median as opposed to below, while in the post-blocking period the opposite was observed because it was wetter (Table 4.2). Dividing the fraction of time pipe H1 produced discharge by that of catchment T showed that pipe H1 flowed more than catchment T in the pre-blocking period with pipe H1 being 1.58, 1.99 and 1.09 more active compared to catchment T in DJF-2018, MAM-2019, JJA-2019 respectively. In the post-blocking period, pipe H1 was less active than catchment T with ratios of 0.83 in SON-2019 and 0.95 in DJF-2019 (Table 4.2).

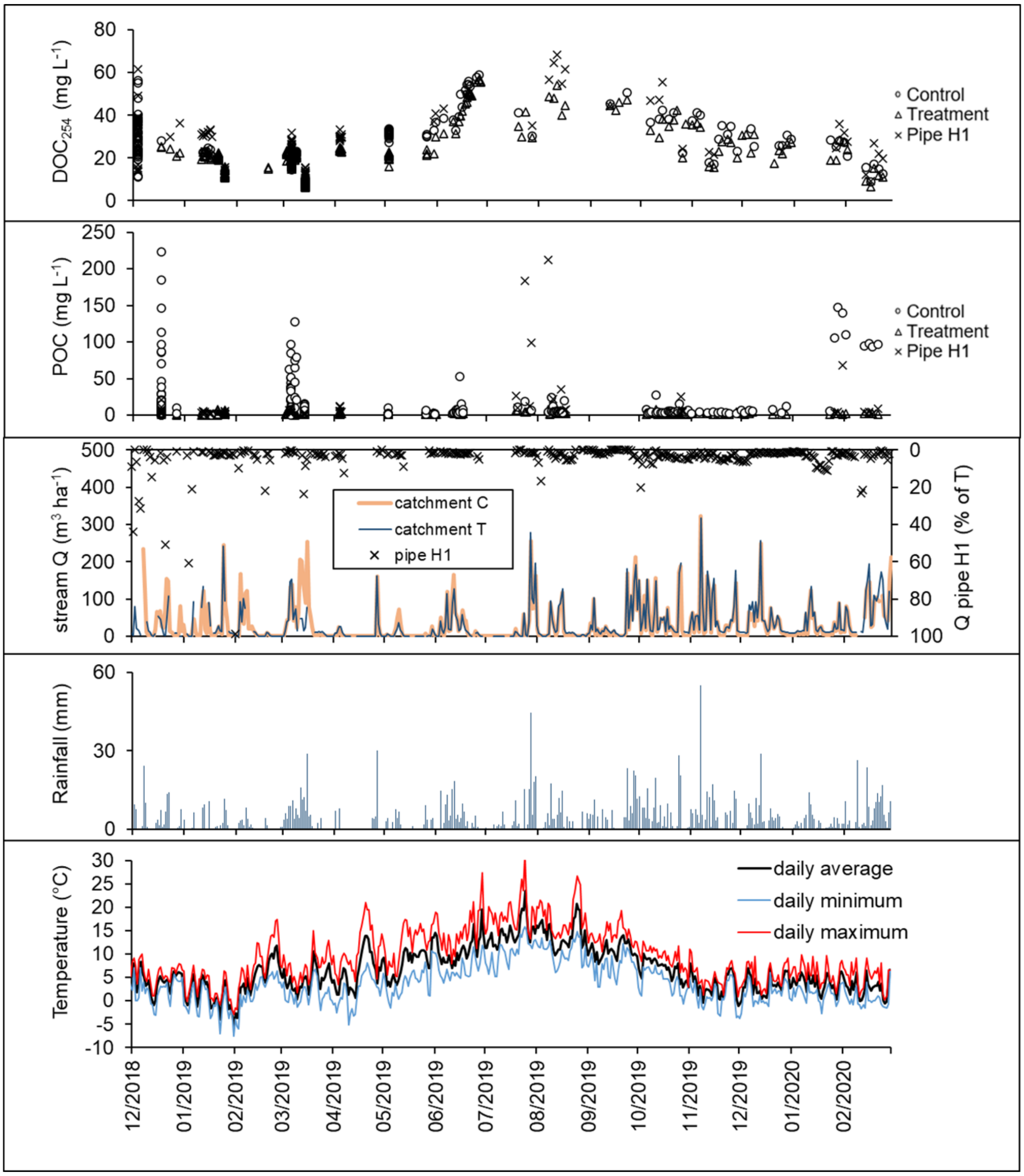

Figure 4.2 Timeseries plot of sampled concentrations of DOC_{254} and POC in mg L^{-1}, and daily totals of stream discharge (m^3 ha-1) and pipe discharge (% of catchment T), rainfall (mm) and temperature (°C), for each outlet (catchment C, catchment T, and pipe H1) over the whole monitoring period.

Table 4.2 Summary of hydrological responses for each outlet (C = catchment C, T = catchment T, P = pipe H1), for the pre- and post-blocking period in terms of discharge distribution over time, in % (NA = data error, NF = no flow, AMD = above median discharge, and BMD = below median discharge). Runoff Coefficient (RC) was calculated for streams in %, and for pipe H1 details on runoff are provided as the percentage that pipeflow from H1 contributed to streamflow in catchment T (% of T).

			Discharge distribution, % of time				**Runoff**	
Period	**Season**	**Outlet**	NA	NF	AMD	BMD	RC (%)	% of T
pre-blocking	DJF-2018 (P = 225 mm)	C	7.7	29.9	36.5	26.0	115.4	
		T	15.6	27.5	32.0	24.9	111.3	
		P	7.6	2.2	68.5	21.7	-	1.8
	MAM-2019 (P = 275 mm)	C	0	67.2	13.2	21.8	77.5	
		T	9.1	49.5	23.0	18.3	49.9	
		P	2	17.9	60.6	21.7	-	2.7
	JJA-2019 (P = 386 mm)	C	0	63.8	18.0	20.4	53.1	
		T	8.9	36.2	31.4	23.4	56.7	
		P	0	42.3	26.4	33.5	-	1.8
	total (P = 886 mm)	C	2.5	52.8	22.2	22.4	76.5	-
		T	11.2	37.8	28.8	22.2	68.5	-
		P	3.2	20.5	51.1	25.3	-	2
post-blocking	SON-2019 (P = 544 mm)	C	0	23	37.4	40.7	77.5	
		T	0.8	3.2	44.6	51.5	83.5	
		P	2.8	18.2	15.5	64.6	-	2.4
	DJF-2019 (P = 388 mm)	C	3.3	3.5	53.9	40.4	97.7	
		T	2.0	0	45.6	52.4	111.4	
		P	6.0	1.1	36.7	57.3	-	2.3
	total (P = 931 mm)	C	1.6	13.1	45.1	40.1	85.9	-
		T	1.4	1.6	45.1	52.0	95.2	-
		P	4.4	9.6	25.8	60.3	-	2.3

4.3.2 Concentrations of DOC and POC

Water colour, and hence DOC_{254} concentrations, in pipe- and stream-water displayed a clear seasonal cycle with highest concentrations observed in summer and lowest in winter, regardless of increasing discharge over the monitoring period (Figure 4.2). DOC_{254} was positively correlated to temperature for catchment C ($\tau = 0.219$, $p < 0.001$, $\alpha = 0.01$), and pipe H1 ($\tau = 0.157$, $p = 0.003$, $\alpha = 0.01$), with R squared values of 0.30 and 0.14 respectively, but no correlation for temperature and DOC_{254} was found for catchment T ($\tau = 0.077$, $p = 0.061$, $\alpha = 0.01$) (Appendix B-Fig 2). Over the entire monitoring period in both catchments, DOC_{254} concentrations ranged between 5-29 mg L^{-1} during the winter and 30-59 mg L^{-1} in the summer (Appendix B-Table 2), and DOC_{254} in pipe-water peaked at 68.5 mg L^{-1} in summer and 36 mg L^{-1} in winter (Appendix B-Table 2). Plotting DOC_{254} over discharge of the respective outlets showed a negative relation, which was particular visible for pipe H1 (Appendix B-Fig 3). In contrast, POC concentrations seemed much more episodic and no clear relationship with discharge was observed (Appendix B-Fig 3). DOC composition, measured as SUVA, did not vary much over the monitoring period (Figure 4.2). In the pre-blocking period, stream-water DOC_{254} concentration ranged from 6.2 to 58.9 mg L^{-1} and 6.7 to 50.8 mg L^{-1} in the post-blocking period. Pre-blocking and post-blocking, DOC_{254} concentrations were similar for both catchments, with a median value of 22.3 mg L^{-1} pre- and 28.8 mg L^{-1} post-blocking for catchment C, and a median DOC of 20.6 mg L^{-1} pre-blocking and 27.6 mg L^{-1} post-blocking for catchment T (Figure 4.3).

Pipe-water DOC_{254} concentrations were slightly lower post-blocking with a median concentration of 29.7 mg L^{-1} pre- and 27.1 mg L^{-1} post-blocking, whereas POC concentrations were slightly higher post-blocking with a median of 3.4 mg L^{-1} pre and 4.5 mg L^{-1} post-blocking (Figure 4.3). The maximum concentration of DOC_{254} for pipe H1 was similar for the pre- and post-blocking monitoring periods, with 68.5 mg L^{-1} pre and 61.7 mg L^{-1} post pipe outlet blocking. Despite pipeflow being observed more frequently in the post-blocking period, especially for above median discharge, the largest POC concentration of 212.2 mg L^{-1} was observed in the pre-blocking period for pipe H1 (Figure 4.3).

The median POC concentration was similar across intervention periods for each catchment, although median POC concentration for catchment C was about three times larger than that observed for catchment T. In the post-blocking period, the maximum POC concentration in catchment C was markedly larger than in the pre-blocking period (311.3 mg L^{-1} post-blocking compared to 127.5 mg L^{-1} pre-blocking), while the maximum POC concentration in catchment T was markedly lower in the post-blocking period, 7.7 mg L^{-1} compared to 44.6 mg L^{-1} in the pre-blocking period (Figure 4.3).

Pipe-water DOC_{254} concentrations ranged from 4.6 to 68.5 mg L^{-1} in the pre-blocking period, and 9.1 to 61.7 mg L^{-1} in the post-blocking period (Table 4.3). Pipe-water POC concentrations ranged from 0.3 to 212.2 mg L^{-1} in the pre-blocking period, and from 2.0 to 67.7 mg L^{-1} in the post-blocking period (Figure 4.3).

The maximum POC concentrations observed in catchment T were markedly lower than that observed in pipe H1, with concentrations up to 4.8 times lower in the pre-blocking period, and 8.8 times lower in the post-blocking period (Figure 4.3). The maximum DOC_{254} concentration of pipe H1 was greater than that of catchment T, but differences were smaller than observed for POC concentrations, with DOC_{254} concentrations of 68.5 versus 56.8 mg L^{-1} pre-blocking, and 61.7 versus 47.3 mg L^{-1} post-blocking, respectively (Figure 4.3). This suggests that the pipe-stream transfer of fluvial carbon is more effective for DOC than POC.

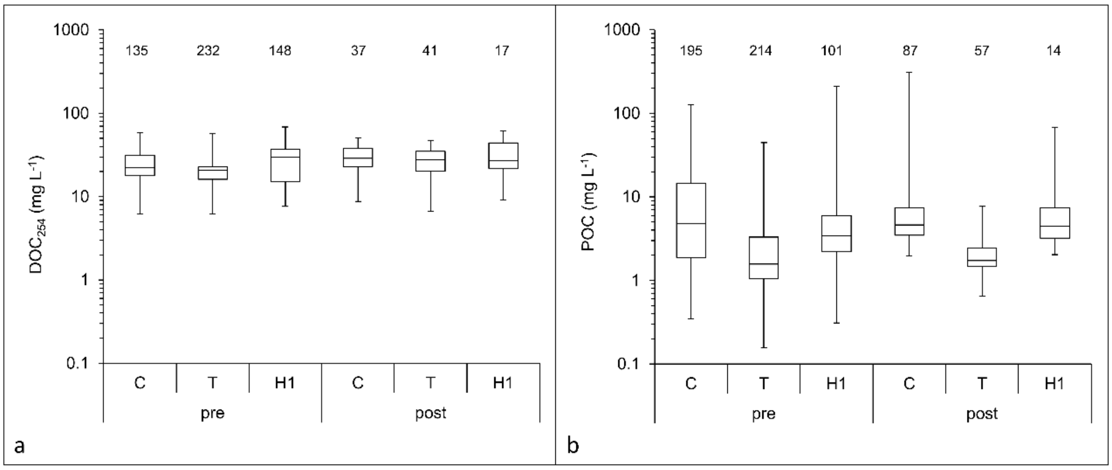

Figure 4.3 Boxplot of a) DOC_{254} (mg L^{-1}) and b) POC (mg L^{-1}) observed in streams (C = catchment C, T = catchment T), and pipe-water (H1 = pipe H1), for both intervention periods (pre- and post-blocking); for each outlet the number of included samples is listed above their respective boxplot. The whiskers indicate the minimum and maximum values.

4.3.3 Water colour

Table 4.3 shows that mean absorbances across the four measured wavelengths peaked in both pipe- and stream-water in summer and autumn, with mean absorbances up to three times higher than in other seasons. Ratios of E2:E4 and E4:E6 were similar for both catchments and pipe H1 over the whole monitoring period (Table 4.3), indicating that the composition of DOC was similar over the monitoring period, and most likely had the same source. In both winters of the study (DJF 2018 and 2019), E2:E6 was similar in pipe-water, but markedly higher compared to the ratios observed in catchment T and catchment C, most likely due to much higher absorbances at 254 nm in pipe-water compared to catchment T (Table 4.3).

Table 4.3 Summary of colour measurements for each outlet by season, showing mean absorbance at 254 nm, 400 nm, 465 nm, 665 nm, and mean Specific Ultraviolet Absorbance (SUVA). Ratios between absorbance at 254, 400 nm and 665 nm are included as E2:E4, E4:E6, and E2:E6 respectively.

	pre-blocking			post-blocking		
Catchment C	DJF-2018	MAM-2019	JJA-2019	SON-2019	DJF-2019	units
665.0 nm (n = 172)	1.1	0.8	2.4	1.9	1.0	AU m^{-1}
465.0 nm (n = 172)	6.8	5.6	15.9	12.4	7.0	AU m^{-1}
400.0 nm (n = 172)	15.9	13.1	36.2	27.3	16.0	AU m^{-1}
254.0 nm (n = 172)	104.1	89.4	223.2	163.3	101.2	AU m^{-1}
E2:E4	6.6	6.9	6.2	6.0	6.4	(-)
E4:E6	16.4	17.2	15.6	14.6	18.7	(-)
E2:E6	110.1	119.0	97.0	87.8	120.4	(-)
SUVA (n = 46)	ND	3.4	4.7	4.8	4.4	L mg^{-1} m^{-1}

	pre-blocking			post-blocking		
Catchment T	DJF-2018	MAM-2019	JJA-2019	SON-2019	DJF-2019	units

665.0 nm (n = 273)	0.7	0.7	2.4	2.1	1.2	AU m^{-1}
465.0 nm (n = 273)	4.9	5.0	16.1	12.4	7.3	AU m^{-1}
400.0 nm (n = 273)	11.3	11.4	35.8	26.4	15.7	AU m^{-1}
254.0 nm (n = 273)	76.4	79.6	223.4	156.0	94.1	AU m^{-1}
E2:E4	6.9	7.1	6.3	5.9	6.2	(-)
E4:E6	17.3	16.8	14.8	12.8	18.1	(-)
E2:E6	119.7	120.3	93.2	75.5	118.3	(-)
SUVA (n = 88)	3.8	3.4	4.8	5.0	4.3	L mg^{-1} m^{-1}

	pre-blocking			**post-blocking**		
Pipe H1 (n = 165)	djf-2018	mam-2019	jja-2019	son-2019	djf-2019	units
665.0 nm	0.9	1.0	6.7	2.5	1.0	AU m^{-1}
465.0 nm	7.6	7.9	23.3	15.3	7.4	AU m^{-1}
400.0 nm	17.5	17.9	46.4	33.0	16.4	AU m^{-1}
254.0 nm	120.4	119.5	267.8	197.2	104.3	AU m^{-1}
E2:E4	6.9	6.8	6.0	6.0	6.5	(-)
E4:E6	21.9	17.9	14.6	14.4	22.9	(-)
E2:E6	152.8	122.4	91.0	87.7	153.1	(-)
SUVA (n = 70)	3.8	4.2	5.1	4.6	4.5	L mg^{-1} m^{-1}

4.3.4 Fluxes of DOC and POC

Ranges of instantaneous flux varied across seasons for both catchments and pipe H1. For both catchments, concentrations of DOC_{254} peaked in summer, but their highest seasonal median instantaneous DOC flux was observed in spring (MAM-2019) (Table 4.4). In DJF-2018 the range of instantaneous DOC_{254} flux of catchment T was 2.34 times larger than that of catchment C, but in the wetter DJF-2019 the range of instantaneous DOC_{254} flux of catchment T was about a third smaller than that of catchment C (Table 4.4). The largest median instantaneous DOC flux for pipe H1 was observed in the autumn (SON-2019), after the pipe outlet was blocked (Table 4.4). The episodic nature of POC concentrations in both pipe- and stream-water (Figure 4.2), translated into a varied pattern in the instantaneous POC flux across seasons. This variation was particularly noted for catchment C, which showed large differences across seasonal medians, of up to two orders of magnitude (Table 4.4).

Table 4.4 Distribution of instantaneous flux of DOC_{254} and POC, as observed in streamflow (C = catchment C, T = catchment T) and pipeflow (P = pipe H1) over seasons.

		Instantaneous DOC_{254} flux (mg s^{-1})				**Instantaneous POC flux (mg s^{-1})**			
season	outlet	N	Median	Maximum	Range	N	Median	Maximum	Range
DJF-2018	C	19	28.1	154.0	152.9	37	8.8	780.6	780.5
	T	67	26.5	364.1	358.1	56	6.3	422.0	421.6
	P	52	1.0	7.0	7.0	35	0.5	2.3	2.3
MAM-2019	C	96	65.9	360.0	354.6	112	120.2	3265.6	3265.2
	T	137	42.1	283.8	283.4	110	9.0	2422.9	2422.8
	P	87	1.1	4.6	4.3	55	0.4	2.5	2.4

JJA-2019	C	20	45.2	731.4	726.2	46	23.5	1357.5	1356.9
	T	28	24.5	591.3	588.4	48	9.1	540.8	540.2
	P	9	1.5	8.9	8.8	11	1.8	46.9	46.8
SON-2019	C	21	50.4	334.9	332.8	72	9.3	1487.8	1487.7
	T	22	25.6	343.1	333.9	41	3.1	646.8	645.5
	P	8	2.8	21.1	20.1	6	0.6	51.0	50.7
DJF-2019	C	16	21.6	158.2	156.2	15	493.8	7181.1	7160.3
	T	19	19.8	113.5	105.2	16	5.9	204.7	203.0
	P	9	1.4	2.3	1.6	8	0.7	3.9	3.5

Across both monitoring periods, instantaneous DOC_{254} flux for both catchments responded in a similar way to discharge, while instantaneous POC flux in response to discharge differed markedly between them (Figure 4.4). The variation in the amplitude of instantaneous POC flux for the same discharge seems larger for catchment C compared to that of catchment T, in both monitoring periods. This effect was particularly noticeable in the post-blocking period, with maximum range of instantaneous POC flux over the same discharge spanning two orders of magnitude for catchment C compared to one order of magnitude for catchment T (Figure 4.4). In the pre-blocking period, instantaneous fluxes of DOC and POC in pipe H1 were roughly two orders of magnitude lower than that of catchment T. A similar trend was observed for pipe H1 in the post-blocking, but only for pipe discharges greater than the median (Figure 4.4).

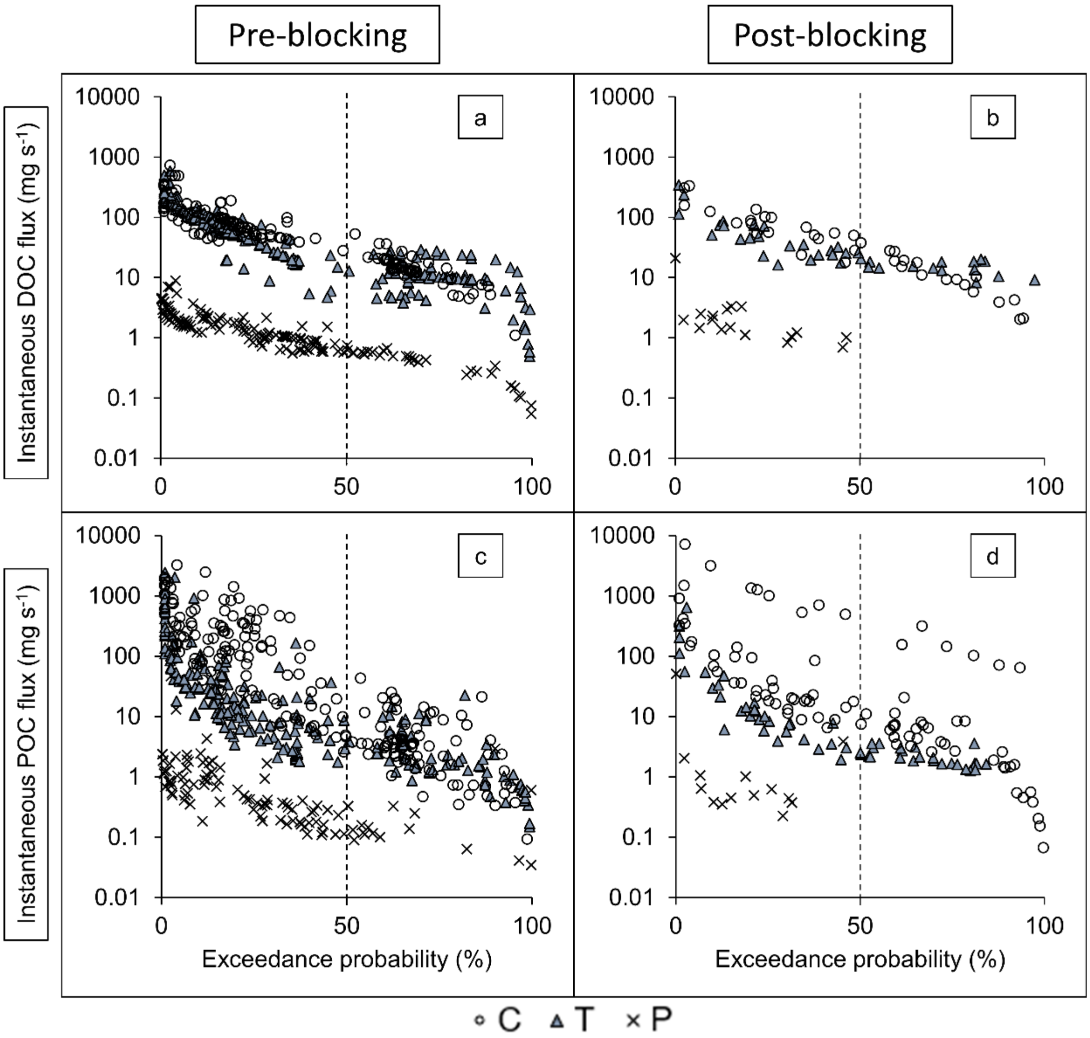

Figure 4.4 Scatterplots showing distribution of instantaneous flux for samples of DOC (mg s^{-1}) and POC (mg s^{-1}) over the exceedance probability of instantaneous discharge for each outlet (C = catchment C, T = catchment T; and P = pipe H1) across monitoring periods (pre- and post-blocking).

Figure 4.5 provides a summary of the estimated yields of DOC_{254} and POC for each season, utilizing the relationships presented in Table 4.1. Overall, catchment C produced markedly higher fluxes of POC compared to catchment T, whereas production of DOC_{254} was similar between both catchments. In the pre-blocking period, catchment C yielded 525 kg DOC_{254} and 396 kg POC, against 379 kg DOC_{254} and 107 kg POC in catchment T. In the post-blocking period, catchment C exported 613 kg DOC_{254} and 462 kg POC compared to 555 kg DOC_{254} and 156 kg POC in catchment T (Figure 4.5). Both catchments and pipe H1 showed markedly higher total fluxes of DOC_{254} and POC post-blocking compared to the pre-blocking period, and for DJF-2019 (winter period post-blocking) as opposed to DJF-2018 (winter period pre-blocking). Pipe H1 exported an estimated 8.0 kg DOC_{254} and 6.2 kg POC in the pre-blocking period, and 13.5 kg DOC_{254} and 10.5 kg POC in the post-blocking period (Figure 4.5). Post-blocking flux contribution to catchment T by pipe H1 was as high or higher compared to that of pre-blocking, with post-blocking values of 2.43 % DOC_{254} and 6.73 % POC, versus 2.11 % DOC_{254} and 5.8 % POC pre-blocking, indicating blocking the outlet of Pipe H1 did not reduce the pipe-to-stream transfer of DOC_{254} and POC.

In the pre-blocking period, above median discharges contributed to 96.2 % of the DOC_{254} flux and 93.2 % of the POC flux in catchment C, versus 87.2 % of the DOC_{254} flux and 87.2 % of POC flux in catchment T (Figure 4.5). In the post-blocking period, a similar pattern was observed at the catchment outlets, showing above median discharge contributing 92.7 % of the DOC_{254} flux and 92.7 % of the POC flux in catchment C, and 89.0 % of the DOC_{254} flux and 88.9 % of the POC flux in catchment T (Figure 4.5). Pipeflow above median discharge accounted for 72.5 % of the DOC_{254} flux and 71 % of the POC flux at pipe H1 in the pre-blocking period, and 93.3 % of the DOC_{254} flux and 94.3 % of the POC flux at pipe H1 in the post-blocking period (Figure 4.5).

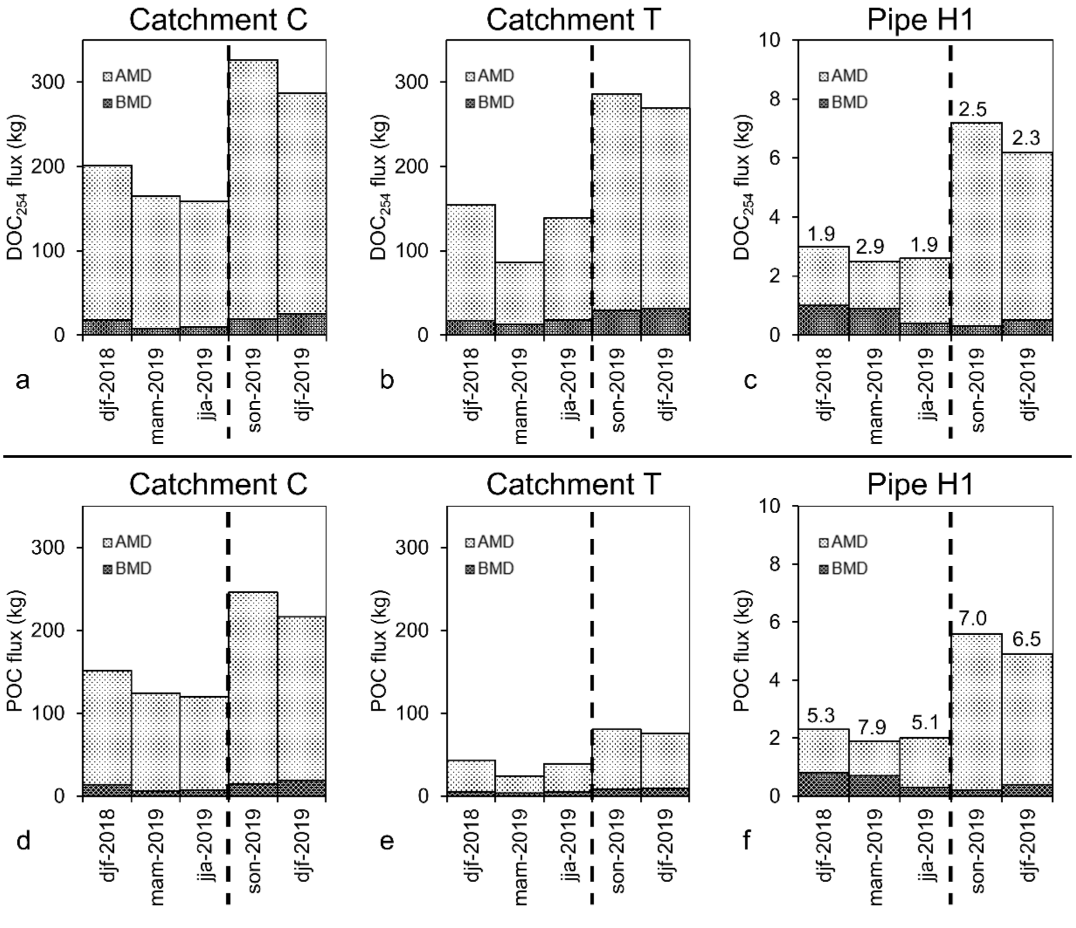

Figure 4.5 Stacked bar diagram showing total estimated flux of DOC_{254} (kg) and POC (kg), for catchments C (a and d) and T (b and e), and pipe H1 (c and f), per season (DJF-2018, MAM-2019, JJA-2019, SON-2019, and DJF-2019). For each season flux was subdivided over flow types Below Median Discharge (BMD), and Above Median Discharge (AMD). For pipe H1, the value above the stacked bar indicates its contribution to catchment T as the percentage of the flux in catchment T. The vertical dotted line marks the start of the intervention: blocking of pipe outlets in catchment T (including pipe H1). A further breakdown on seasonal DOC_{254} and POC flux is provided in Appendix B Table 3.

4.4 Discussion

4.4.1 The effect of pipe outlet blocking on DOC and POC in pipe- and stream-water

Our study is the first, as far we are aware, to examine the influence of blocking natural soil pipes in blanket peat on downstream water quality. The control-treatment experimental design allowed us to examine whether impeding pipeflow through pipe outlet blocking had an impact on fluvial carbon export and water colour, at the stream and ephemeral pipe network scale.

Dividing median DOC and POC concentrations for the post-blocking period by the pre-blocking median concentration (as provided in Figure 4.3) results in ratios of 1.29, 1.34, and 0.91 for DOC_{254} and 0.96, 1.06, and 1.32 for POC, for catchment C, catchment T, and pipe H1 respectively. The similarity in the ratio for catchments C and T shows that blocking 48 % of the pipe outlets in catchment T had no impact on stream-water DOC and POC. While the median DOC_{254} concentration for pipe H1 was smaller post-blocking, its median POC concentration was markedly larger post-blocking, but both trends may have been skewed by a reduced sample size post-blocking. For both DOC_{254} and POC, regardless of a reduced sample size post-blocking, catchment T showed a stronger positive change in median concentrations than catchment C. In addition, throughout the monitoring period no change was observed in the composition of water colour for both pipe- and stream-water. Together, these findings suggest that pipe outlet blocking had no impact on pipe- and stream-water DOC and POC concentrations and is therefore not an effective method for reducing POC, DOC or water colour in degraded blanket peatlands.

We also showed that the pipe-to-stream flux of fluvial carbon was stable across the monitoring period, with increases of pipe flux for DOC_{254} and POC during a wetter post-blocking period. At the catchment scale, increases in DOC_{254} and POC flux post-blocking, as result of a wetter post-blocking period, were near identical for both catchments with ratios of 1.17 for DOC_{254} and 1.46 for POC, rendering the effect of pipe outlet blocking on fluvial C flux at the catchment scale marginal. Across the whole monitoring period, the variation in the seasonal POC flux was smaller for catchment T compared to that observed in catchment C. This difference may be caused by the presence of gully dams in the upper sections of catchment T into which a third of the identified pipes in catchment T drain. However, pipe blocking occurred downstream of these gully dams and, as such, our results did not indicate that pipe blocking had an effect on fluvial carbon fluxes in catchment T.

4.4.2 Fluvial carbon patterns at the catchment scale

DOC_{254} concentrations and stream-water absorbance levels for catchments C and T show a clear seasonal pattern, with elevated values observed between June and March, which is in line with multi-annual DOC and water colour records in peat-dominated catchments showing a strong temperaturedependency (Chapman *et al.*, 2010). Observed summer and winter concentrations of stream DOC_{254} for catchments C and T (summer: 29.6 – 58.9 mg L^{-1}; winter: 6.7 – 33.5 mg L^{-1}), are consistent with those reported in previous studies on the wider eroded area of Bleaklow Plateau (Billett *et al.*, 2010), but up to twofold higher than those observed in streams draining more intact peat of the northern Pennines in the UK, with 17 – 35 mg L^{-1} in summer and 7 – 15 mg L^{-1} in winter for Cottage Hill Sike (20 ha), and 7 – 23 mg L^{-1} in summer and 4 – 10 mg L^{-1} in winter for the larger catchment of Trout Beck (1150 ha) (Clark *et al.*, 2007).

As pipe outlet blocking had no measurable effect on fluvial carbon concentrations in both pipe H1 and catchment T, we estimated the annual total DOC and POC flux for the catchments and pipe H1 in the calendar year 2019, MAM-2019 to DJF-2019 using equation 8. This enabled comparisons for overall erosion rates at catchment level (Table 4.5) and pipe-to-stream carbon transfers to be compared with those found in other studies (Appendix B-Table 4). Table 4.5 shows that the DOC flux for both catchments (catchment C = 21.7 g C m^{-2} yr^{-1}; catchment T = 20.8 g C m^{-2} yr^{-1}) is consistent with the DOC flux obtained at the catchment outlet of UNG (18.5 g C m^{-2} yr^{-1}) (Pawson *et al.*, 2008) and similar in magnitude to DOC fluxes found in other vegetated blanket peat catchments in the region (Billett *et al.*, 2010), northern Pennines of England (Holden *et al.*, 2012; Worrall *et al.*, 2009), Scotland (Dinsmore *et al.*, 2010), and Wales (Billett *et al.*, 2010). Fluxes of POC in the two sub-catchments of UNG were 5.9 – 16.4 g C m^{-2} yr^{-1} lower than the flux of 74 g C m^{-2} yr^{-1} reported at the catchment outlet by Pawson *et al.* (2008), indicating that, although pipes may contribute markedly to their POC budget, other additional POC sources exist in UNG. POC flux for the two sub-catchments was an order of magnitude smaller than that of smaller catchments with proportionally more bare surfaces (Li *et al.*, 2019), but of similar magnitude to larger blanket peatland catchments in the UK (Dinsmore *et al.*, 2010; Worrall *et al.*, 2009). However, in this study samples were collected primarily at set time intervals, with additional water samples collected during some storms. Frequency of stream-water sampling is an important determinant for flux calculations (Pawson *et al.*, 2008). For instance, the larger DOC and POC flux estimated for the stream at Cottage Hill Sike, as reported by Holden *et al.* (2012), may have resulted from a more intense sampling campaign, including water sampling during storms. The authors observed, when fluxes were based only on two-weekly sampling, much lower fluxes for DOC in the range of 29.7 - 36.5 g C m^{-2} yr^{-1}, which are consistent with those found for catchment C and T in UNG in this study. Information about piping frequency for catchments with DOC and POC flux data would aid interpretation of the role of piping in influencing peatland aquatic carbon fluxes.

4.4.3 Fluvial carbon patterns in pipe-water

Water colour in pipe H1 followed a similar temporal pattern to that of catchment T, but seasonal means of absorbance were higher than those observed in catchment T. As the composition of DOC was the same for pipe- and stream-water, water colour and DOC concentrations in pipe-water should be assumed to be temperature-dependent given the significant relationships observed. However, wider comparisons of specific controls on water colour from pipe-water do not exist, and need further research. In earlier work at UNG, POC concentration in stream-water was found to be positively related to discharge (Pawson *et al.*, 2008), but for catchment C and T, and pipe H1, no such relationship was found (Appendix B-Fig 3).

To date, the only other comprehensive assessment of DOC and POC in pipe-water was conducted by Holden *et al.* (2012), investigating pipe-to-stream fluvial carbon transfer at Cottage Hill Sike, a relatively uneroded blanket bog in the northern Pennines of England. For the pre-blocking period, we observed a mean DOC concentration of 27.9 mg L^{-1} for pipe H1, which is very similar to that reported by Holden *et al.* (2012) for ephemeral and perennial pipes at Cottage Hill Sike (30.5 and 27.9 mg L^{-1}, respectively). Despite degrading blanket bogs being often associated with increased POC fluxes (Evans *et al.*, 2006b), pipe-to-stream fluvial carbon transfer in UNG was more effective for DOC than POC concentrations, both pre- and post-blocking. However, pre-blocking, the mean POC concentration of pipe H1 (9.8 mg L^{-1}) was nearly twice that of ephemeral pipes and fourfold higher than that of perennial pipes at Cottage Hill Sike (5.4 and 2.2 mg L^{-1}, respectively) (Holden *et al.*, 2012).

For calendar year 2019, we estimated that pipe H1 produced 18.5 kg DOC_{254} and 14.4kg POC, which accounted for 2.37 % and 6.56 % of the DOC_{254} and POC flux, respectively, of catchment T (Appendix B-Table 4). The annual DOC_{254} flux in kg from pipe H1 was consistent with the average pipe DOC flux of 22.05 kg observed at Cottage Hill Sike, and the POC flux in kg from pipe H1 was similar to the flux observed from an ephemeral pipe (P8 – outlet 10 cm diameter) monitored at Cottage Hill Sike by Holden et al. (2012), which was ten times higher than any other ephemeral pipe monitored at Cottage Hill Sike. To compare pipe H1 to individual monitored pipes at Cottage Hill Sike, the area-weighted fluvial carbon flux for pipe H1 was calculated by dividing the sum of DOC_{254} and POC flux over 2019 by its maximum dynamic contribution area of 1152 m^2 (Regensburg *et al.*, 2021), resulting in ~28 g C m^{-2} yr^{-1}. This area-weighted carbon flux is similar to that of large ephemeral and perennial pipes at Cottage Hill Sike (Holden *et al.*, 2012), but pipe H1 alone has a larger area-weighed fluvial flux than catchment T (Appendix B-Table 4), which is in contrast to combined observations of pipes at Cottage Hill Sike (P1-8 < 26 g C m^{-2} yr^{-1} versus 57 g C m^{-2} yr^{-1} for the catchment outlet) (Holden *et al.*, 2012). As POC flux from pipe H1 accounted for ~40 % of its total suspended sediment load, the area-weighted fluvial flux estimated for pipe H1 translates to ~70 t km^{-2} of particulate organic carbon, which alone is about 20 to 30 % of the organic sediment yield range estimated for the whole UNG catchment by Evans *et al.* (2006b). Such high rates support the speculative association between the onset of gullying and pipe development, a theory developed following the characterization of dominant erosion processes on degrading blanket bog by Bower (1961). However, beyond our work there is virtually no available evidence to test this widely discussed hypothesis, illustrating the need for further research on the link between pipe erosion and gully development in blanket peatlands.

4.4.4 The role of pipes in fluvial carbon budgets

This study investigated the pipe-to-stream transfer of fluvial carbon of a pipe outlet issuing onto a streambank with signs of headward retreat (head pipe), as opposed to pipes issuing onto straight streambank sections (edge pipes). Regensburg *et al.* (2021) reported that head pipes contributed a greater proportion of water to streamflow than edge pipes. Excavation of a small part of two head pipes (H1 and H2 – both with discharge monitored in Regensburg *et al.* (2021)), after monitoring had stopped, showed contrasting features, with pipe H1 being a narrow but straight 4 cm wide vertical crack of ~60 cm deep running perpendicular to the gully edge with its roof ~20 cm below the peat surface, whereas pipe H2 drained a ~8 cm wide confined circular tube-like channel perpendicular to the gully edge with its bottom on a seemingly fixed horizon about 45 cm under the peat surface. Cunliffe *et al.* (2013) found the pipe-peat interface in blanket bog to be more permeable in the roof section than on the lateral sides or under it, but only studied one perennial pipe at ~0.3 m depth. However, the occurrence of biaxial and triaxial anisotropy of hydraulic conductivity in near-surface peat and in peat around pipes in blanket bog may be an important control for the variation in the routing of the pipe segments we found at greater depths. This heterogeneity of hydraulic conductivity across the peat profile might control the spatial reach over which pipes can drain water, and during wetter conditions, would provide good hydrological connectivity of the pipe network explaining runoff excess beyond the surface topographic catchment area. Dividing the total proportion of flow over the weir of DJF-2019 by DJF-2018 (as provided in Table 4.2) results in ratios of 1.5, 1.72 and 1.04 for catchment C, catchment T and pipe H1 respectively, suggesting a longer duration of hydrological connectivity during wetter periods in catchment T than in catchment C, where fewer pipes were observed. However, the duration of flow in pipe H1 was similar in both winters, and pipe H1 was active for longer in winter 2018 than catchment T, but the opposite was observed in the same period in 2019, suggesting wetter conditions on the surface do not necessarily result in better hydrological connectivity in pipe networks. These discrepancies highlight the complexity of the mechanisms that control flow in pipe networks, and these factors that control flow need further research.

Earlier studies on piping in the northern Pennines of UK showed that pipes undulate through the peat profile (Holden, 2004) and they may transport carbon of very different ages (Billett *et al.*, 2012). Those studies were mainly conducted at pipes in landscapes with wide and shallow gullying, whereas UNG has pipes situated in close proximity to deep eroded gullies, which may not allow for long, uninterrupted branching pipe networks. In addition, sediment budgets of UNG have shown gully bank erosion to play a significant role in stream DOC and POC flux (Evans *et al.*, 2006b). The absorbance ratios were consistent between pipe H1 and catchment T, indicating the humic fraction of their effluent had the same composition and originated from the same source. This suggests that DOC concentrations at pipe H1 may have been influenced from water infiltrating near the gully banks, via surface runoff entering the pipe via vent holes, or infiltration close to the pipe outlet, as hypothesised by Daniels *et al.* (2008). The larger POC flux from pipe H1 compared to other pipes in more intact blanket bog, could be indicative of internal erosion processes working differently in more degraded peats, but comparisons on piping processes between sites of differing degradation status do not exist and thus further research on this is recommended.

Table 4.5 Summary of literature on DOC and POC fluxes in UK blanket peat catchments for which data was collected by periodic stream-water sampling.

catchment name	location	catchment area (km^2)	altitude (m amsl)	slopes (degrees)	mean annual precipitation (mm)	mean annual temperature (C)	DOC flux (g C m^{-2} yr^{-1})	POC flux (g C m^{-2} yr^{-1})	Notes	Source
Catchment T, Upper North Grain, S. Pennines*	53°26′28″N , 001°50′30″W	0.038			1592		20.8	5.9	blanket bog, severe erosion, 2019, DOC: n = 206, POC: n = 215	This study
Catchment C, Upper North Grain, S. Pennines*	53°26′31″N , 001°50′16″W	0.043			1592		21.7	16.4	blanket bog, severe erosion, 2019, DOC: n = 153, POC: n = 245	This study
Catchment Tr, Bleaklow, S. Pennines		0.0007		4.3				92.5	Bare, deep gullies, 2007	As reported by Bi al. (2010)
Catchment P, Snake Pass, S. Pennines	53°26′07″N , 001°51′54″W	0.005		7.9			13	1.9 - 3.4	blanket bog, Eriophorum spp., 2008	As reported by Bi al. (2010)
Catchment WC, North slopes of Bleaklow, S. Pennines	53°28′37″N , 001°49′13″W	0.02		13.1			65.6	37.7	blanket bog, shrubs Vaccinium spp. and Empetrum spp., 2008	As reported by Bi al. (2010)
Fleet Moss, Yorkshire Dales	54°14055″N, 2°12053″W	0.017	550 - 580		1997			340.9	blanket bog, 60 % bare, 2016 - 2017	Li et al. (2019)
Upper North Grain, S. Pennines*		0.38	490 - 541		1200		18.5	74	blanket bog, severe erosion, 2005-2006, n = 247	Pawson et al. (2008)
Cottage Hill Sike, N. Pennines*	54°41′N, 2°23′W	0.174	545 - 580	0 - 5	2012	5.8	51.5 – 63.4	2.4 - 3.0	98% blanket bog, relatively uneroded catchment, 2008-2009	Holden et al. (2012)
Nant y Brwyn, Migneint, Wales	55° 47′ N, 03°14′W	1	415 - 487		2200	5.6	19.3	0.9	peat dominated, 2006 - 2008	As reported by Billett et al. (2010)
Lady Clough, S. Pennines		1.33						44.8		Pawson (2008)
Auchencorth Moss, Scotland	55° 47′ N, 03° 14′W	3.4	249 - 300		1155	10	25.4	3.6	low-lying ombrotrophic peatland (85% peat), 2007 - 2008	Dinsmore et al. (2010)
Brocky Burn, N.E. Scotland		1.3	270 - 549		1164	7.5	16.9		Blanket bog with heather moorland	Dawson et al. (2002)
Trout Beck, Moor House NNR, N. Pennines*	54° 65′ N, 2°45W	11.4	450 - 893		1982	5.3	10.3 - 25.2	7–22.4 ±86%	ca. 90% peat, 1993 – 2005	Worrall et al. (2009)

* Reported to have included water sampling during storms

In this study, examining differences at the catchment outlet following pipe blocking was the main objective, and pipe H1 was monitored to assess some of the processes involved. Pipe H1 produced fewer discharge than pipe H2 (Regensburg *et al.*, 2021), therefore concentrations for DOC and POC from pipe H1 may not be representative of all head pipes in the catchment. However, if we use the fluxes observed for pipe H1 as a potential maximum flux for all other head pipes and scale up the DOC_{254} flux for pipe H1 to all 24 head pipes identified in catchment T by Regensburg *et al.* (2020), we can estimate that pipes contribute up to 56 % of the stream DOC_{254} flux of catchment T, providing the DOC is not precipitated or transformed on route to the stream network (Palmer *et al.*, 2016). If we scale up the POC flux from pipe H1 to the 24 head pipes, the contribution of POC from pipes would potentially exceed the observed POC flux of catchment T for 2019, suggesting that the majority of the POC exported from pipes in this system are deposited at the pipe outlet (pipe fan), or trapped in the vegetated parts of the streambed (Evans and Warburton, 2005; Evans *et al.*, 2006b), or transformed to DOC within the stream (Palmer *et al.*, 2016). The temporary storage of POC in pipe fans and in the vegetated streambed are likely to control the episodic nature of POC export observed at the catchment outlet, with POC being re-mobilised during large storms. While pipe H1 had a flow peak of ~0.86 L s^{-1} (Regensburg *et al.*, 2021), the data on DOC and POC flux from pipe H1 presented here were mostly collected at discharges smaller than 0.5 L s^{-1} (Appendix B Fig. 4), and it may be that calibration with more data at larger discharges would alter the relationships presented in Table 4.1, particularly affecting sediment dynamics in the gully system. Pipe surveys conducted by Regensburg *et al.* (2020) demonstrated that in UNG, a catchment which drains towards the south west, gully walls with a south west and west-facing aspect hosted ~40% of all identified pipe outlets in the catchment. The aspect of gully walls is considered an important control on sediment distribution on the gully wall (Shuttleworth *et al.*, 2017). Aspect may be an important factor in the distribution of particulates deposited at pipe outlets, and its magnitude may be exacerbated due to the orientation of the catchment. In a degraded system such as UNG, the constant and excessive POC export by pipes may enhance DOC availability in the stream throughout the year via biodegradation and photodegradation (Worrall and Moody, 2014). However, the residence time and fate of particulate sediment in pipe fans is unknown, but could play an important role in carbon budgets of piped peatland systems, and thus needs further research. Higher POC fluxes in catchment C may be the result of gully walls collapsing rather than the addition of POC from pipes, as it had considerably fewer (head) pipes than catchment T. In summary, the uncertainty in flux estimates of DOC and POC is indicative of pipes being a more complex component in the carbon cycling of degraded blanket peats than thought previously. Pipe networks in UNG are not just a passive pathway for water and carbon flow through the catchment, but form an active contributor, with loads that are quite different to those at stream outlets.

4.5 Conclusions

Impeding pipeflow by blocking the outlets of pipes in a degraded blanket bog catchment has been shown to be ineffective in moderating the export of fluvial carbon at both the pipe outlet and catchment scale. Therefore, it is not recommended that peatland practitioners undertake blocking of pipe outlets on gully walls as part of restoration measures to reduce aquatic carbon loads. We suggest that this recommendation applies to other piped environments where sediment load reductions are sought because hydraulic pressures near pipe outlets may lead to new outlets forming in the vicinity of the blocked outlet, as observed in our study. Further research could test the role of pipe blocking at several points further upslope away from pipe outlets as this may have a different impact on aquatic carbon flux. However, that would be more laborious and require mapping of subsurface pipe networks. In the case of highly degraded peatlands, we hypothesise that upslope pipe blocking (rather than pipe outlet blocking) is more likely to be effective in reducing POC fluxes than DOC fluxes since we found that pipe and stream water DOC had very similar composition, indicating a similar source.

Despite the fact that impeding pipeflow by pipe outlet blocking at UNG was not successful in reducing water colour or DOC and POC concentrations and fluxes, we showed pipe erosion from a head pipe in UNG to be as high as the highest rates observed in a large ephemeral pipe in more intact blanket bog. The frequency of head pipes at UNG may form implications for peatland practitioners to consider when dealing with pipeflow and pipe erosion in the drainage network of degraded peatlands. We showed that fluvial carbon export in pipe-water has a distinctive role in the fluvial carbon export of a degraded blanket bog system, and should therefore be included in future carbon budgets of blanket peatlands.

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Chapter 5: Synthesis and conclusions

Degraded peatlands affect a range of ecosystem services. For example, high erosion rates can lead to reservoir infilling (Yeloff *et al.*, 2005) and poor water quality (Williamson *et al.*, 2020). Degraded peatlands may also lose their climate regulation function and instead serve to exacerbate carbon release to the atmosphere (Worrall et al., 2009). Hence, there has been an increase in peatland restoration projects within the UK, and more widely across the world, with the aim of stabilising these systems and restoring their ability to sustain their range of ecosystem services. Peatland restoration projects usually include one or more of water management, re-vegetation, and vegetation management, with the aim of restoring hydrological function and active peat forming vegetation.

Many restoration projects have focussed on a combination of ditch blocking (Holden *et al.*, 2017) to raise the water table (Holden *et al.*, 2011) and/or re-vegetation with gully blocking to slow the flow (Shuttleworth *et al.*, 2019). However, many of these degraded blanket peatlands contain peat pipes (Holden, 2005a). Soil pipes often occur in complex networks with varying channel sizes, undulating through the soil profile. Their prevalence is often linked to controls such as topographic location, slope, aspect, vegetation cover, climate, and properties of the surrounding soil (Holden, 2005a, 2009; Jones *et al.*, 1997). Diversion of water to these pipes from areas intended to retain more water upstream as result of ditch and/or gully blocking, is a cause of concern to peatland restoration practitioners (Lunt *et al.*, 2010), as soil pipes can bypass them and transport large quantities of water and sediment to streams during storms (Holden *et al.*, 2012b). Restoration practitioners are therefore keen to understand the driving factors of piping as a mechanism and how to prevent piping erosion. They are also unsure whether and how to block them to reduce erosion and flood risk when conducting restoration work. Therefore, this research project was carried out to assess the impact of piping and pipe outlet blocking on the hydrology and carbon export within a heavily degraded blanket bog in the Peak District.

This chapter presents a synthesis of the findings from Chapters 2 – 4. Each chapter's findings are briefly summarised, followed by a discussion on characteristics of piping and characteristics of streams in degraded peatland to explain wider implications for peatland restoration, before describing limitations of this study and directions for future research.

5.1 Major research findings

The main aim of this thesis was to assess the impact of piping and pipe blocking in a heavily degraded blanket bog. The observational and experimental studies carried out to achieve this overall aim were driven by three main research questions. A further question addressed the implications of the research findings for restoration practitioners, which will be addressed in section 5.3. Here, I present a summary of the major research findings that addresses pipe outlet prevalence and characteristics (Chapter 2), effects of pipe outlet blocking on hydrological responses of soil pipes and streams (Chapter 3), and effects of pipe outlet blocking on fluvial organic carbon removal by soil pipes and streams (Chapter 4).

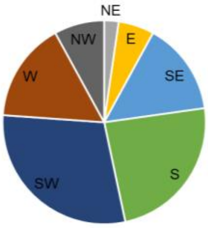
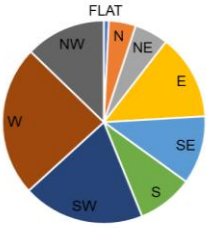
5.1.1 Pipe outlet prevalence and characterization

Chapter 2 addressed the question 'Where do pipe outlets occur in degraded peatland systems that are heavily gullied and how do their characteristics vary spatially?

Where pipes issued onto the peat margin, pipe outlets were mostly found at the interface of the organic layer and the mineral bedrock, whereas the pipe outlets observed on streambanks in gullies were generally found within the peat deposit. I identified two types of pipe outlets based on their position in the landscape: where the streambank showed signs of headward retreat (referred to as head location; location of outlet of head pipe), and where pipe outlets issued onto uniform streambank edges (referred to as edge location; location of outlet of edge pipe). The characteristics of these two types of pipe outlet are presented in Table 5.1. I found a mean pipe outlet frequency of 22.8 km^{-1} streambank, with a total of 346 pipe outlets (Table 5.1) over a stream length of 7.71 km. The maximum pipe outlet frequency was estimated as 91 km^{-1} of streambank in a wide and deeply eroded gully. Pipe outlets at Upper North Grain occupied 0.73 m^2 km^{-1} streambank occupying about 30 % larger area than the average observed by Holden (2005a) across 160 UK blanket bog sites, and more than twice that observed in deep peat sites in the Northern Pennines that were naturally revegetated (Holden *et al.*, 2012a). This would indicate that piping is more prevalent in deeply gullied peat systems than intact ones.

Within the gully profile outlets of edge pipes were found deeper in the peat deposit than outlets of head pipes, and outlets of edge pipes had significantly smaller cross-sectional areas compared to outlets of head pipes (Table 5.1). The most common pipe outlet shape was circular, which had significantly smaller cross-sectional area than that of other outlet shapes. Topographic position and vegetation cover appeared to be important controls on the size and depth of pipe outlets. Aspect had a large influence on pipe outlet frequency, with more than 43 % of identified pipe outlets being observed on southwest and west-facing gully banks (Table 5.1). Bare surfaces hosted proportionally more pipe outlets at edge locations than head locations compared to vegetated surfaces. Pipe outlets issuing onto bare surfaces sat generally deeper in the profile and were smaller, than those observed in vegetated surfaces. West-facing bare surfaces hosted markedly more pipe outlets than bare surfaces at other aspects. Vegetated surfaces facing both south and southwest had markedly more pipe outlets than vegetated surfaces at other aspects.

Table 5.1 Summary of the distribution and morphology of the two types of pipe outlets identified in this study – head and edge (see Chapter 2 for more detail).

Pipe outlet prevalence	**head**	**edge**
Number of pipes	88	258
Pipe outlet morphology	head	edge
Circular in shape (%)	47.7	71.7
Horizontally lenticular in shape (%)	5.7	1.9
Vertically lenticular in shape (%)	30.7	20.2
Median cross-sectional area (cm^2)	292.2	88.0
Pipe outlet position	head	edge
Median depth from surface (D_v) (cm)	20	49
Relative depth of pipe outlet on streambank (1 = streambank edge, 0 = at streambed level)	0.95	0.80
Median streambank slope (°)	35	40
Aspect		

5.1.2 Impact of pipe outlet blocking on hydrology

Chapter 3 addressed the question ‘What is the effectiveness of impeding pipeflow by pipe outlet blocking on the discharge hydrograph of pipe and streamflow?’

Hydrograph indices from two streams were collected, before and after 48 % of pipe outlets were blocked in the treatment (T) sub-catchment. The control (C) sub-catchment was 4.3 ha (with 5 head and 39 edge pipe outlets), while the treatment catchment was 3.7 ha (with 25 head and 40 edge pipe outlets). Over the whole monitoring period, the rainfall-runoff coefficient was comparable in both catchments (T = 85.9 %; C = 85.2 %). Storm runoff was the same in both catchments post-blocking, whereas pre-blocking storm runoff in the treatment catchment was about a fifth lower than in the control. Both catchments responded more to rainfall post-blocking, which reflected the much wetter antecedent conditions in the period post-blocking. Both catchments had comparable peak lag times in both intervention periods. In addition, analyses of stormflow responses in both sub-catchments showed that the distribution of peak discharge and the hydrograph shape were the same in the post-blocking period, as opposed to pre-blocking, meaning that the effect of pipe outlet blocking on stream scale hydrological response was marginal.

Two additional objectives were met in Chapter 3. Firstly, in order to derive advice on pipe outlet blocking as a new technique in peatland restoration, the effectiveness of two methods used to block pipe outlets was assessed through observations of seepage at each blocked pipe outlet. Secondly, the hydrological functioning of four pipes (two head, two edge) and the water table in the peat surrounding them, were assessed for effects of pipe outlet blocking by collecting hydrograph indices sampled from discharge and water-table data collected at those four pipe outlets before and after their respective outlets were blocked.

Pipe outlets were blocked using two methods: 1) by plugging pipe outlets with on-site available materials, or 2) by placing a vertical screen perpendicular to the projected pipe course. In chronological order pipe outlets were blocked with jute bags filled with peat, a mixture of peat and stone, wooden planks, or plastic piling (Figure 5.1). Where pipes that were blocked with jute bags kept leaking, blocks were replaced by either wooden planks or plastic piling. Leakiness was assessed for the 31 blocked pipes using a total of 86 observations over 12 visits. Seepage was observed at a median of 14 days since blocking. All blocked pipes leaked at some point, with seepage occurring around all blocked pipe outlets within 90 days of blocking. Seepage was observed within 26 days of blocking at pipe outlets plugged with a mixture of peat and stones, as early as 5 days since blocking with wooden plank screens, and as early as the day of blocking where plastic piling screens were used. New pipe outlets were only observed forming near pipe outlets blocks by screens, with proportionally more new outlets being observed for pipe outlets blocked by wooden screens than those blocked by plastic piling (Figure 5.1). During the 17-month pre-blocking period, the four monitored pipe outlets contributed together to 11.3% of streamflow, with the two head pipes contributing 4.65 times more than the two edge pipes (Table 5.2). In the post-blocking period, pipe water that escaped from the blocked pipes contributed 4.3 % to stream stormflow (Table 5.2). Pre-blocking head pipes produced significantly larger discharge volumes per storm, larger peak flows, and had larger DCAs compared to edge pipes (Table 5.2). However, peak lag of the storm response was the same across pipe outlet locations. A distinctive distance-decay effect was observed for the water table around pipe outlets, with deeper water tables around edge pipes (Table 5.2).

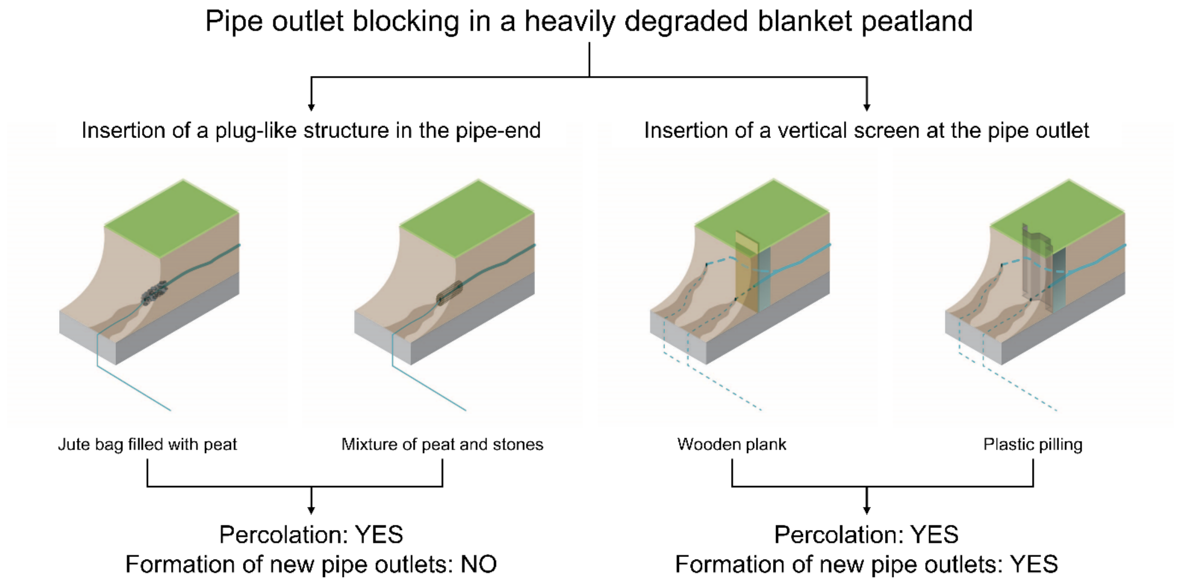


Figure 5.1 Schematic of results of the two methods used to block pipe outlets.

Table 5.2 Summary of hydrological responses of head and edge pipe outlets during the pre- and post-blocking monitoring periods (see Chapter 3 for more detail).

	pre		**post**	
Parameters	head	edge	head	edge
Pipe outlets monitored	H1 and H2	E1 and E2	H1 and H2	E2
Number of pre-blocking hydrographs	153	109	50	17
Stream discharge (%)	9.3	2	4.1	0.1
Maximum peak discharge (L s^{-1})	0.86	0.35	0.84	0.05
Median dynamic contributing area (DCA) (m^2)	325.7	68.3	318.6	0
Median water table depth at 1 m (mm)	407.4	537.4	279.4	407.6
Median water table depth at 3 m (mm)	300.5	452.8	193.1	336.1

5.1.3 Impact of pipe outlet blocking on fluvial carbon export

Chapter 4 answered the research question ‘What is the effectiveness of impeding pipeflow by pipe outlet blocking on the export of fluvial organic carbon at the pipe and catchment scale?’.

Dissolved and particulate organic carbon (DOC and POC) concentrations and spectral absorbance were analysed for water samples collected from the outlet of the two monitored catchments (C & T) and one pipe outlet (H1). These data were then coupled to discharge data from the respective stream and head pipe to estimate the flux of DOC and POC. Pipe outlet H1 was monitored for water quality both pre and post-blocking as new pipe outlets had formed around its block.

Concentrations of stream water DOC displayed a seasonal pattern, being higher in late summer/autumn than late winter, and were of a similar magnitude to those reported from other sites on the Bleaklow plateau (Billett *et al.*, 2010), but about a twofold higher in both winter and summer than observed in streams draining more intact blanket bog in the northern Pennines of the UK (Clark *et al.*, 2007). Concentrations of stream water POC were much more episodic in nature than DOC and highest concentrations were observed during summer storms, as observed in other peat erosion studies. In both catchments increases in DOC and POC flux were near-identical post-blocking suggesting pipe outlet blocking was ineffective in reducing fluvial carbon export from pipe networks. Difference between concentrations in pipe- and stream-water showed that pipe-to-stream transfer was more effective for DOC than POC. Post-blocking, pipe H1 had a reduced median DOC_{254} concentration compared to pre-blocking, as opposed to an increase in its median POC concentration (Table 5.3). The monitored pipe accounted for 2.1 % of the DOC and 5.8 % of the POC stream flux pre-blocking, and 2.4 % of the DOC and 6.7 % of the POC stream flux post-blocking (Table 5.3). In addition, throughout the monitoring period no change was observed in the composition of water colour for both pipe- and stream-water (Table 5.3). Aggregating fluxes of DOC and POC for pipe H1 over 2019 resulted in a total fluvial carbon flux of ~28 g C m^{-2} yr^{-1}, which was larger than the area-weighted fluvial carbon flux of catchment T, but at par with that of large ephemeral and perennial pipes found at a more intact blanket bog in the UK. All together, these findings therefore suggest that pipe outlet blocking is not an effective method for reducing pipe-to-stream transfer of POC, DOC, and water colour in degraded blanket peatland.

Table 5.3 Summary of DOC and POC concentrations and fluxes from the outlet of pipe H1 and its contribution to stream water DOC and POC flux during the pre- and post-blocking monitoring periods (see Chapter 4 for more details).

	Pre	**Post**
Contribution to stream discharge (%)	2.0	2.3
Pipe activity (produced discharge % of time)	76.4	86.1

DOC$_{254}$ (mg L^{-1})	4.6 - 68.5	9.1 - 61.7
Median DOC$_{254}$ (mg L^{-1})	29.7	27.1
Max. pipe DOC$_{254}$ (mg L^{-1}) relative to stream (-)	1.2	1.3
Max. instantaneous DOC$_{254}$ flux (mg s^{-1})	8.9	21
Total DOC$_{254}$ flux (kg)	8.0	13.5
Proportion of DOC$_{254}$ flux at AMD* (%)	72.5	93.3
Contribution to stream DOC$_{254}$ flux (%)	2.11	2.43
Mean SUVA (L mg^{-1} m^{-1})	4.37	4.55

POC (mg L^{-1})	0.3 - 212.2	2.0 - 67.7
Median POC (mg L^{-1})	3.4	4.5
Max. pipe POC (mg L^{-1}) relative to stream (-)	4.8	8.8
Max. instantaneous POC flux (mg s^{-1})	46.9	51
Total POC flux (kg)	6.2	10.5
Proportion of POC flux at AMD* (%)	71.0	94.3
Contribution to stream POC flux (%)	5.8	6.73

* median was calculated for the whole monitoring period.

5.2 Integration of findings

This section describes the coherence and contrasts found in the results presented in Chapters 2 – 4, and examines some common themes that the three results chapters provide evidence for.

5.2.1 Characteristics of piping in degraded blanket peatland

In this study, I identified two types of pipe outlets, head and edge, based on their location in the landscape, which have not been identified or characterised in previous studies of pipe outlets in blanket peatlands. For instance, Jones and Cottrell (2007) and Holden *et al.* (2012a) categorised pipes based on their flow behaviour, being either ephemeral (storm based) or continuous (perennial). Time-lapse footage recorded at several pipe outlets (both head and edge) in Upper North Grain showed discharge from pipe outlets to cease after each rain event, meaning that all pipes were in the catchment were considered ephemeral. Therefore, categorizing the pipe outlets based on flow behaviour was not feasible, but pronounced differences were found when looking at the topographic setting of pipe outlets that enabled the two pipe outlets to be characterised (see Table 5.1).

Overall, I found a greater prevalence of pipe outlets at edge locations compared to head locations (Table 5.1), but pipe outlets at head locations had significantly larger cross-sectional areas. Pipe outlets at head locations were found significantly closer to the surface (median $D_V = 20$ cm) compared to pipe outlets in edge areas (median $D_V = 49$ cm) (Table 5.1). Pipe outlets at head locations produced significantly greater peak storm discharge and markedly larger discharge contribution to the stream compared to that of pipe outlets at edge locations (Table 5.2). During the pre-blocking period, pipe outlets at head locations had a significantly larger DCA compared to pipe outlets at edge locations (Table 5.2). However, peak lag, during this pre-blocking period, was not different across pipe outlet locations, and peak lag and length of the recession limb for both pipe types was the same as for the stream. This would suggest that both pipe outlet types respond to rainfall in a similar way, but other factors determine the quantity of water discharged via their outlets. A possible factor is the difference in depth at which they occur in the streambank, and as result the means by which they source their water. For instance, hydraulic conductivity of peat at deeper layers may often be restricted due to ongoing humification and compression as result of the weight of the peat column above it (Holden *et al.*, 2014; Rezanezhad *et al.*, 2016; Rycroft *et al.*, 1975). In contrast, peat closer to the surface is often prone to desiccation and wind erosion scouring, breaking peat apart and allowing water ingress via emerged cracks. In this thesis I have shown that aspect was a strong control on pipe prevalence with sun-facing streambanks, accounting for 63.2 % of pipe outlets at edge locations and 84.1 % of pipe outlets at head locations (Table 5.1). This indicates that, in periods with prolonged dry weather, desiccation may be a dominant factor in how water transport is distributed in streambanks. Previous work has indicated that desiccation-stress cracking on the surface may promote ingress of water to soil peat column, inducing local sapping activity, which, in turn, can lead to further piping (Parker and Jenne, 1967). However, the propensity of piping as a result of desiccation may vary across the peat profile. For instance, as gullies develop and expand, more humified peat from deeper in the peat profile may become exposed on the streambank, yet its low hydraulic conductivity restricts the formation of high energetic preferential flowpaths regardless of water being present or drawn to it via hydraulic gradients. The difference in water transport capacity between peat at deep and shallow depths from the surface would therefore explain why edge pipes that issue from deeper in the peat are smaller and produce less discharge compared to head pipes that are found closer to the surface. In addition, during survey work undertaken for Chapter 2, surface depressions and vent holes close to pipe outlets were only observed at head locations. Pre-blocking, surface runoff was observed flowing into a vent hole just upslope of the outlet of pipe H1. Excavations of the head pipe area after monitoring had ceased showed a clear connection between the observed vent hole and the pipe course leading to the pipe outlet of pipe H1. I therefore propose that any surface runoff entering vent holes and/or desiccation cracks may add to the energy of pipe water and help enlarge the pipe network through the peat mass via erosion. In addition, water from head pipes and the stream showed a similar seasonal pattern for water colour (254 nm, 400 nm, 465 nm, and 665 nm) and ratios of spectral absorbance (254 nm : 665 nm, 254 nm : 400 nm, and 400 nm : 665 nm), suggesting that the source of water to head pipes is the same as the dominant source of stream water, which is likely to be mainly surface runoff. It is therefore hypothesised that water discharged from head pipe outlets has a strong connection with surface runoff. Given the observed differences between the geometry of pipe outlets at head and edge locations (Table 5.1), pipe outlet position on the streambank (Table 5.1), and the storm discharge responses (Table 5.2), and related dynamic drainage reach (Table 5.2), I hereby propose that the two pipe types receive their water from alternative water sources, which I will outline below.

Given that water transport is generally restricted in deeper peat layers, the potential energy of overland flow may only be effective in pipe enlargement for pipe networks closer to the peat surface. This would suggest that pipe outlets at head locations may be the product of pipe networks with a strong connection to large quantities of surface runoff (Figure 5.2b), which could develop a high erosive pipeflow and convey high amounts of peat sediment to pipe fan areas. I hereby propose that where surface runoff is able to enter the pipe network, via vent holes or desiccation cracks, pipe enlargement is controlled by water flux, which was also postulated by Wilson *et al.* (2017). A similar theory was put forward by Gilman and Newson (1980), long before the prevalence of piping was shown in blanket bog (Holden, 2005a; Holden and Burt, 2002). They stated that soil pipes are directly fed from overland flow at the surface via a collapsed pipe roof or through near-surface cracks and macropores. Whereas in the absence of a strong connection with overland flow, I hypothesise for degraded blanket bog that where pipe outlets occur deeper in the peat profile, pipe enlargement is controlled predominantly by the hydraulic gradient in the peat adjacent to the pipe. In turn, pipe outlets at edge locations would therefore tap their water from the sapping zone in streambanks only (Figure 5.2c), limiting the quantity of water that can shape the pipe channel radius.

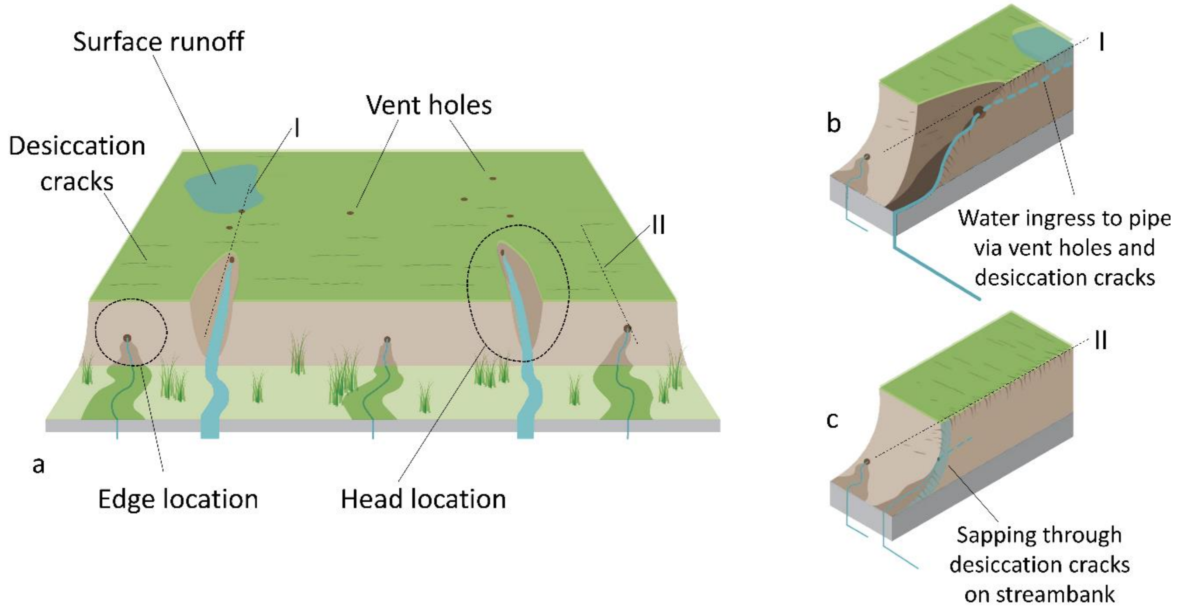


Figure 5.2 Schematic representation of a) outlook of a streambank with pipe outlets at b) head locations and c) edge locations, showing their potential contrasting sources of water. Dotted lines with respective roman numbers I and II are used to indicate across which transect line in 5.2a cross-sections in 5.2b and 5.2c were taken. Head pipes may source the majority of their water from surface connections, amplified by inflow of overland flow via desiccation cracks and ventholes further away from the streambank. In contrast, edge pipes may source their water from desiccation cracks in the sapping zone close to the streambank edge which only enables small discharges to build up. Illustrations by Philippa Lewis.

Chapter 2 showed that Flow Contribution Area (FCA) across outlets of both head and edge locations was an unrealistic 1 m^2. Based on flow data collected presented in Chapter 3, I expected a large difference in FCA between head and edge pipe outlets, given that head pipes produced significantly greater discharges. The absence of this effect may be the result of the size of surface expressions of piping. FCA was based on a DTM with the ground resolution of 50 cm. Any surface depression being much smaller than that would not be detected, and therefore it is possible that FCA was markedly underestimated. I concluded that topography alone is a poor guide for estimating flow from pipe outlets as there was no relation between pipe outlet location, pipe outlet size, and upslope topographic drainage area. These findings corroborate with earlier attempts to estimate the drainage area of soil pipes (Jones, 1997; Smart *et al.*, 2013), yet warrant attention for future research that aims to quantify piping connectivity using digital mapping.

In addition, Chapter 3 showed that water tables had a stronger drawdown at edge locations compared to head locations (Table 5.2), but it is not clear whether the observed differences in water-table drawdown around pipe outlet locations also translates into a stronger differences in hydraulic head feeding into the pipe wall, promoting infiltration from the peat body to the pipe. Nonetheless, Holden (2006) showed that where water tables are lowered in consecutive drought periods, pipe frequency may increase. Therefore, drought periods that result in lowering of the water table and desiccation of the peat, which is more prone on bare peat surfaces than vegetated ones such as gully edges, can make streambanks extremely prone to further pipe formation. Influences of water table on pipeflow behaviour could potentially explain both temporal and spatial differences between the two pipe types. However, little is known about this interaction or how to study it in a non-destructive way, and thus further research is required.

5.2.2 Variability in the hydrological and fluvial carbon response to rainfall events of two sub-catchments of similar scale

The data presented in Chapters 3 and 4 were collected as part of a before-after-control-intervention approach (BACI), in which I found that two adjacent peat sub-catchments responded rather differently to rainfall in terms of storm responses and fluvial carbon export. Such a result would not have been detected using a control-treatment approach where there is no pre-monitoring period. For instance, runoff in the pre-blocking period was ~20 % lower in the treatment catchment compared to the control. For the same period, dividing median storm peak discharge by contribution area showed that the treatment catchment produced 0.88 L s^{-1} ha^{-1} compared to 1.25 L s^{-1} ha^{-1} in the control catchment, whereas in the post-blocking period it was 1.78 and 1.77 L s^{-1} ha^{-1} respectively. In contrast, storm flow duration was the same across both catchments and across intervention periods.

I also found that POC transport varied significantly between the catchments. In 2019, POC yield was 148 kg ha^{-1} for the control catchment versus 52 kg ha^{-1} for the treatment catchment, whereas DOC yield was of similar order of magnitude in each ranging 186 – 196 kg ha^{-1}. Future work that examines the effect of interventions in one catchment and attempts to upscale conclusions should therefore adopt a BACI approach to avoid the issues of adjacent catchments behaving differently.

In that context, the observed discrepancies in the flow responses between catchments (Chapter 3), and the differences of net fluvial carbon export (Chapter 4), may be indicative of different processes controlling hydrological and erosional (dis)connectivity within the two catchments. In the following section I will further discuss the underlying factors that may be responsible for these differences.

In Chapter 3 I showed that head pipes can contribute markedly to streamflow, so a difference in the number of head pipes between the two catchments may account for the difference in hydrological response observed. I found that in the control catchment pipe outlets at head locations mainly occurred in the head of the gully, whereas in the treatment catchment pipe outlets at head locations were more spread out across the drainage network (Figure 2.3 and Figure 3.1b). For Chapter 3 and 4 head pipes were monitored in the midslope section of the treatment catchment. Pipe H1 and H2 contributed ~9 % of stormflow of the treatment catchment pre-blocking, and produced an irrefutable contribution to streamflow in terms of discharge and fluvial carbon export. Holden (2005a) argued that increased gradient at midslopes inhibit wandering of the pipe network, inferring a stronger hydrological connectivity for existing pipes relative to those found near topslope or footslopes sections of blanket peatlands. Over the course of the monitoring period, with wetter conditions post-blocking than pre-blocking, the treatment catchment showed a larger increase in runoff than the control catchment. The extent of the presence of pipe outlets at head locations in the treatment catchment in the lower part of its drainage system may therefore explain this difference in runoff production. However, for degraded blanket peatland no data are available about the hydrological and erosional behaviour of pipes in gully heads, but deriving such comparisons between pipes across the hillslope may be helpful to understand which areas in degraded blanket bog are more connected to the pipe network. Identifying such areas need attention when aiming to mitigate flows and erosion from pipe networks in the context of peatland restoration.

In Chapter 4 I showed that head pipes can play a major role in the export of POC to streams. But POC flux of the treatment catchment in 2019 was 2.78 times lower than that from the control catchment, suggesting that the factors controlling transport of POC in streams go beyond difference in piping between the catchments and vary between adjacent catchments. For instance, provided pipe outlets at head locations make up only 40 % of identified pipe outlets in the treatment catchment compared to only 12 % in the control, I would have expected POC export contribution of pipe outlets to be larger in the treatment catchment. However, gully blocks had been installed as part of an earlier restoration activity in both catchments (Figure 2.3 and Figure 3.1c). In the treatment catchment gully blocks captured water from a third of the identified pipe outlets, as opposed to the control catchment, where gully blocks were only placed in three small tributaries, where no pipe outlets were detected upslope of the gully blocks. In summer periods, gully blocks in the treatment catchment may have buffered the contribution of flow from a third of its pipes, possibly lowering or delaying runoff to the catchment outlet (Shuttleworth *et al.*, 2019). Finally, whereas pipe H1 unmistakably produced large quantities of POC, incidental hagg collapse across the catchment could increase POC export to much larger extent than pipes do, but monitoring of hagg processes is difficult. Previous sediment budget studies identified erosion of the streambank surfaces as a key sediment source in degraded blanket bog (Evans *et al.*, 2006), and therefore hagg collapse warrants attention besides pipe contributions when monitoring POC export continuously in peatland streams.

5.2.3 Implications of findings for peatland restoration management

In this thesis, I have shown that blocking pipes at their outlet does not appear to have any impact on streamflow or aquatic carbon export. However, my findings do suggest that other restoration techniques may be more beneficial, such as gully re-vegetation and blocking further up the pipe network. These require further research to test their impacts on flow and carbon export from existing pipe outlets, and streamflow, and pipe development in general.

In Chapter 2 – 4 I have shown that the prevalence of piping and its contribution to streamflow and fluvial carbon export in a degraded blanket bog in the southern Pennines markedly differs from that reported by others for more intact blanket bog sites in the northern Pennines. Therefore, the proposed mechanisms for flow in head and edge pipes (Figure 5.1) should be taken into account when considering treating pipe networks as part of peatland restoration activities. However, it should be noted that some practices currently applied as part of a restoration project may conflict and perhaps even cause piping to occur. For instance, soil around weirs and dams placed in gullies and ditches, and around bare peat areas, to slow the flow and retain runoff for water-table stabilization in adjacent peat, could be prone to cracking caused by subsidence or the high seepage pressure force associated with the large hydraulic gradient between the upper and the lower part of the blockage (Holden *et al.*, 2017). Although water-table rise is often the main aim of the measure, it also poses the risk of increasing the contrast between frequently wet and dry areas locally, therefore potentially increasing transport of water due to increased seepage pressures to the surrounding peat. Piping is thought to be a product of increased macropore flow at sharp gradients of hydraulic pressure in peat (Holden, 2005b). In addition, I have shown that along the course of existing soil pipe networks the water table can sit deeper than in the rest of the peat. It is therefore of great importance to accurately determine piping prevalence on streambanks prior to installing dams and blocks in gullies and ditches so the risk of further pipe formation as a result of it could be characterised.

The research covered in this thesis has shown that pipes, particularly at head locations, form an integral part of streamflow behaviour and carbon cycling in degraded peatlands. In that context I suggested that blocking pipes higher up slope in their network may be more beneficial than blocking their outlets. Any pipeflow that is then redirected to the peat surface would then spill on to vegetated surface, which inhibits fast runoff and reduces sediment transfer to the stream (Grayson et al., 2010). However, blocking pipes higher in the network would only be possible for pipe networks that are relatively close to the peat surface, i.e. those networks associated with head pipes, and which show visual signs like vent holes or surface depressions, or where pipe course detection from the surface can be achieved. To prevent further influence of surface connections to the pipe network, reducing the incidence of desiccation-stress cracking further away from the streambank is key. A solution would be to redirect overland runoff away from streambanks, by placing bunds across the contour of the surface slope (Figure 5.3a). This would potentially reduce ingress of water via vent holes and desiccation cracks that connect to pipe networks close to the peat surface (Figure 5.3a). The placement of the bunds may shorten the flow length of surface runoff across the hill, thereby reducing the risk for runoff to develop high energetic velocities and so limit erosive flows to enter the pipe network (Figure 5.3b). In turn, limiting the incidence of inputs from surface runoff to pipes could halt the proliferation and further extension of the pipe network. In addition, the area upslope of the bunds may provide temporal storage of runoff water, increasing the time for collected water to recharge the water table locally. The newly created ponding areas could benefit the establishment, nourishment, and survival of peat-forming *Sphagnum* species. However, the spacing of bunds should be addressed in context with pipe prevalence, spatial incidence of vent holes and/ or desiccation-stress cracking, and the expected benefit for stabilizing water-table fluctuations around the bund itself.

I also have shown that while impeding pipeflow by pipe outlet blocking did not work due to the formation of new pipe outlets after pipe outlet blocking, indicating that streambanks in degraded blanket bog are a potential weak spot for pipe formation. This idea is further underpinned by observations of a strong water-table drawdown around pipe outlets at edge locations, inferring a close link to desiccation effects on streambanks. In addition, I showed that edge pipes mainly issued onto streambanks with a sun-facing aspect. It is therefore advised that streambanks affected by desiccation should be treated in order to protect streambanks from further pipe formation. I propose that where bare streambanks occur, streambanks are reprofiled and revegetated, in order to lower the risk of desiccation effects, inhibiting sapping and so lowering the potential formation of new edge pipes (Figure 5.2a and 5.2c).

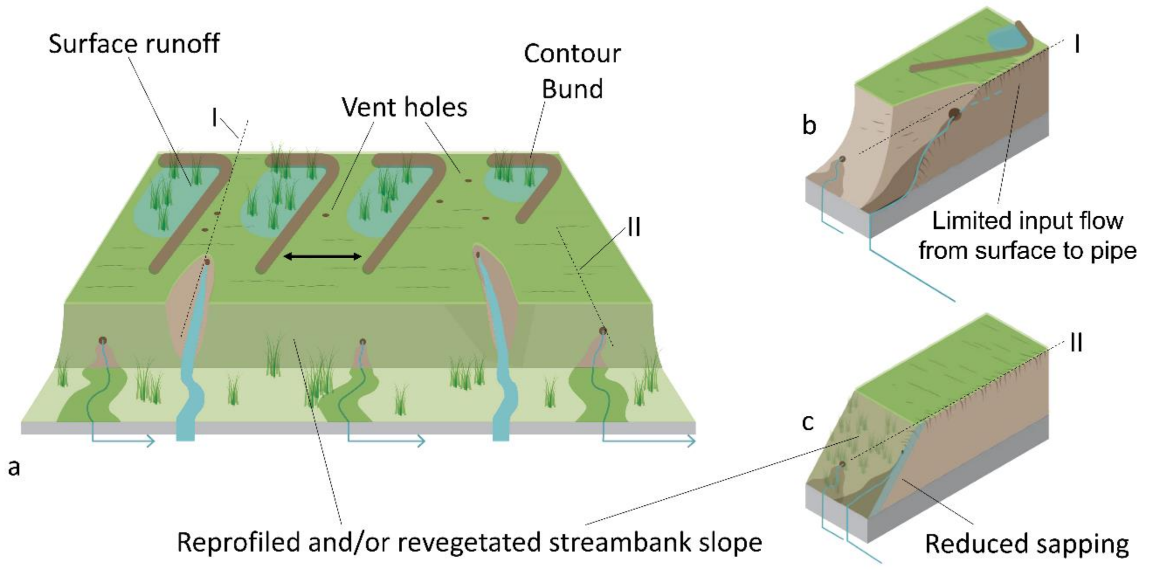


Figure 5.3 Schematic of a peat catchment highlighting a) possible restoration techniques geared towards prevention of pipe formation, showing simplified examples of bunds placed on the contour of peat surface, and reprofiled and/or revegetated streambank surfaces, with cross-sections b) and c) showing these scenarios for head locations, and edge locations, respectively. Dotted lines with respective roman numbers I and II are used to indicate across which transect line in 5.3a the cross-sections in 5.2b and 5.2c were taken. Revegetation of gully edges will reduce desiccation, whereas bunds across the slope will reduce preferential flow and interaction between overland flow and pipe networks.

5.3 Limitations of the study

I believe that this study has provided important data on the prevalence and geomorphology of two types of peat pipes in degraded blanket peat. It has also tested the impact of blocking pipe outlets on stream hydrology and aquatic carbon export. However, several inevitable limitations were encountered due to resource and financial constraints that I will outline below.

While results using a before-after-control-intervention approach to study the impact of pipe outlet blocking has shown that it was the right method to use, pre- and post-blocking periods were not of equal length and the weather was not similar during these periods. This skewed the distribution of results on discharge production and fluvial carbon export per monitoring period markedly. In addition, DOC and POC was only gauged on one pipe outlet. It would have been better to monitor carbon export for all four pipes that were monitored for flow but unfortunately this was not feasible within the financial constraints of the project. Water samples from pipe- and stream-water were initially sampled per storm using trigger mechanisms in each flow gauge, but the performance of this approach was not consistent, as the pipe and streams did not always respond to rainfall at the same time. To overcome this problem and improve the consistency in water sampling, the automatic water samplers were programmed to take samples at regular intervals of 6 to 12 hours. Though there was a risk of sampling in dry conditions, and also missing out on samples during peak discharge of storm responses it was felt that this was the best option to ensure samples were collected from the two streams and the pipe at the same time and were therefore comparable.

Gully blocks in various tributaries of streams across the catchment, as a result of restoration works preceding the start of the research reported in this thesis, made finding unimpacted stream catchments with comparable geometry and piping activity challenging. Most field visits for pipe surveys coincided with low flow conditions, which made it difficult to identify pipe locations for monitoring, and restricted the number of pipe outlets considered useful for monitoring pipeflow. Finally, only ~47 % of pipe outlets in the treatment catchment were blocked. Despite results showing that blocking of pipe outlets was not effective, it would have been better to block all of the identified pipe outlets in the treatment stream, to ensure a solid comparison.

This research also showed that there is no such thing as 'one size fits all' approach for pipe outlet blocking, and that, regardless of the method used, blocking of pipe outlets is an intensive practice which requires a certain precision, while information about the actual pipe course was not available. Construction of the monitoring site, including instrumentation of pipeflow gauge locations, catchment outlet weirs, and the blocking of pipe outlets, was therefore a dynamic process, driven by site access restrictions, practical labour costs and sustainable resource use constraints. A combination of factors such as restricted site access due to bird breeding season, lack of access due to snow fall in winter and spring, lack of pipe discharge over summer and during most field visits, delayed testing pipe outlet blocking techniques and their development, and at which point in time pipe outlet blocks could actually be installed. As a result of the way in which outlet blocking was developed, the study design did not include measurements to assess the blocking impact of singular pipe blocking methods, as impact of pipe outlet blocking was only quantified at the stream outlet. Furthermore, as the four monitored pipe outlets were all blocked to establish the full extent post-blocking across pipe outlet locations, it is not known whether unblocked pipe outlets produced similar hydrograph indices and sediment fluxes during the post-blocking period (i.e. there was no pipe outlet control within either of the sub-catchments). In hindsight, it would have been good to monitor head and edge pipes in the control catchment throughout the whole monitoring period. Whereas results have shown that the streams respond differently in the sub-catchments, similar data for pipes was not gathered. Not having multiple pipe outlets monitored, using both control and treated versions, and in multiple streams to assess for site specific differences, fits the common challenge of working in remote peatland areas while on a limited budget.

5.4 Directions for future research

This work presents results from one of the first studies that have attempted to impede pipeflow by blocking the outlets of soil pipes in a degraded blanket peatland. I have shown that pipe outlet blocking was unsuccessful, but presence of pipes in degraded blanket bog can have an important role in drainage and transfer of DOC and POC to streams. The processes controlling erosion by pipeflow in blanket peatlands are not well studied. I also observed that pipe outlets issue mainly on streambanks that face towards aspects that receive more sunlight, and water tables sit lower where pipes issue onto streambanks, but linkages between the water table and pipe networks have received little attention to date. Mechanistic work on the processes involved in the formation of soil pipes in peat, such as sapping, suffusion, and internal erosion, are also lacking in the wider piping literature (Bernatek-Jakiel and Poesen, 2018; Wilson et al., 2017). It is therefore important to examine pipe prevalence in current restoration sites to evaluate how the results presented in this thesis affects the effectiveness of current restoration measures and how their approach could be adjusted to account for piping activity in any future peatland restoration plans. In an attempt to continue to look for options to treat pipes, I would advise further exploring the following aspects of piping in degraded blanket peatlands in advance of applying peatland restoration techniques:

- Investigate whether head and edge pipes are found in other degraded blanket bogs.
- Determine whether drivers of piping are uniform in blanket bog across degradation status.
- Determine whether drivers of piping in blanket bog also apply to other degraded mire types.
- Develop methods to accurately determine the location of soil pipes that are smaller than 10 cm in diameter. This would aid the assessment of the subsurface drainage density.
- Monitor impacts of surface interventions (gully blocking, bunding, revegetation of bare streambanks) on pipe outlet flow responses (timing and discharge) and pipe water chemistry (e.g. an assessment of the effect of water-table rise on hydro-chemistry of pipe effluent).
- Assess the hydrology and hydro-chemistry differences between head pipes at the head of gullies and those in the rest of the catchment (i.e. do pipe erosion rates differ?).
- Determine whether water-table drawdowns are different between deep and shallow streambanks and how those corroborate with pipe prevalence (head and edge presence).
- Assess which factors contribute to pipe enlargement in degraded blanket peatland, so adequate measures can be taken to prevent pipe enlargement.
- Include piping in modelling of blanket peatland processes to accurately account for their influence on stream hydrology and fluvial carbon yield.

5.5 Conclusions

The aim of this thesis was to understand the impact of piping and pipe outlet blocking on the hydrological responses and associated fluvial carbon export of streams in a heavily degraded peatland headwater. The research has shown that aspect is a strong control on the position of pipe outlets on streambanks, and that pipe outlets that issue onto uniform streambanks (referred to as 'edge pipes') sat deeper in the profile, were smaller, and produced less discharge than pipe outlets that occur on streambanks with signs of headward retreat ('head pipes'). Blocking of pipe outlets by impeding pipeflow did not result in a reduction of streamflow and associated aquatic carbon export at the stream scale, and may even exacerbate pipe development in streambanks. Despite blocking its outlet, a 'head pipe' produced a greater annual area-weighted fluvial carbon flux than the catchment it was located in, which observed difference was larger than was observed for any pipe previously monitored in more intact blanket bog. The differences in geomorphology, and hydrological responses between the two types of pipe outlets, and the differences in water chemistry between pipes and streams, suggest impediment of pipeflow needs careful reconsideration as controls on pipe activity in uniform streambanks may differ markedly from those with signs of headward retreat. Future restoration work in degraded blanket peatlands should prioritise limiting surface runoff inputs to pipe networks, and revegetate bare gullies to reduce the incidence of desiccation on streambanks, to prevent further pipe formation.

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Appendices

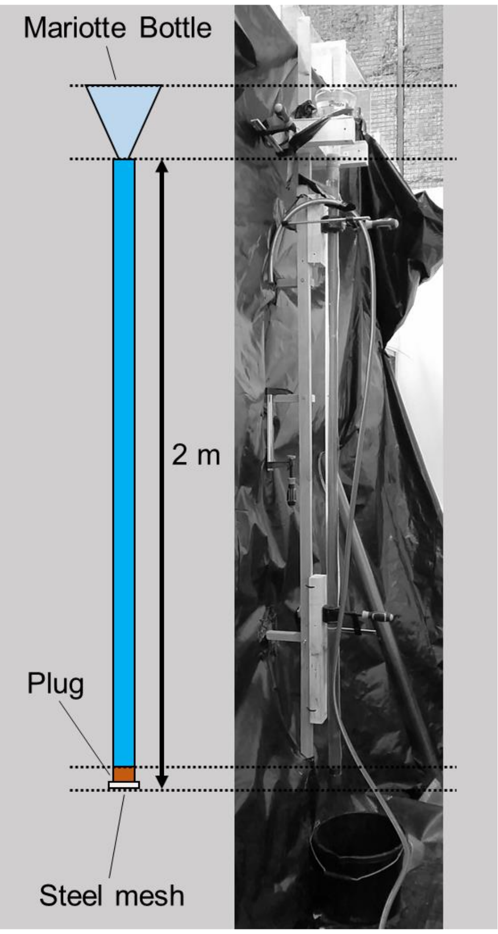
Appendix A. Supplementary Information for Chapter 3

Supplementary information in support of:

Regensburg, T.H., Chapman, P.J., Pilkington, M.G., Chandler, D.M., Evans, M.G., Holden, J., 2021. Effects of pipe outlet blocking on hydrological functioning in a degraded blanket peatland. *Hydrological Processes*, 35(3), e14102.

Laboratory test on sealing strength of peat

A water column was established in a two-metre long acrylic tube with an inner diameter of 36 mm. A plug structure consisting of peat was sourced from compressed peat pellets used for plant propagation, which were fabricated in fine netting, and when rewetted provided a cylindrical body with a diameter of 36 mm and height of 5 cm. Peat plugs were placed on one side of the tube and held in position by a steel mesh fitted to a standard PVC end-cap (Appendix A-Fig 1). Before filling the tube with water, a standard PVC end-cap was sealed with gaffer tape so water could not escape the tube when erected. The tube was then placed vertically and filled with water, and a Mariotte-bottle was connected to the top end of the tube to keep a constant head (Appendix A-Fig 1). To start the test, the gaffer tape was removed from the bottom of the tube. The water pressure compressed the plug to such an extent that in all runs percolation stopped within an hour of the start of the test.



Appendix A-Fig. 1 Schematic of a laboratory test to assess sealing strength of peat

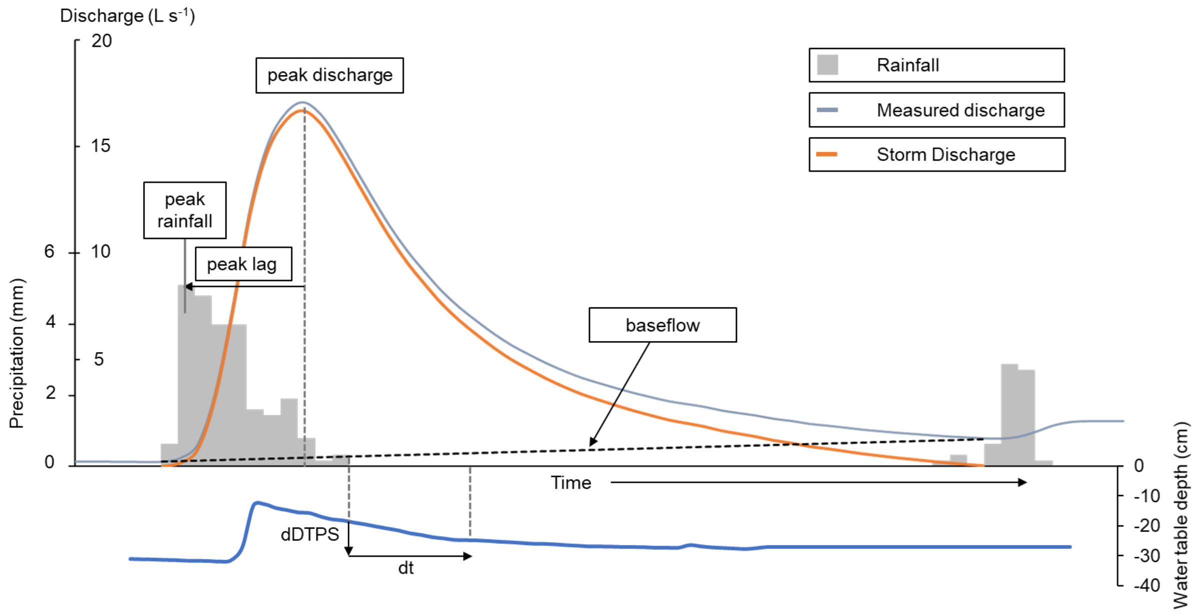
Gap filling of rainfall data

All precipitation records had periods of missing data, due to battery failure or animal disturbance. For the period between April and December 2018, only RF2 was active (Chapter 3 Figure 3.1). Gaps in RF2 over the period 20/08/2018 – 02/10/2018 were compared through benchmarking to two rainfall gauges located at weirs in Urchin Clough (UC), a neighbouring catchment ~3 km west of Upper North Grain (UC Weir 12: 53.437 ° N, -1.877 ° W; UC Weir 6: 53.434 ° N, -1.871 ° W). Regression of 1 hour sums of precipitation between the locations was undertaken for the period 10 April 2018 – 20

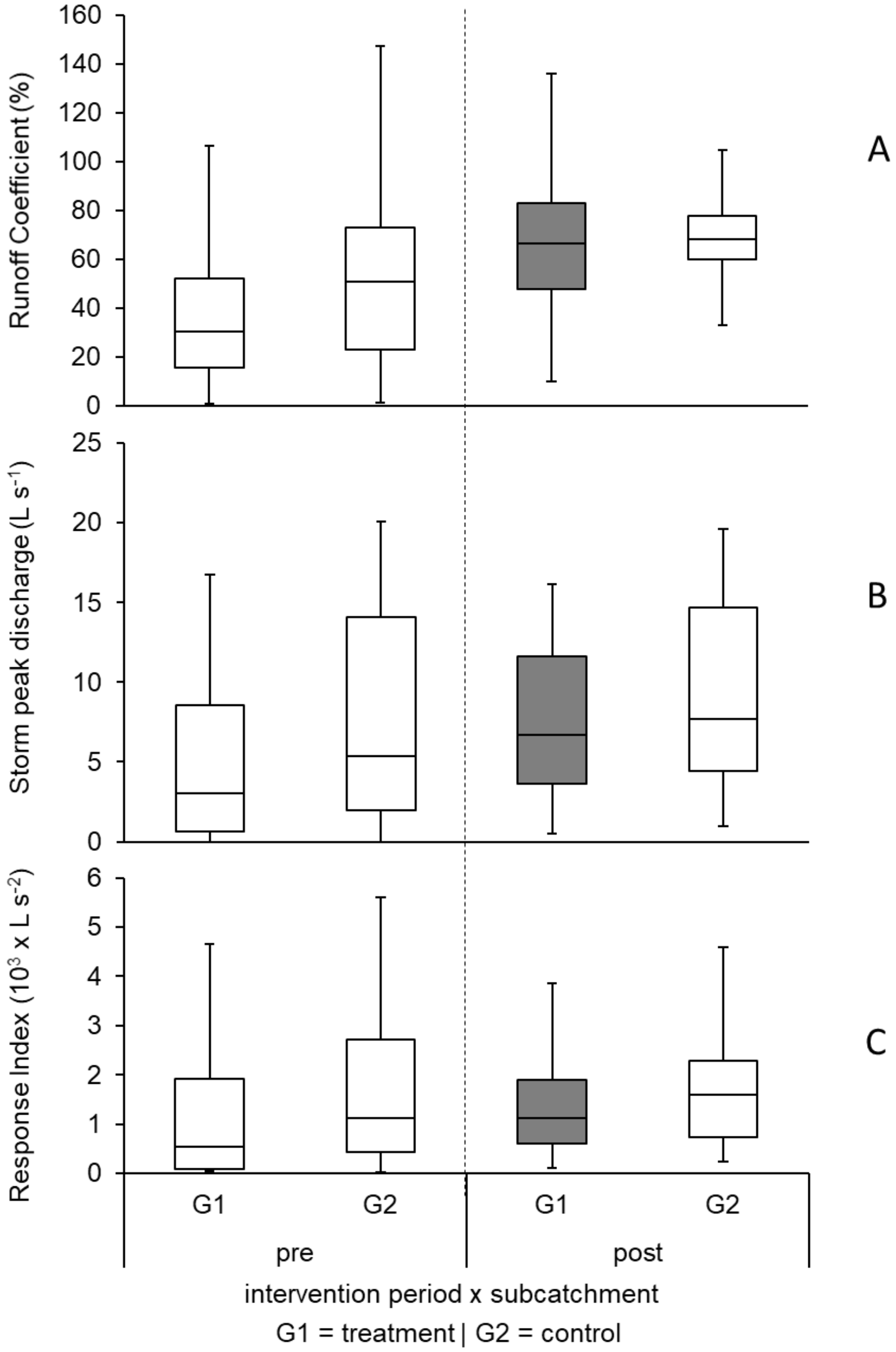
December 2018, which was forced through the origin in order to reduce the likelihood of over-/under-predicting periods without precipitation:

$$P_{RF2} = 0.754 \cdot P_{UCweir12} - 0.079 \cdot P_{UCweir6}$$

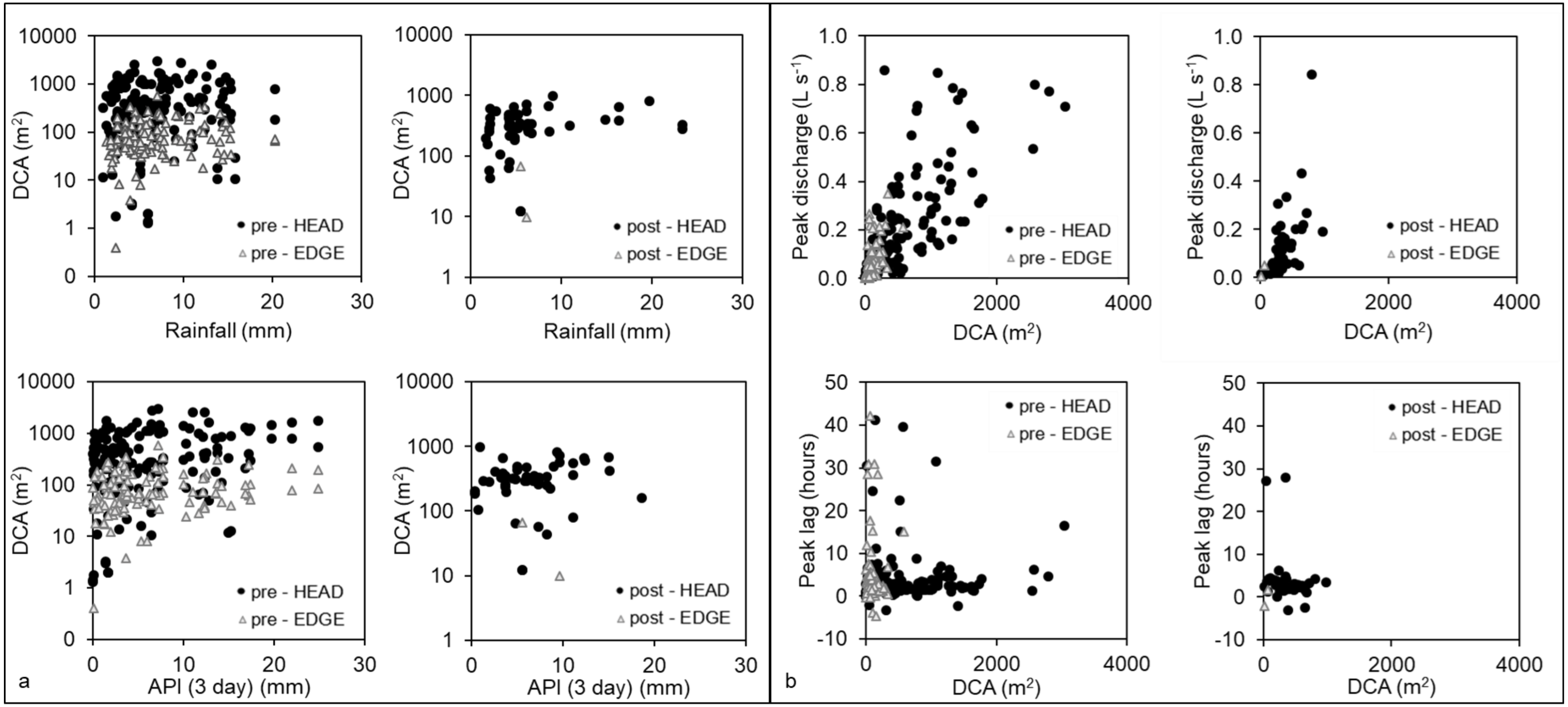
where P is the hourly rainfall. With a predominant wind at UNG coming from a west-south-west direction (Clay and Evans, 2017), the difference between gauges was as expected. The function P_{FR2} was used to fill gaps in hourly precipitation time series to construct monthly summaries of rainfall for UNG. For the period between December 2018 and February 2020, at least three of six rainfall gauges at UNG were active at the same time throughout the remaining monitoring period. For this period, precipitation levels were derived by averaging recorded data across any of the active rainfall stations (Chapter 3 Figure 3.1). To characterise event responses of streams, pipes and water table two rainfall series were used: 1) raw data of RF2 (May 2018 to December 2018); 2) mean rainfall across UNG for December 2018 to February 2020. Events that occurred during September 2018 were omitted from analyses due to missing rainfall data.



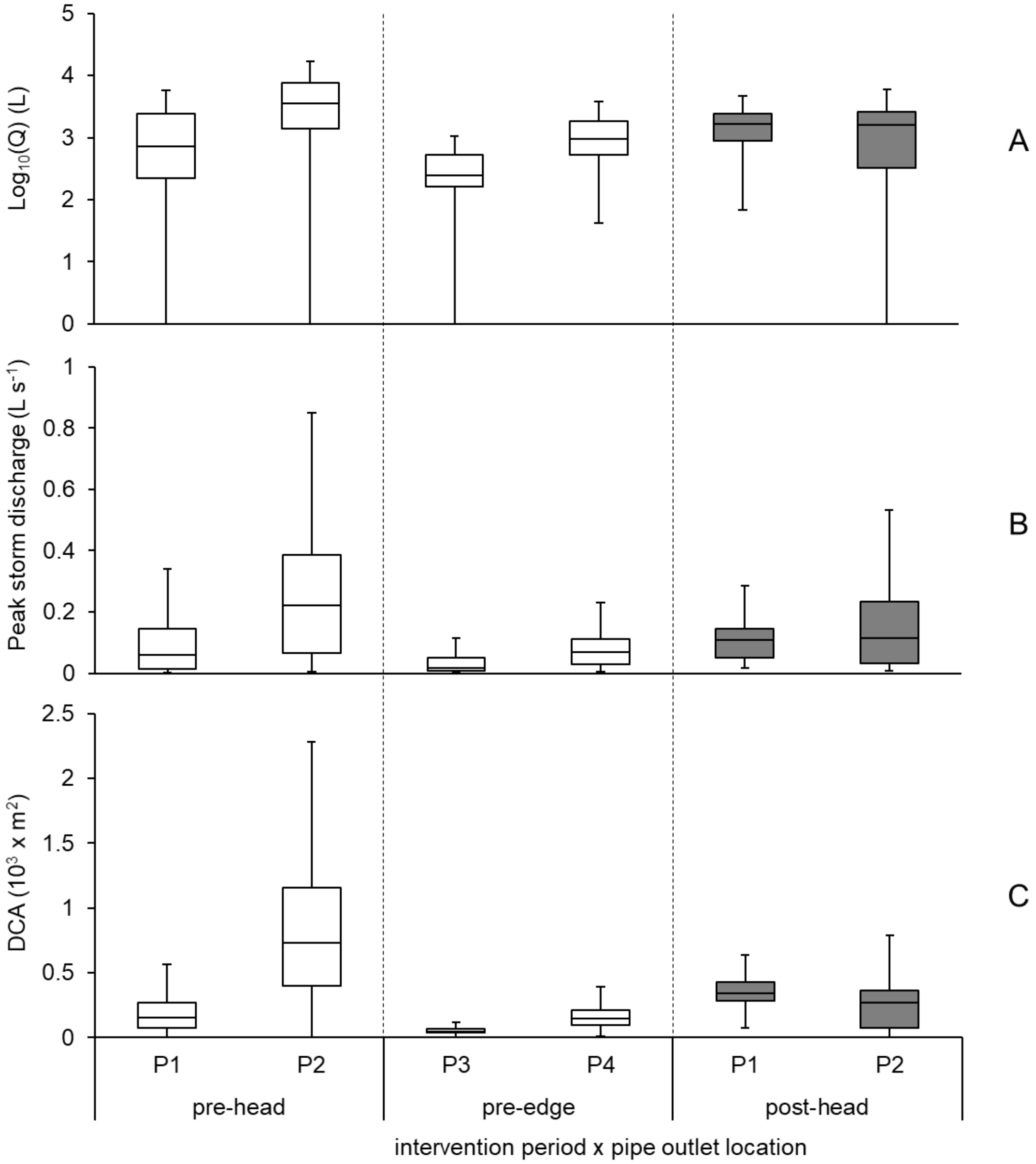
Appendix A-Fig. 2 Primary components used to analyse storm responses of streams, pipe outlets and water table. Storm discharge is the sum of discharge larger than the baseflow during a storm response (litres). Peak lag is the time between the rainfall peak and the peak discharge (hours). Peak discharge is the maximum storm discharge during a storm response ($L\ s^{-1}$). The storm response of the water table is expressed by the rate of recession of the water table (dDTPS/dt) at 6 and 12 hours after the last drop, in millimetres per hour. Data for the plot was sourced from a real-time event that took place at 18 October 2019 with the discharge curves (control catchment) and water table (pipe H1).



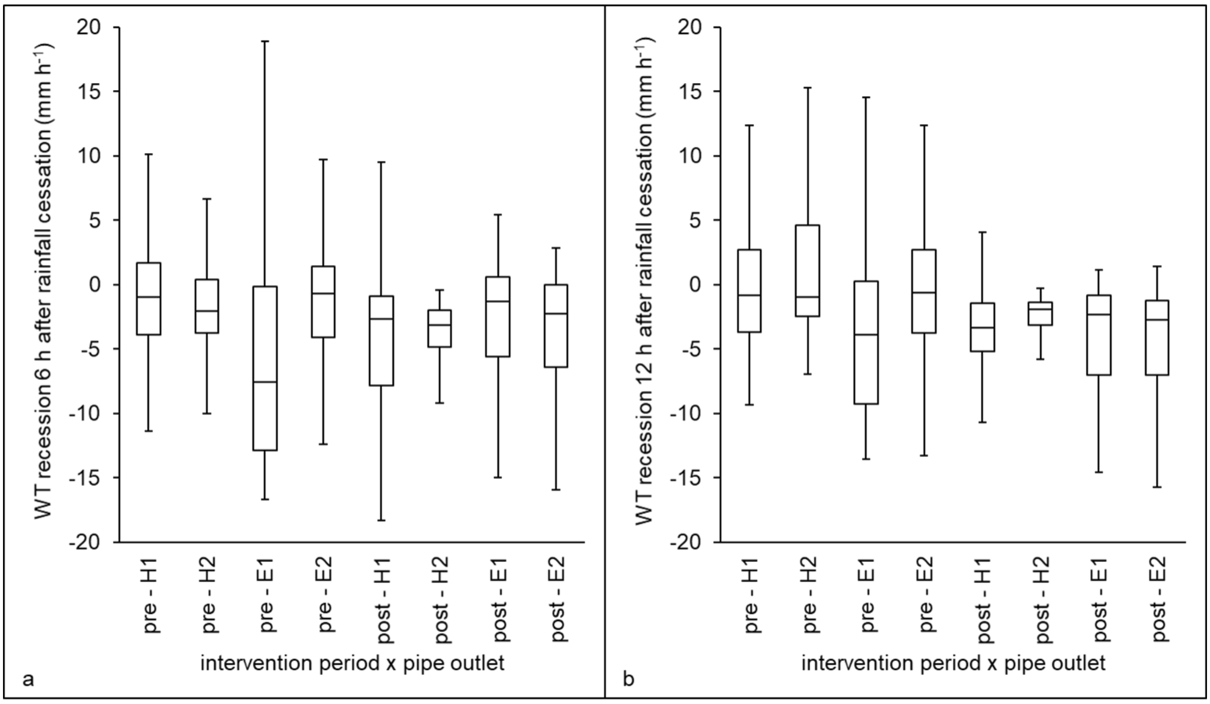
*Appendix A-Fig. 3 Boxplot showing distribution of A) runoff, B) storm peak discharge, C) response index across monitoring catchments (treatment and control), and intervention periods (pre-blocking and post-blocking). Shaded boxes indicate treated stream. The boxes show the interquartile range between 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)].*



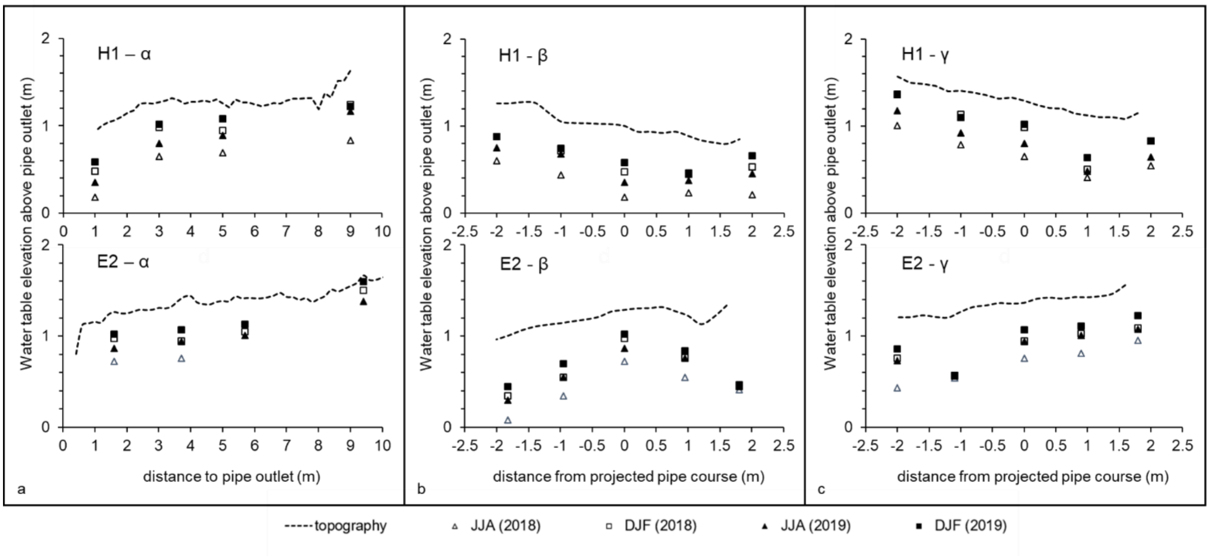
Appendix A-Fig. 4 Scatter plots specified for responses of pipe outlets at head and edge locations for the pre- and post-blocking period: a) storm discharge responses over rainfall parameters; b) storm peak responses over dynamic contribution area (DCA).



*Appendix A-Fig. 5 Boxplot showing distribution of a) discharge (Q), b) storm peak discharge and c) dynamic contribution area (DCA), for pipe outlet locations (head and edge) and intervention periods (pre and post). Data for E1 were not available for the post-blocking period. During the post-blocking period, discharge for E2 only occurred during two storm responses and is therefore not plotted. Shaded boxes indicate treated pipe outlets. 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)].*



*Appendix A-Fig. 6 Boxplot showing distribution of recession rates of water-table depths (WT) for pipe outlet locations (head and edge) and intervention periods (pre and post) for: a) 6 hours after rainfall cessation, and b) 12 hours after rainfall cessation. 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)].*



Appendix A-Fig. 7 Water-table depth relative to the pipe outlet for H1 (head) and E2 (edge) with median values for periods JJA (2018 and 2019) and DJF (2018 and 2019) for a) transect α, b) transect β, c) transect γ. Water-table depth is expressed in metres above the pipe outlet. In panel (a) the pipe outlet is located at the intersect of the x and y axis. In panel (b) and (c) the projected pipe course is located at x = 0. Dipwell positions are displayed from left to right according to their transect direction (see details in Figure 3a, main text). Dashed lines follow the surface topography of each transect respectively.

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

Appendix B: Supplementary information for Chapter 4

Supplementary information in support of:

Regensburg, T.H., Holden, J., Pilkington, M., Evans, M.G., Chandler, D., Chapman, P.J., *In review* in *Earth Surface Processes and Landforms*. Aquatic carbon concentrations and fluxes in a degraded blanket peatland with piping and pipe outlet blocking.

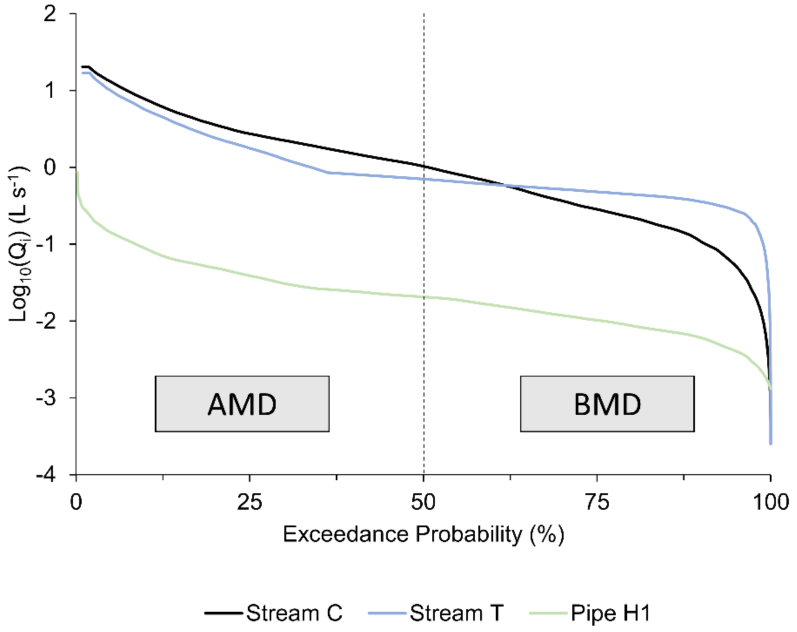
Data cleaning methods used on POC

POC samples were checked for inconsistencies in the weighing procedure. POC samples were included for analyses if the following criteria were met:

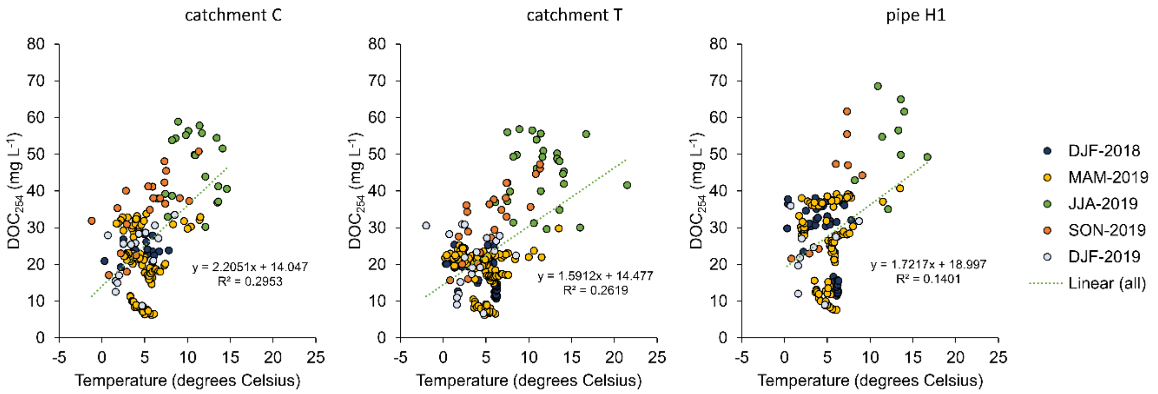
1. W_dry – W_pa > 0 g
2. W_ig – W_dry > 0 g
3. For all: F = ((W_pa – W_ig)/ (W_dry – W_pa)) =< 0.12
4. If 0 < F =< 0.12 then % POC = 100, if F < 0 then % POC calculated as described in Ball (1964), with all samples % POC > 0.

with the mass of W detailing the weight of a crucible plus filter paper for each step of the POC analyses process: mass after pre-ashing (W_{pa}), mass after drying at 105 °C for 24 h (W_{dry}), and mass after ignition at 375 °C for 16 h (W_{ig}).

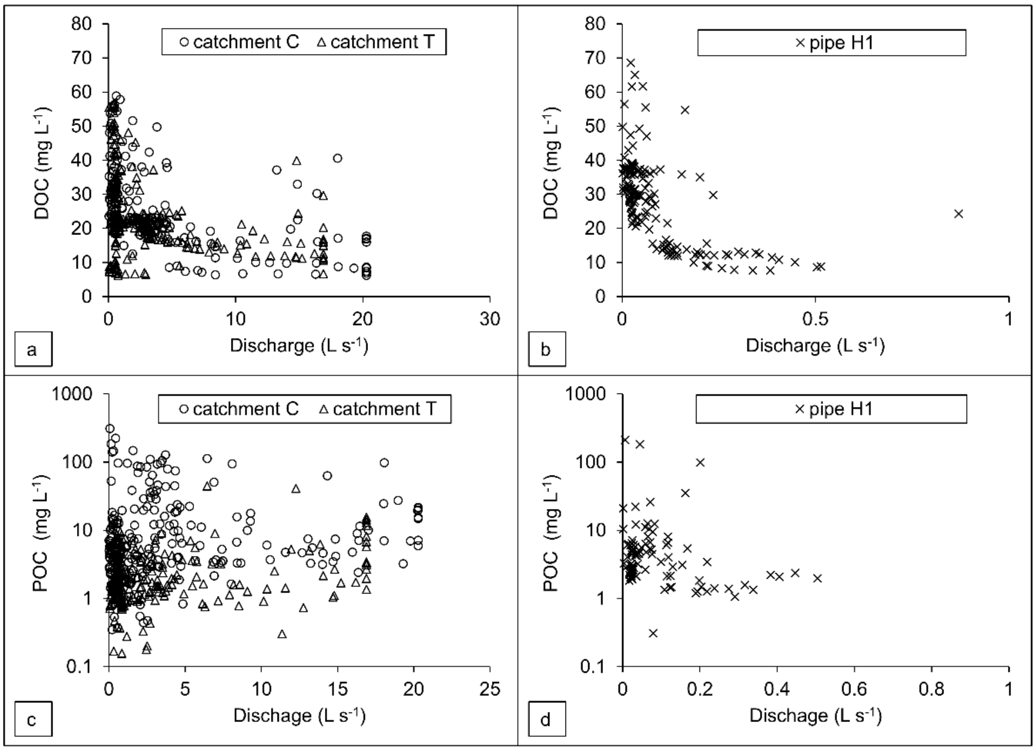
Ball, D. F. (1964). Loss-On-Ignition As An Estimate Of Organic Matter And Organic Carbon In Non-Calcareous Soils. *Journal of Soil Science, 15*(1), 84-92. doi:https://doi.org/10.1111/j.1365-2389.1964.tb00247.x



Appendix B-Fig. 1 Distribution of instantaneous discharge over the exceedance probability of instantaneous discharge, derived for stream- and pipe-water outlets. The probability of exceedance is expressed in the % chance that a set discharge may be equalled or exceeded (0 % resemble peak discharge, 100 % resemble the minimum discharge).



Appendix B-Fig. 2 Scatterplots of DOC$_{254}$ concentration over ambient temperature for each outlet, split by season.



Appendix B-Fig. 3 Scatterplots showing DOC$_{254}$ and POC concentration over discharge.

Appendix B-Table 1 Functions to express DOC concentrations (mg L^{-1}) as a function of absorbance units (AU m^{-1}) at 254 nm and 400 nm.

	DOC (254 nm) (mg L^{-1})	DOC (400 nm) (mg L^{-1})
Catchment C	0.1963 abs (AU m^{-1}) + 3.1645 $r^2 = 0.9650$	1.1452 abs (AU m^{-1}) + 4.7277 $r^2 = 0.9412$
Catchment T	0.1840 abs (AU m^{-1}) + 3.8919 $r^2 = 0.9483$	1.0275 abs (AU m^{-1}) + 5.9252 $r^2 = 0.9033$
Pipe H1	0.1860 abs (AU m^{-1}) + 3.8945 $r^2 = 0.9666$	1.1236 abs (AU m^{-1}) + 5.6216 $r^2 = 0.9560$

Appendix B-Table 2 Summary of concentrations for DOC_{254} and POC for catchments C and T, and pipe H1. Data were aggregated to seasonal values for: C = catchment C, T = catchment T, P = pipe H1.

		DOC_{254} (mg L^{-1})			**POC (mg L^{-1})**		
Season		C	T	P	C	T	P
DJF-2018	N	19	67	52	37	56	35
	Mean	23.6	18.0	26.3	6.6	1.4	3.1
	Median	23.5	19.4	30.8	3.9	0.9	2.4
	Minimum	19.2	10.6	11.5	0.3	0.2	0.3
	Maximum	28.2	25.4	38.1	19.7	7.8	8.1
MAM-2019	N	96	137	87	112	110	55
	Mean	20.7	18.5	26.1	17.1	3.3	4.4
	Median	21.3	20.4	28.1	5.7	1.5	4.2
	Minimum	6.2	6.2	7.6	0.5	0.4	1.1
	Maximum	36.9	29.8	40.7	127.5	44.6	12.4
JJA-2019	N	20	28	9	46	48	11
	Mean	47.0	45.0	53.7	8.8	4.0	57.6
	Median	49.8	47.1	54.8	4.6	3.3	22.1
	Minimum	30.2	29.6	35.0	1.9	1.4	5.1
	Maximum	58.9	56.8	68.5	52.7	11.8	212.2
SON-2019	N	21	22	8	72	41	6
	Mean	35.2	32.6	40.6	5.0	2.2	8.4
	Median	37.3	34.6	45.7	4.1	1.7	5.8
	Minimum	17.1	15.7	21.6	2.0	1.1	2.5
	Maximum	50.8	47.3	61.7	27.5	7.7	25.3
DJF-2019	N	16	19	9	15	16	8
	Mean	23.0	21.2	23.3	128.9	1.9	12.2
	Median	25.6	22.4	24.6	105.6	1.7	4.1
	Minimum	8.8	6.7	9.1	14.1	0.7	2.0
	Maximum	33.5	31.0	36.0	311.3	4.1	67.7

Appendix B-Table 3 Breakdown of total estimated flux of DOC254 (kg) and POC (kg) for flow types (BMD and AMD) in streams (C and T) and pipe H1 (P), for the two intervention period (pre- and post pipe outlet blocking). For each intervention period values are detailed to its respective seasons (pre: DJF-2018, MAM-2019, JJA-2019, and post: SON-2019, and DJF-2019). For pipe H1, its contribution to catchment T is given as a percentage of the flux in catchment T.

		stream DOC flux		**pipe DOC flux**		**stream POC flux**		**pipe POC flux**	
		C (kg)	T (kg)	P (kg)	% of T	C (kg)	T (kg)	P (kg)	% of T
pre	AMD	330.7	505.1	5.8	1.8	93	368.8	4.4	4.7
	BMD	48.6	35.4	2.3	4.7	13.7	26.9	1.8	13.1
	Sum	379.4	525.1	8	2.1	106.6	395.7	6.2	5.8

pre	*DJF-2018*	AMD	183.2	137.3	2.0	1.4	137.9	38.6	1.5	4.0
		BMD	18.2	17.4	1.0	5.7	13.9	4.9	0.8	16.2
		Sum	201.4	154.8	3.0	1.9	151.8	43.4	2.3	5.4
	MAM-2019	AMD	157.1	72.9	1.6	2.1	118.4	20.5	1.2	6.0
		BMD	7.7	13.1	0.9	6.7	5.8	3.7	0.7	18.8
		Sum	164.8	86.0	2.4	2.8	124.2	24.2	1.9	8.0
	JJA-2019	AMD	149.4	120.5	2.2	1.8	112.5	33.9	1.7	5.1
		BMD	9.5	18.1	0.4	2.0	7.2	5.1	0.3	5.7
		Sum	158.9	138.6	2.6	1.8	119.7	39.0	2.0	5.2

post	AMD	494.2	568.9	12.6	2.5	138.9	428.4	9.9	7.1
	BMD	61.1	44.5	0.8	1.3	17.3	33.9	0.6	3.5
	Sum	555.3	613.4	13.5	2.4	156.2	462.2	10.5	6.7

post	*SON-2019*	AMD	307.1	256.5	6.9	2.7	231.2	72.1	5.4	7.5
		BMD	19.3	29.6	0.3	1.0	14.8	8.4	0.2	2.7
		Sum	326.4	286.1	7.2	2.5	246	80.5	5.6	7.0
	DJF-2019	AMD	261.8	237.7	5.7	2.4	197.2	66.8	4.5	6.7
		BMD	25.2	31.5	0.5	1.7	19.1	8.9	0.4	4.8
		Sum	287.0	269.2	6.3	2.3	216.2	75.7	4.9	6.5

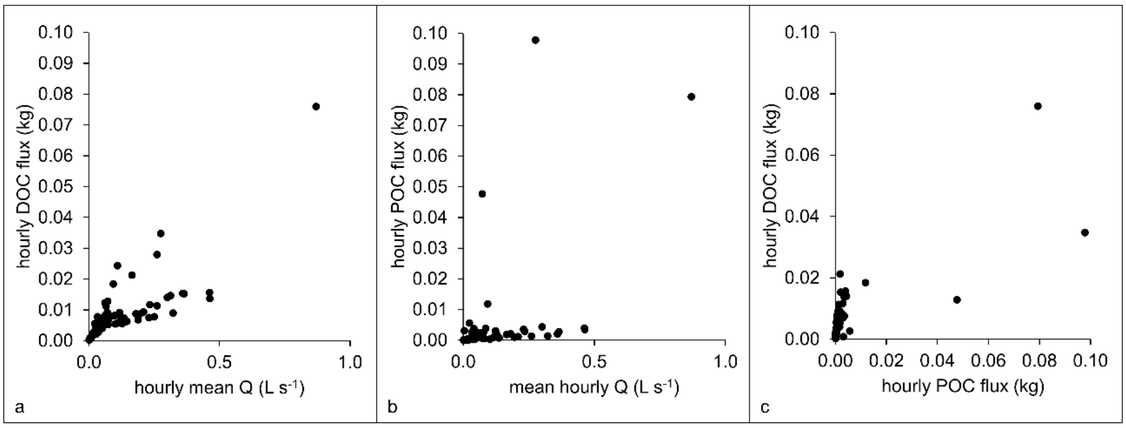
Appendix B-Table 4 Comparison of pipe-to-stream transfer of DOC and POC between in UK blanket peat catchments.

Catchment name	Catchment area (km^2)	R^a	DOC (g C m^{-2} yr^{-1})	DOC-T^b	POC (g C m^{-2} yr^{-1})	POC-T^b	source
Catchment T, Upper North Grain, S. Pennines	0.038	65 / 1	20.8	2.37	5.9	6.56	This study
Catchment C, Upper North Grain, S. Pennines	0.043	41 / 0	21.7		16.4		This study
Cottage Hill Sike, N. Pennines	0.174	84 / 8	57.3	1.91	2.7	5.08	Holden et al. (2012)

[a] R = n pipes in catchment/ n pipes gauged

[b] T = % pipe-to-stream

Holden, J., Smart, R.P., Dinsmore, K.J., Baird, A.J., Billett, M.F., Chapman, P.J., 2012.
Natural pipes in blanket peatlands: major point sources for the release of carbon to the aquatic system.
Global Change Biology, 18(12), 3568-3580.



Appendix B-Fig. 4 Scatter plots of a) hourly DOC flux and b) hourly POC flux, plotted over mean hourly discharge (Q) (L s^{-1}), with c) showing the relationship between hourly DOC and POC flux for matching samples in time.