Temporary Streams in a Peatland Catchment: Pattern, Timing, and Controls on Stream Network Expansion and Contraction.

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Review

Temporary Streams in a Peatland Catchment: Pattern, Timing, and Controls on Stream Network Expansion and Contraction.

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ABSTRACT

In peatlands, poorly maintained baseflows mean that network expansion during storm events can be rapid and pronounced, resulting in large changes in catchment connectivity. This has implications for the timing and magnitude of material fluxes from these environments, understanding of which is becoming increasingly important due to peatlands' significance as global carbon stores. In this study, Electrical Resistance (ER) technology has been used to create sensors capable of detecting the presence and absence of flow in ephemeral portions of the channel network. These sensors provide data on the patterns of network variation in the Upper North Grain research catchment, a small peatland headwater catchment in the South Pennines, UK. Networks of around 40 sensors were deployed in autumn 2007 and summer 2008, giving a total of almost 4 months of high-resolution monitoring data. Drainage density in the catchment was found to vary between 1.4 and 30.0 km/km², suggesting significant differences in connectivity between the expanded and contracted networks. Water table depth was identified as the key factor determining the temporal pattern of stream flow at both the site- and catchment-wide scales. In

terms of the spatial pattern of flow, network expansion and contraction occurred in a disjointed pattern, occurring in a similar pattern between events, suggesting that localised controls are important for flow generation. Spatial controls on flow generation relate to local water table levels, and include drainage area, local dissection, channel slope and gully morphology. The importance of water table as the key control on catchment connectivity suggests that potential future change in catchment water tables associated with projected climate change or with peatland restoration by rewetting will modify the frequency of full catchment connectivity.

Short title: Temporary Streams in a Peatland Catchment.

Keywords: Ephemeral Streamflow, Hydrological Connectivity, Peatland Hydrology, Drainage Density, Runoff Generation.

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38 **INTRODUCTION**

39 Concepts of hydrological and geomorphological connectivity have been widely
40 discussed in the last decade (Bracken and Croke, 2007; Fryirs *et al.*, 2007;
41 Wainwright *et al.*, 2011; Bracken *et al.*, 2013). Advancing our understanding of
42 system connectivity has an important role in the development of modelling
43 approaches (Lexartza-Artza and Wainwright, 2009) and is key to effective
44 environmental management.
45
46 Bracken *et al.* (2013) identify connectivity as an important framework for the analysis
47 of runoff and runoff generation with overland flow and subsurface flow as key
48 mechanisms generating catchment connectivity. They argue that a process based
49 understanding of connectivity is a prerequisite for effective catchment management.
50 Within this definition they recognise two key types of connectivity which are structural
51 connectivity and process-based connectivity. Structural connectivity is a function of
52 the physical adjacency of landscape units and evolves only at the timescale of
53 morphological change in the landscape system, whereas process-based connectivity
54 relates to the dynamic evolution of connected flow pathways within a catchment or
55 land system at timescales driven by synoptic or seasonal changes in hydro
56 meteorology.
57
58 A major focus of current work on process based connectivity has been the
59 development of hillslope channel linkages driven by the development of overland
60 flow (Gomi *et al.*, 2008; Reaney *et al.*, 2013) or sub surface flow (McGuire and
61 McDonnel, 2010; Wainwright *et al.*, 2011). However, an aspect of connectivity which
62 has received less recent attention is the temporal variability of the connected

channel system. In strongly ephemeral systems this problem effectively spans the definition of structural and process based connectivity since the adjacency of hillslopes to active channel systems changes at synoptic timescales in response to the development of connected flow in upper channel reaches.

Ephemeral streams

A number of studies of ephemeral stream system connectivity were undertaken in the two decades post 1960 but recent interest in this area has been somewhat limited. Intermittent and ephemeral streams have been observed in a variety of environments as the extent of the flowing stream network expands from the perennial channels into headwater reaches during stormflow events. These temporal variations in the extent of the flowing stream network can lead to dramatic variations in the drainage density within a catchment and many studies have reported drainage densities of the fully expanded drainage network to be several times that of the perennial 'contracted' network (i.e. Roberts and Klingeman, 1972; Day, 1980). The ranges of drainage density values found in a selection of these studies are presented in Table 1.

Three patterns of network expansion have been observed. The first is 'bottom-up' expansion. As the catchment becomes wetter, the water table rises and there is a progressive up-slope movement of the ground-surface intersection of the water table, causing the head of the stream network to gradually extend up stream. As the catchment dries out, the water table drops and the flowing channel head recedes downstream (Morgan, 1972). The second is a disjointed pattern of network expansion where surface flow occurs in discrete segments of the channel which

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88 expand and contract in an upstream and/or downstream direction. This is thought to
89 be due to the effect of localised physical controls, such as saturated slopes and
90 depressions around the flowing channel. Network contraction may also be disjointed,
91 with flow disintegrating into several flowing segments (Day, 1978; 1980). The third
92 pattern is 'top down' growth, whereby flow begins from an upper section of the
93 catchment from saturated areas, which then flows downslope and becomes part of a
94 larger flowing network (Day, 1978).

95

96 Previous studies have found that variations in network extent are related to both
97 transient characteristics of the catchment (temporal variations), including
98 precipitation (Gregory and Walling, 1968; Morgan, 1972) and antecedent moisture
99 conditions (Gurnell, 1978), and to more permanent characteristics (spatial variations)
100 including water table levels (Day, 1978), lithology (Gurnell, 1978; Day, 1980), soil
101 properties such as compaction (Gurnell, 1978) and infiltration capacity (Wingington
102 *et al.*, 2005), vegetation type and amount (Gregory and Walling, 1968; Day, 1978;
103 Gurnell, 1978), drainage area (Day, 1980; Fritz *et al.*, 2008), catchment and channel
104 slope (Day, 1980), subsurface piping (Morgan, 1972), and localised in-channel
105 controls, including channel morphology (Day 1978; 1980).

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107 Changes in drainage density and the associated changes in connectivity have
108 important implications in terms of the timing and magnitude of catchment discharge
109 and the source areas of sediments and solutes. For example, a greater density of
110 flowing channels increases drainage efficiency as the distance that runoff must travel
111 to a channel decreases. As channelised flow reduces travel times, this means that
112 greater quantities of water travel to the basin outlet faster, thereby increasing peak

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3 113 flows (Kirkby, 1975). In fact, many studies on network expansion have found that
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5 114 changes in drainage density are highly correlated with changes in discharge
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7 115 (Gregory and Walling, 1968; Blyth and Rodda, 1973; Day, 1978). In addition, the
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9 116 locations of flow within the channel network have been found to vary during changes
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11 117 in network extent (Day, 1980), suggesting that it is possible to determine which
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13 118 portions of a basin contribute most to runoff (Blyth and Rodda, 1973).
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19 120 Changes in network extent may also impact upon water quality. The greater
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21 121 connectivity associated with an expanded stream network can lead to an increase in
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23 122 non-point source pollutants directly entering stream channels (Wingington *et al.*,
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25 123 2005). The rewetting of ephemeral parts of the channel may also affect the fate of
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27 124 nutrients and organic matter that accumulate during the dry period, as the inundation
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29 125 of dry organic matter may release large quantities of dissolved organic carbon (DOC)
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31 126 (e.g. 'blackwater events', Bond and Cottingham, 2008). Therefore, both the quantity
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33 127 and quality of catchment runoff may be influenced by the amount and rate of network
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35 128 expansion (Wharton, 1994). Thus, the inclusion of a measure of drainage network
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37 129 expansion in hydrological models could potentially lead to significant improvements
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39 130 in prediction accuracy.
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44 45 132 **Dynamic Connectivity in Peatlands**

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47 133 Significant variations in network extent have been observed in peatlands (Bay, 1969;
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49 134 Holden and Burt, 2003), where baseflows are often so poorly maintained due to the
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51 135 limited amount of seepage that many small streams dry up completely, particularly
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53 136 during the dry season (Burt *et al.*, 1990). This has implications for connectivity, as a
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55 137 fully expanded drainage network represents a significantly higher degree of
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138 connectivity within a catchment than the contracted perennial network. In terms of
139 the hydrology of these systems, blanket peatlands are renowned for their ‘flashy’
140 hydrological regimes as water is rapidly and efficiently transferred from the hillslopes
141 to the channel, resulting in short lag times and large storm peaks. Consequently
142 blanket peat catchments tend to be sources of flooding rather than attenuators of
143 flow (Holden and Burt, 2003). Where peatlands are eroded, as is the case for most
144 U.K. upland systems (Evans and Warburton, 2007), large quantities of sediment are
145 also removed. This has several repercussions. Firstly, it can result in the infilling of
146 reservoirs and water discolouration, leading to problems for water resource
147 managers (Butcher *et al.*, 1992; Worrall *et al.*, 2002). Secondly, it has implications for
148 carbon storage. Peat erosion by water leads to an increased fluvial flux of carbon out
149 of peatland catchments, potentially turning them from carbon sinks to sources
150 (Worrall *et al.*, 2003; Pawson *et al.*, 2012.). Upland peatlands in the Southern
151 Pennines, U.K. are also severely polluted (Rothwell *et al.*, 2007). Significant
152 concentrations of heavy metals are transported in particulate and dissolved form in
153 peatland streams with potential implications for aquatic ecosystems and drinking
154 water supplies downstream (Rothwell *et al.*, 2007). Although network expansion has
155 been previously observed in peatland systems it has not been well studied. A proper
156 understanding of the dynamic connectivity of peatland catchments is therefore
157 required to understand the role of connectivity in controlling material fluxes from
158 eroding peatland systems.
159
160 A key influence on this dynamic connectivity is the temporal and spatial pattern of
161 runoff production. In ombrotrophic peatland systems the dominant runoff producing
162 mechanism is saturation-excess overland flow, so that temporal patterns of runoff

are strongly controlled by antecedent moisture conditions, with significant volumes of runoff only generated when water tables are at or close to the surface (Evans *et al.*, 1999; Holden and Burt, 2003; Daniels *et al.*, 2008). Similarly, spatial variations in runoff are driven by the spatial pattern of water table level, influenced by both topography (Holden and Burt, 2003; Allott *et al.*, 2009) and drainage. This 'drainage' may take two main forms; drainage ditches deliberately cut into the peat (Holden *et al.*, 2006) or erosional gullies which act as 'natural' drainage channels (Daniels *et al.*, 2008). Pipe networks and macropore flow have also been found to make significant contributions to catchment discharge, with piping being a common feature in peatland catchments (Holden, 2006). For example, Holden and Burt (2003) found that up to 10% of runoff may travel through the pipe network at Moor House in the North Pennines. Therefore, the location and density of pipe outlets may also influence which portions of the stream network are active at any given time.

Aims and Objectives

The logistical demands of mapping channel extent mean that there is little empirical evidence on the spatial patterns of dynamic ephemeral channels. It is likely that these logistical difficulties have limited the scope of previous work. However, upsurge of interest in catchment connectivity in the last decade has coincided with the increasing availability of low cost approaches to extensive monitoring of streamflow (Goulsbra *et al.*, 2009; Bhamjee and Lindsay, 2011, Bracken *et al.*, 2013). This paper aims to take advantage of these approaches to develop understanding of connectivity in peatland stream systems. Upland peatland systems have a high proportion of temporary streams, and are systems where understanding

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of water and sediment flux has important implications for pollutant flux and carbon budgets. Thus, this paper has four main objectives:

- characterising the behaviour of temporary streams in a peatland study catchment,
- determining controls on the short term variability of drainage density,
- determining the spatial controls on network expansion and contraction, and
- investigating whether the relationship between drainage density and catchment discharge holds in peatland catchments.

METHODS

Study Site

The study took place in the Upper North Grain catchment, a small headwater catchment of the River Ashop, which feeds the Ladybower Reservoir in the Upper Derwent Valley, South Pennines, UK (Figure 1). The field site was selected as a typical example of a severely gully eroded blanket peatland of the type widespread across upland Britain. The catchment has been closely monitored over a number of years, so that there is good contextual data for this study (e.g. Daniels *et al.*, 2008; Rothwell *et al.*, 2005, 2007). The catchment is 0.434 km² in size to the pressure transducer which monitors stage, and 0.490 km² to the confluence with a major adjacent tributary (Figure 1), lying between altitudes of around 480 and 540 m. The principle land cover is blanket peat with maximum depths of 4 m. The catchment has a vegetative cover comprising predominantly *Eriophorum vaginatum*, *Calluna vulgaris*, *Erica tetralix*, *Vaccinium myrtillus*, *Empetrum nigrum* and patches of *Sphagnum* spp. Mean monthly temperature for the Upper North Grain catchment from the period 2007 to 2009 is 7.0°C and mean annual precipitation is 1513 mm.

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213 The catchment is heavily eroded with deep Bower Type I peat gullies (Bower, 1961)
214 often cut to the base of the peat, although some gullies have begun to revegetate
215 (Crowe *et al.*, 2008). The topography of the catchment therefore effectively dictates
216 the channel system as these gullies concentrate flow, and channels are found within
217 the gully floors. The flashy hydrological regime and poor drainage of the peat mean
218 that ephemeral streams are found in this channel system. Most of the gullies in the
219 catchment directly connect to perennial channel system (Figure 1). However, in a
220 small number of gullies, flow is less topographically constrained at the interface
221 between the hillslope and the perennial channel. In these cases, water travels short
222 distances in the form of concentrated overland flow before reaching the main
223 channel. Outside of the gully network, flow remains unchannelised as diffuse
224 overland flow or subsurface storm flow. Piping is also prevalent in the catchment,
225 with a high density of outlets, particularly in more mature gullies (Wallet, 2004).

226

227 **Instrumentation**

228 The catchment is instrumented with a Skye automatic weather station (AWS) which
229 monitors precipitation and water table depth (Figure 1). Precipitation was recorded at
230 hourly intervals using a Campbell Scientific tipping bucket rain gauge, with tipping
231 intervals of 0.202 mm. Water table elevation was recorded at hourly intervals using
232 an Intelisys pressure transducer at a single dipwell. The dipwell was constructed
233 from polypropylene waste pipe with an internal diameter of 30 mm, with 5mm
234 diameter perforation holes at 100 mm intervals. All water table values referred to
235 from here on in refer to water table measured at the AWS. This is a wet blanket peat
236 site with high mean water table. The water table values reported are not intended to

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237 be representative of the entire catchment, but rather provide a relative measure of
238 relative antecedent moisture conditions. Shorter term measurements at other
239 catchment sites indicate that the AWS site is representative of broad temporal trends
240 in catchment water tables. Stage is monitored on the main stream channel of the
241 catchment, at a site which has a flat mineral base and is roughly box shaped (Figure
242 1). Stage was measured at 20 minute intervals using a Druck pressure transducer
243 and logged using a Skye Datahog. Stage was converted to discharge using a well-
244 established rating curve (Daniels, 2006).
245
246 Data on the presence or absence of flow were collected using the ephemeral
247 streamflow (ES) sensors developed by Goulsbra *et al.* (2009). These sensors are
248 based on electrical resistance sensors, which register high conductivity during flow
249 conditions when there is a continuous circuit between the sensor electrodes, and low
250 conductivity when flow is absent and the circuit is broken, providing binary data on
251 whether or not a reach is occupied by a temporary stream at any point in time. The
252 sensors used are Onset HOB0 pendant 4 K temperature data loggers (product ID
253 UA-001-64) which have user-selectable sampling intervals of between 1 s and 18 h,
254 and a 64 K memory storing over 52,000 readings. The loggers were converted to ER
255 sensors by the removal of the thermistor and the addition of two lengths of 0.3 mm,
256 single strand, plastic insulated wire to form the sensor electrodes. Laboratory testing
257 carried out by Goulsbra *et al.* (2009) confirmed that the sensors are able to clearly
258 distinguish between the presence of water between the electrodes, irrespective of its
259 conductivity (a 'flow' or 'wet' reading), and the absence of water between the
260 electrodes (a 'dry' or 'no flow' reading). The electrodes were housed in a custom built
261 'sensor head', 42 mm in diameter and 50 mm in height (Goulsbra *et al.*, 2009). This

sensor head has several unique design features including a sunken sediment trap which prevents false positive readings caused by deposition around the electrodes, situating the electrodes in an optimal position for monitoring flow. The data collected by the ES sensors requires only minimal processing; a threshold is set with all ER readings below the threshold being defined as 'dry' or not flowing and those higher being defined as 'wet' or flowing. Due to the significant difference between measured ER during wet and dry conditions, this threshold can be set with confidence.

Field measurements

Data collection took place over two periods, autumn 2007 and summer 2008, in an attempt to capture relatively dry conditions when the drainage network is likely to be at its most dynamic. In autumn 2007 (11 September to 14 November), a network of 41 ES sensors was installed over five gullies, shown by the pale grey circles in Figure 1. One of the instrumented gullies discharges downstream of the pressure transducer used to calculate discharge. This gully was instrumented in order to capture a range of spatial characteristics of the gullies monitored and does not compromise the results presented here. In summer 2008 (25 July to 8 September), 40 ES sensors were installed over four gullies (black circles). To provide a comparison between the two study periods, one of the gullies monitored in 2007 was re-instrumented in 2008 (dark grey circles). ES sensors were sited where there was a clearly incised single channel, as opposed to reaches where flow was diffuse or channels braided, and on riffles rather than pools to avoid the sensors detecting ponded water. Within a gully, ES sensors were located at approximately equal intervals from the headwaters to the bottom of the gully (i.e. where the gully joins the main channel), with a mean distance between ES sensors of 60 m.

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5 288 Repeat field observations have shown the limit of the perennial flowing network to be
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7 289 relatively stable, representing a drainage density of the contracted network of 1.41
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9 290 km/km², shown in Figure 1. The maximum total stream length is equivalent to the
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11 291 total length of gullies in the catchment, at 14.70 km, representing a drainage density
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13 292 of the fully expanded network of 29.98 km/km². The combined coverage for the 2007
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15 293 and 2008 monitoring constitutes 62% of this total stream length, at 9.08 km, with the
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17 294 contributing area for these streams equating to 55% of the catchment area,
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19 295 representing a maximum drainage density of 33.52 km/km².
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25 297 The loggers were set at sampling intervals of 1 minute, and downloaded
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27 298 approximately once every two weeks using a Hobo Waterproof Shuttle. During the
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29 299 2007 study period problems were found with three of the ES sensors due to logger
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31 300 malfunction (1 site), damage to the equipment (1 site), or repositioning due to
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33 301 unsuitable bed morphology (1 site). This leaves a total of 38 sites which have
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35 302 continuous monitoring data. During the 2008 study period problems were found with
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37 303 three of the ES sensors due to damage to the equipment (1 site), or repositioning
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39 304 due to unsuitable bed morphology (2 sites), leaving 37 sites which have continuous
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41 305 monitoring data for the entire study period.
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47 307 **Sources of spatial data**
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49 308 High resolution LiDAR data are available for the catchment (2 m ground resolution,
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51 309 250 mm z resolution), flown in 2002. A digital elevation model (DEM) of the
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53 310 catchment is shown in Figures 2 and 3. Terrain Analysis System (TAS) software
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55 311 (Lindsay, 2005) was used to extract various terrain attributes from the DEM,
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including slope, the wetness index (WI) (Beven and Kirkby, 1979), and the network wetness index (NWI) (Lane *et al.*, 2004). Two other sources of spatial data were available for the catchment. The first of these was a gully map developed by Evans and Lindsay (2010), shown in Figure 1. The areal extent of erosional gullies was derived by combining areas of low difference from mean elevation and high positive plan curvature, and gully depth is modelled by interpolating between gully edges. The second is the water table model, developed by Allott *et al.* (2009) which predicts the median water table depth at the site scale. The model does not predict the water table in the gullies. Several characteristics of each site were recorded in the field, including the width of the top of the gully, the width of the gully floor, and the depth of the gully. Table 2 provides a summary of the spatial data collected for each site. Note that some attributes relate to the catchment area of each site whilst others relate to its specific location. As gullies tend to have very high associated slope values due to their steep walls, this may have the effect of skewing catchment averages for some attributes such as WI and NWI, as they are partially based on slope. Therefore, average slope, WI and NWI were also calculated for each site's contributing area excluding the area occupied by gullies (i.e. hillslopes only).

RESULTS

The Pattern of Stream Network Expansion

The processed data show the catchment response to a number of rainfall events based on when each site goes from 'dry' to 'wet'. In each of the 2007 and 2008 datasets there was only one event which caused all the sites to go from 'dry' to 'wet'. The timings and pattern of streamflow initiation for these two events are illustrated in

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337 Figures 2 and 3 respectively. Both figures show that the wetting up of the ephemeral
338 channels in this system is variable both within and between gullies. It seems that the
339 pattern of network expansion is neither 'bottom up' nor 'top down', but in fact most
340 closely corresponds to the 'disjointed' pattern of network expansion described by
341 Day (1978, 1980). This suggests that local controls on runoff may be significant in
342 terms of the generation of flow in ephemeral portions of the channel.

343
344 To determine if the pattern of drainage network expansion is consistent for different
345 storms, Spearman's rank correlation analysis was used to compare the order in
346 which sites became wet for different network expansion events. Only pairs of events
347 where ten or more sites responded to both events were considered. Correlation
348 matrices showing the results of Spearman's rank analysis for events in the 2007 and
349 2008 periods are displayed in Tables 3 and 4 respectively.

350
351 For the 2007 dataset, there were 9 pairs of events where ten or more sites
352 responded to both events. Of these, three pairs of events showed no significant
353 correlations between the order in which sites registered flow, one showed
354 correlations significant at the 0.10 level, three at the 0.05 level, and two at 0.01 level
355 (Table 3). On all three occasions where no significant relationship was found, one of
356 the events was a storm on 5 November 2007. Before this event, the water table at
357 the AWS was just 9 mm below the surface, compared to at least 34 mm for all other
358 events. During this event, all sites that were previously dry became wet within one
359 hour of the start of rainfall. There was just a 43 minute difference between the
360 response of the first and last site. The high water tables and almost instantaneous

361 wetting up of the catchment may explain why the pattern of network expansion
362 during this event was different from the others.

363
364 For the 2008 dataset, there were 8 pairs of events where ten or more sites
365 responded to both events. Of these, two pairs of events showed no significant
366 correlations between the order in which sites registered flow, three showed
367 correlations significant at the 0.10 level, one pair of events showed correlations
368 significant at the 0.05 level, and two at 0.01 level (Table 4). Where there was no
369 significant relationship, the characteristics of the rainfall events were found to be very
370 different. This was the case for two of the eight pairs. In both cases, a rainfall event
371 on 29 July 2008, which had very high intensities at the start of the storm (6.86 mm in
372 the first hour), was compared with an event which had much lower intensities (0.4
373 mm in the first hour). For all other pairs of events the characteristics of the rainfall
374 event were much more similar.

375

376 **The Rate of Stream Network Expansion**

377 Substantial differences in the rate of network expansion can be observed in Figures
378 2 and 3. In the 2007 example (Figure 2) the first site responds five hours after rainfall
379 initiation, with the last site responding a further 12 hours after this. This is in contrast
380 to the 2008 example (Figure 3) where 63% of the sites respond within one hour of
381 the start of rainfall, with all sites being wet three hours after this. In both examples
382 water tables were low prior to the onset of rainfall (a drawdown of 212 mm in 2007
383 and 190 mm in 2008). The difference in the timing of network response is probably
384 due to differences in the characteristics of the rainfall events, specifically rainfall
385 intensity. In the 2008 example, rainfall intensities were much higher at the start of the

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rainfall event (6.9 mm in the first hour) compared with the 2007 example (5.2 mm in 14 hours), giving rise to a more rapid expansion of the network.

This rapid streamflow response to high rainfall intensities can be seen at other points in both datasets. Table 5 shows the three events in each dataset where, with the exception of the examples shown in Figures 2 and 3, the highest number of sites went from dry to wet. In every example all sites went from dry to wet within a maximum of five hours of the initiation of rainfall. Variations in network response are evident within this dataset. For example, on 5 November 2007, all sites went from wet to dry within one hour of the start of rainfall. This is despite the fact that in the first hour of the storm, only 0.4 mm of rainfall fell. In contrast, by the second hour of the storms on 9 October and 28 October 2007, totals of 0.8 mm and 1.0 mm of rainfall had fallen respectively, yet some sites remained dry. This was due to antecedent water table levels. On 5 November, the water table was just 9 mm below the surface, whereas it was at a depth of 34 mm on 9 October and 116 mm on 28 October. This would suggest that both rainfall characteristics and antecedent conditions can affect the rate of network expansion.

The Temporal Controls on Temporary Stream Flow

Using the data from the ES sensors, there are three ways in which to describe the extent of the drainage network at any given time. The first is simply how many sites are 'wet' or 'dry', although this does not take into account the spatial arrangement of the locations of channel flow. The second is the number of sites which are both 'wet' and connected to the perennial stream network. The third is the drainage density of the monitored gullies based on the sites which are both wet and connected, with the

gully network representing the maximum possible extent of the drainage network. These three metrics were calculated at hourly intervals for both the 2007 and 2008 datasets (the sites which had gaps in monitoring data were not included).

A series of potential temporal controls on network extent were calculated using the AWS data, including water table depth, total precipitation in the previous 1 - 12 hours, 1 - 6 days, and 1 - 4 weeks, and the number of hours since the last rainfall. The only significant predictor for all three measures of network extent in both the 2007 and 2008 datasets was the depth of the water table. For the 2007 dataset, R^2 values for water table and the number of sites wet, the number of sites connected, and the drainage density were 0.93, 0.79 and 0.84 respectively, and these values were 0.91, 0.75 and 0.81 for the 2008 dataset. These relationships are shown in Figures 4 and 5. This suggests that the depth of the water table has a very strong influence on network extent at the catchment scale.

At the site scale, the controls on the presence of flow were investigated using binary logistic regression. This analysis used the wetness predictor variables described above to determine the probability of flow at each site at hourly intervals. Where the probability of flow is <0.5 the site is predicted to be dry; where the probability of flow is >0.5 the site is predicted to be wet. Again, water table depth was the most significant predictor variable for all sites, with significance levels consistently <0.01 . This allowed the calculation of a 'critical water table depth' at each site, below which the site would be dry and above which the site would be wet. The regression analysis has high accuracies of 94.8% and 95.8% for the 2007 and 2008 datasets respectively. An example of this can be seen in Figure 6, showing the observed and

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436 predicted data for a site in the 2007 dataset. The critical WT depth set by the
437 regression analysis at this site is 22.6 mm, with an accuracy of 97.4%. It should be
438 noted here that it is unlikely that the water table as measured at the AWS is the
439 direct control upon flow at any site; rather local water tables may vary linearly with
440 the water table as measured at the AWS (an estimate of relative catchment
441 wetness).
442
443 Based on the data presented in Figure 6, it would seem that the critical water table
444 depth is a good predictor of the occurrence of channel flow. However, although this
445 may be true for sites which experience dry periods throughout the study period, this
446 may be less sound for sites which experience less transient flow. Figure 7 shows an
447 example of a site from the 2008 dataset. Binary logistic regression indicated a critical
448 water table depth of 123 mm at this site, with an accuracy of 99.9%. However,
449 setting the threshold anywhere between 90 and 135 mm would give the same
450 accuracy as there is only one data point in this range throughout the study period
451 (representing 0.2% of the study period). This may make it difficult to pinpoint critical
452 water table depth for some sites which experience flow in all but the driest
453 conditions.

454
455 **The Spatial Controls on Ephemeral Stream Flow**

456 The propensity for a site to contain flow may be quantified by two key measures. The
457 first is the proportion of the study period during which each site is 'wet', and the
458 second is the critical water table depth at each site above which the site is predicted
459 to be wet, and below which dry, modelled using binary logistic regression as outlined
460 above. However, the proportion of time each site is wet is strongly linked to water

table depths during the study period. As the distribution of water table depths during the 2007 and 2008 monitoring periods differ, it is not appropriate to compare the proportion of flow at each site from the different periods. However, the critical water table depth at each site is insensitive to when the data were collected. The critical water table depth has been calculated for sites in both monitoring periods for which there is a complete, continuous dataset. Some sites in the gully that was instrumented in both 2007 and 2008 displayed a disparity in the critical water table threshold between the two years of data as the ES sensors could not be sited in exactly the same place. Where this was the case, data from the more recent 2008 dataset were used. The spatial pattern of the critical water table threshold at each site is displayed in Figure 8, with the small circles representing sites which are 'driest' and large circles those which are 'wettest' ($n = 65$).

Multiple linear regression was performed to see if the critical water table depth could be successfully explained using the spatial characteristics of each site outlined in Table 2. The very wet sites for which the critical water table depth could not be pinpointed were excluded from the analysis. The model which performs the best is shown in equation 1, where *Contributing Area* is the size of the catchment area of each site (m^2), accounting for 18.5 % of the variance in *Critical Water Table Depth*; *Average Gully Depth* is the average gully depth (a measure of dissection) in the contributing area of each site (m), accounting for 8.9 % of the variance; *Depth Field* is the gully depth at each site as measured in the field (m), accounting for 11.3 % of the variance; and *Slope9* is the channel slope within a 9 grid cell reach of the site (%), accounting for 12.9 % of the variance in *Critical Water Table Depth*. All four explanatory variables have a significance of <0.001 . The model has an R^2 of 0.52

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(Adjusted $R^2 = 0.48$) and the standard error of the estimate is 27.4. The ANOVA F statistic is 13.9.

*Critical WT depth = 49.042 + (0.002 * Contributing Area) - (263.717 * Average Gully Depth) + (29.686 * Depth Field) - (498.646 * Slope9)* [1]

Modelling Drainage Density Variations

Due to the strong relationship between water table depth and flow incidence at each site, it was possible to model how network extent changes with water table level. Using the critical water table threshold values for all sites, the number of sites ‘wet’, the number of sites connected, and the drainage density for each sub-catchment were calculated over a range of water table depths. The data from each sub-catchment was then combined to calculate network extent for the entire monitored area over a range of water table values (Figure 9, top).

The long water table record for the catchment means that it is possible to calculate the frequency at which various water table depths are exceeded. Three years of water table data (1 July 2007 to 30 June 2010) were examined to determine the cumulative temporal distribution of water table depth, shown in Figure 10 alongside water table levels during the 2 monitoring periods in this study. Water table levels during the two monitoring periods are not atypical, particularly the autumn 2007 data which shows a similar distribution to the long term record. The long term water table data allowed the frequency of various network extents to be calculated (Figure 9, bottom). It was found that when water tables fall below 180 mm, flow in ephemeral channels is completely absent, being restricted to the perennial channel network.

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3 511 This represents a drainage density of 1.41 km/km^2 and occurs around 13% of the
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5 512 time. Complete connectivity of the fully expanded network is not achieved until water
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7 513 tables are within 3 mm of the surface (at the AWS site), which occurs 39% of the
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9 514 time. This represents a drainage density of 29.98 km/km^2 , 20 times greater than that
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11 515 of the contacted perennial network. For the remaining 48% of the time the extent of
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13 516 the network varies between these two extremes.
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518 **Drainage Density and Discharge**

519 The relationship between discharge and drainage density at hourly intervals during
520 both the 2007 and 2008 study periods is plotted in Figure 11. It is apparent that a
521 range of drainage density values were observed when the discharge was low, and a
522 range of discharge values were observed when the drainage density was high.
523

524 An example of this can be seen in Figure 12, which shows how the three key
525 descriptors of network extent, water table and discharge varied over the course of a
526 storm on 19 – 20 September 2007. At the start of the storm (12:00 on 19
527 September), small inputs of relatively low intensity rainfall lead to recharge of the
528 water table and flow was produced at several of the sites. However, there was
529 almost no increase in discharge at the catchment outlet, and not until the rainfall
530 intensity increased to 15.75 mm h^{-1} at 03:00 on 20 September did discharge
531 increase. Peak discharge occurred at 04:00 (when the water table was 1 mm below
532 the surface). This was coincident with the peak in the proportion of sites wet, sites
533 connected and drainage density, which all reached their maximum at 04:00. Upon
534 the cessation of rainfall, discharge decreased rapidly, returning to baseflow levels by
535 around 14:00. Although water table levels and all three measures of network extent

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536 also decreased upon the cessation of rainfall, this was much less rapid, and levels
537 remained much higher than before the rainfall event.

538
539 **DISCUSSION**

540 This study has demonstrated that ES sensors can be used to detect streamflow in
541 ephemeral portions of the channel network, enabling the collection of high temporal
542 and spatial resolution data on ephemeral streamflow in the Upper North Grain
543 catchment. The data collected on variations in network extent represent perhaps the
544 most comprehensive dataset on network expansion and contraction currently
545 available.

546
547 **Water Table as a Key Control**

548 Much of the data on the timing of the production of flow in ephemeral portions of the
549 channels ties in with established notions of peatland hydrology and are consistent
550 with the dominance of saturation excess overland flow as the primary mechanism for
551 runoff generation (Evans *et al.*, 1999; Holden and Burt, 2003). The rate of network
552 expansion has been found to be dependent on both antecedent conditions and
553 rainfall characteristics, being rapid when water tables are high and rainfall is intense.
554 When water tables are low, incident rainfall infiltrates into the peat until water tables
555 are at or close to the surface; only then does widespread runoff occur. This leads to
556 a longer delay in runoff production when water tables or rainfall intensities are low.

557
558 This dependence on water table levels is further evidenced by the strong relationship
559 between catchment-wide network expansion and water table level. It is also apparent

at the site scale, with the incidence of flow at any site being strongly dependent on water table level.

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563 **Spatial Patterns of Ephemeral Flow**

564 In terms of the pattern of network expansion and contraction, the wetting up of the
565 ephemeral channels is variable both within and between gullies. Network expansion
566 is neither 'bottom up' nor 'top down', but most closely corresponds to the 'disjointed'
567 pattern of network expansion described by Day (1978, 1980). The pattern of network
568 expansion is similar between storms, with sites wetting up in a similar order each
569 time, particularly when storms are similar in terms of antecedent water table levels
570 and rainfall characteristics. This suggests that local controls on runoff may be
571 significant in terms of the generation of flow in ephemeral portions of the channel.

572

573 When examining the spatial controls on site wetness, the most significant model
574 accounted for 52 % of the observed variance. The size of each site's contributing
575 area is significant, with sites with a larger contributing area containing flow more of
576 the time. This is likely to be because larger catchment areas take longer to drain,
577 thus flows are more prolonged. The degree of dissection of this contributing area is
578 also important, as represented the average gully depth variable in Equation [1]. Sites
579 with a more heavily dissected contributing area, indicated by a high average gully
580 depth, tend to be drier. This is likely to be due to the water table drawdown
581 associated with gullying (Daniels *et al.*, 2008; Allott, 2009), reducing surface
582 saturation, and therefore, runoff production. In addition to the characteristics of a
583 site's contributing area, site specific characteristics have also been found to be
584 important. Sites with high channel slope tend to be drier as these sites are well

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585 drained and water is rapidly evacuated downstream. Many of these factors can be
586 seen to influence local water table, with sites which have a smaller, more dissected
587 contributing area and high local channel slopes having deeper local water tables.
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589 The final explanatory factor relates to gully morphology, with deeper gullies tending
590 to be wetter. This may be due to the influence of pipeflow. It has been found that soil
591 pipe density significantly and linearly increases with age of drainage in blanket peat
592 (Holden, 2006). If gully depth can be taken as a proxy for age then this may indicate
593 that deep gullies may have a higher density of soil pipes. This was found by Wallet
594 (2004) who observed that, in the Upper North Grain catchment, the greatest
595 densities of pipe outlets were primarily located in more mature gullies, which had
596 eroded down to the underlying mineral substrate. Pipes can rapidly deliver water to
597 the channel network and have been found to contribute to low flows and maintain
598 baseflows in many peatland systems (Holden and Burt, 2002; Smart *et al.*, 2013),
599 suggesting that they deliver water to the channel after other delivery mechanisms
600 cease. Therefore, portions of the channel with a high density of pipe outlets may
601 experience prolonged flow.
602
603 Although the majority of the variation in site wetness can be explained by the spatial
604 factors examined here, 48% of the variation in flow occurrence cannot be explained
605 by the factors outlined in Table 2, suggesting that the controls on flow production
606 may be factors which have not been considered. The first possible influence is
607 pipeflow. Although pipeflow may be correlated with gully depth to some degree, local
608 pipe inputs are likely to impact on wetting up at the site scale. Therefore, the location
609 of pipe outlets and the nature of pipeflows in the catchment may help to explain

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3 610 some of the variance in channel flow which is unaccounted for. A second possible
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5 611 factor is small scale variations in channel bed topography that are unable to be
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7 612 detected at the scale of the DEM.
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11 614 **Models of Dynamic Connectivity**

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14 615 As the monitored sites all show a strong dependence on water table level, it was
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16 616 possible to model how network extent, and by implication, connectivity, varied with
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18 617 water table in the instrumented gullies. The increase in drainage density of over
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20 618 2,000% observed in this study is large when compared to the findings of other
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22 619 studies (Table 1). The high maximum drainage densities reported in the Upper North
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24 620 Grain study catchment are characteristic of eroded peatlands, and the large range in
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26 621 observed drainage density is effectively a function of the high degree of ephemerality
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28 622 of the headwater streams.
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33 624 **Drainage Density and Discharge**

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36 625 It appears that the relationship between discharge and drainage density observed by
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38 626 other studies (i.e. Gregory and Walling, 1968; Blyth and Rodda, 1973; Day, 1978)
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40 627 does not hold in this catchment. Rather, the data presented in Figures 11 and 12
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42 628 suggest that there are two quite distinct states, when the catchment may be thought
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44 629 to be relatively hydrologically active, and hydrologically inactive.
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50 631 Following wet antecedent conditions, incident rainfall causes discharge to increase
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52 632 rapidly from baseflow to stormflow. The high water tables at these times also give
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54 633 rise to a fully expanded drainage network. This represents a hydrologically active
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56 634 catchment, depicted by the vertical 'edge' of the data in Figure 11, and the peak in
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635 discharge at 04:00 on 20 September 2007 in Figure 12. When rainfall ceases,
636 discharge rapidly returns to baseflow values as storm runoff is evacuated from the
637 catchment. Drainage density values during baseflow conditions vary as the water
638 table drops. This represents a hydrologically inactive catchment, depicted by the
639 horizontal 'edge' of the data in Figure 11, and from 06:00 on 20 September 2007 in
640 Figure 12.

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642 The catchment may also be thought of as hydrologically inactive during rainfall
643 events which occur following dry antecedent conditions, as shown by the period up
644 to 06:00 on 20 September 2007 in Figure 12. The absence of any increase in
645 discharge during this period, despite rainfall additions, is likely to be due to a lowered
646 water table, so that most of the incident rainfall infiltrates into the peat to make up
647 this deficit. The incidence of channel flow as detected by the sensors may have been
648 due solely to rain falling directly into the channel or localised areas of runoff.
649 However, this water did not reach the channel outlet, possibly because the water in
650 the channel was only enough to generate localised areas of ponding as opposed to
651 connected flow, or because it re-infiltrated into the channel bed at some downstream
652 point. Again, these variations in network extent despite discharge remaining at
653 baseflow levels is depicted by the horizontal 'edge' of the data in Figure 11, and
654 represents a hydrologically inactive catchment.

655
656 The evidence above suggests that drainage density does not influence discharge;
657 rather water table levels influence both the production of runoff and drainage density.
658 The data also indicate relatively rapid switching between a connected state and a

659 disconnected state. This again highlights the importance of water table on peatland
660 hydrology and the 'flashy' nature of runoff production in peatlands.

661

662 **Implications for Material Flux and Catchment Management.**

663 Previous work on peatland sediment systems has demonstrated the importance of
664 sediment supply as a control on sediment flux, particularly emphasising the
665 importance of temporal variation in supply (Evans and Warburton, 2007). The
666 significant changes in drainage density observed in this study and the consequent
667 expansion of the connected sediment supply and reduction in hillslope sediment
668 transport path lengths suggest that spatial controls on sediment supply are equally
669 important in controlling storm sediment flux.

670

671 The dominance of water table (catchment wetness) in controlling catchment
672 connectivity, and potentially therefore material flux, has implications for the
673 management of peatland catchments into the future. Changes to the water table
674 regime induced by future climate conditions will have implications for the periodicity
675 and magnitude of fluxes. Projected wetter winters and drier summers across upland
676 peatlands (Clark *et al.* 2010) imply stronger seasonal variability in water table and
677 consequently in catchment connectivity. A second potentially significant driver of
678 water table change across many UK upland systems is peatland restoration through
679 the blocking of drainage ditches and erosional gullies (Ramchunder *et al.*, 2009).

680 Elevated water tables associated with peatland restoration are likely to drive
681 increased channel connectivity and drainage density and may impact on the
682 periodicity of material flux from peatlands.

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Further Work

These potential changes in connectivity linked to climate change and peatland restoration are an important area for further work. A related question in the context of assessing the impact of connectivity changes on sediment flux is investigation of the linkage between the lower reaches of ephemeral gullies and the perennial stream system. In this study the four dendritic gullies instrumented to the north and east of the catchment grade evenly to the head of the perennial stream channel. The four gullies to the south and west which are approximately normal to the main stem drain at their outlets a short distance across vegetated valley sides and floodplains. These steep links are equivalent to the vegetated interface between slopes and channels identified in re-vegetated gully systems in the North Pennines by Evans and Warburton (2005). These slopes have been identified as zones of disconnection in the sediment system. Because the flow in these zones was not channelised it did not form part of the monitoring campaign in this study, but there is potential, at least in the context of sediment flux, that the effective connectivity in the system is somewhat less than indicated by measurement of drainage density. This is an area which requires further work.

Further work on the impact of connectivity changes on the quantitative hydrology of the catchment could consider the extent of the network not only in terms of its linear dimensions (i.e. total stream length/drainage density), but in terms of its total volume (Gregory and Ovenden 1979). A consideration of network volume may produce a stronger relationship with discharge and would also give a clearer indication of the spatial controls on runoff within the catchment.

CONCLUSIONS

The use of a high density network of low cost wetness sensors has, for the first time, empirically described spatial and temporal patterns of channel wetting in peatland systems. The key findings are:

1. Catchment water table is the dominant control on channel wetness and the channel network exhibits a rapid transition from a disconnected state to a connected state as the catchment soils approach saturation.
2. Channel wetting occurs in a disjointed manner, controlled by both upstream catchment conditions (specifically the size and degree of dissection of each site's contributing area) and local channel slope.
3. This typical gullied headwater peatland system experiences in excess of an order of magnitude change in drainage density between dry and fully saturated conditions. The strongly episodic nature of sediment and solute fluxes from peatland systems (Evans and Warburton, 2007) is consistent with catchment connectivity being a key control on material flux from peatland systems.
4. Future change in peatland water tables driven by climate change or peatland restoration are likely to modify the degree of connectivity in ephemeral headwater streams.

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733 **REFERENCES**

734

735 Allott TEH, Evans MG, Lindsay JB, Agnew CT, Freer JE, Jones A, Parnell M. 2009.

736 Water tables in Peak District blanket peatlands. Report No. 17, Moors for the Future:

737 Edale.

738

739 Bay RR. 1969. Runoff from small peatland watersheds. *Journal of Hydrology* **9**: 90-

740 102.

741

742 Beven KJ, Kirkby MJ. 1979. A physically based, variable contributing area model of

743 basin hydrology. *Hydrological Sciences Bulletin* **24**: 43-69. DOI:

744 10.1080/02626667909491834

745

746 Bhamjee R, Lindsay JB. 2011. Ephemeral stream sensor design using state loggers.

747 *Hydrology and Earth System Sciences* **15** (3): 1009-1021. DOI: 10.5194/hess-15-

748 1009-2011

749

750 Blyth K, Rodda JC. 1973. A Stream Length Study. *Water Resources Research* **9**:

751 1454-1461. DOI: 10.1029/WR009i005p01454

752

753 Bond NR, Cottingham P. 2008. Ecology and hydrology of temporary streams:

754 implications for sustainable water management. eWater Technical Report. eWater

755 Cooperative Research Centre, Canberra.

756

- 1
2
3 757 Bower MM. 1961. The distribution of erosion in blanket peat bogs in the Pennines,
4
5 758 *Transaction of the Institute of British Geographers* **29**: 17–30.
6
7 759
8
9
10 760 Bracken LJ, Croke J. 2007. The concept of hydrological connectivity and its
11
12 761 contribution to understanding runoff-dominated geomorphic systems. *Hydrological*
13
14 762 *Processes* **21** (13): 1749–1763. DOI: 10.1002/hyp.6313
15
16 763
17
18 764 Bracken LJ, Wainwright J, Ali GA, Tetzlaff D, Smith MW, Reaney SM, Roy AG. 2013.
19
20 765 Concepts of hydrological connectivity: Research approaches, pathways and future
21
22 766 agendas. *Earth-Science Reviews* **119**: 17–34. DOI: 10.1016/j.earscirev.2013.02.001
23
24
25 767
26
27 768 Burt TP, Heathwaite AL, Labadz JC. 1990. Runoff production in peat covered-
28
29 769 catchments. In *Process Studies in Hillslope Hydrology*, Anderson MG, Burt TP (eds).
30
31 770 Wiley: Chichester; 463–500.
32
33 771
34
35 772 Butcher DP, Claydon J, Mice JC, Pattinson, VA, Potter AWR, White P. 1992
36
37 773 Reservoir sedimentation and colour problems in southern Pennine reservoirs. *Water*
38
39 774 *and Environment Journal* **6**: 418–430. DOI: 10.1111/j.1747-6593.1992.tb00771.x
40
41
42 775
43
44 776 Clark JM, Gallego-Sala AV, Allott TEH, Chapman SJ, Farewell T, Freeman C, House
45
46 777 JI, Orr HG, Prentice IC, Smith P. 2010. Assessing the vulnerability of blanket peat to
47
48 778 climate change using an ensemble of statistical bioclimatic envelope models.
49
50 779 *Climate Research* **45** (1): 131–150. DOI: 10.3354/cr00929
51
52
53 780
54
55
56
57
58
59
60

1
2
3 781 Crowe SK, Evans MG, Allott THE. 2008. Geomorphological controls on the re-
4
5 782 vegetation of erosion gullies in blanket peat: implications for bog restoration. *Mires*
6
7 783 *and Peat 1*: 1-14.
8
9 784
10
11 785 Daniels S. 2006. *Controls on Streamwater Acidity in South Pennine Headwater*
12
13 786 *Catchments*. Unpublished PhD Thesis, University of Manchester, 2006.
14
15 787
16
17 788 Daniels SM, Agnew CT, Evans MG, Allott TEH. 2008. Water table variability and
18
19 789 runoff generation in a degraded peatland, South Pennines, UK. *Journal of Hydrology*
20
21 790 **361**: 214-226. DOI: 10.1016/j.jhydrol.2008.07.042
22
23 791
24
25 792 Day DG. 1978. Drainage density changes during Rainfall. *Earth Surface Processes*
26
27 793 *and Landforms 3*: 319-326.
28
29 794
30
31 795 Day DG. 1980. Lithologic controls of drainage density: A study of six small rural
32
33 796 catchments in New England, N.S.W. *Catena 7*: 339-351.
34
35 797
36
37 798 Evans MG, Lindsay JB. 2010. High resolution quantification of gully erosion in
38
39 799 upland peatlands at the landscape scale. *Earth Surface Processes and Landforms*
40
41 800 **35**: 876-886. DOI: 10.1002/esp.1918
42
43 801
44
45 802 Evans, MG, Warburton J. 2005. Sediment budget for an eroding peat moorland
46
47 803 catchment in northern England. *Earth Surface Processes and Landforms 30*: 557-
48
49 804 577. DOI: 10.1002/esp.1153
50
51 805
52
53
54
55
56
57
58
59
60

- 806 Evans MG, Warburton J. 2007. *Geomorphology of Upland Peat: Erosion, Form, and*
807 *Landscape Change*. Blackwell: Oxford.
- 808
- 809 Fritz KM, Johnson BR, Walters DM. 2008. Physical indicators of hydrologic
810 permanence in forested headwater streams. *Journal of The North American*
811 *Benthological Society* **27**: 690-704. DOI: 10.1899/07-117.1
- 812
- 813 Fryirs KA, Brierley GJ, Preston NJ, Kasai M. 2007. Buffers, barriers and blankets:
814 The (dis)connectivity of catchment-scale sediment cascades. *Catena* **70** (1): 49-67.
815 DOI: 10.1016/j.catena.2006.07.007
- 816
- 817 Gomi T, Sidle RC, Miyata S, Kosugi K, Onda Y. 2008. Dynamic runoff connectivity of
818 overland flow on steep forested hillslopes: scale effects and runoff transfer. *Water*
819 *Resources Research* **44**: W08411. DOI: 10.1029/2007WR005894
- 820
- 821 Goulsbra CS, Lindsay JB, Evans, MG. 2009. A new approach to the application of
822 electrical resistance sensors to measuring the onset of ephemeral stream flow in
823 wetland environments. *Water Resources Research* **45**: W09501. DOI:
824 10.1029/2009WR007789
- 825
- 826 Gregory KJ, Ovenden JC. 1979. Drainage network volumes and precipitation in
827 Britain. *Transactions of the Institute of British Geographers* **4**: 1-11.
- 828
- 829 Gregory KJ, Walling DE. 1968. The variation of drainage density within a catchment.
830 *Bulletin of International Association of Scientific Hydrology* **13**: 61-68.

1
2
3 831
4
5 832 Gurnell AM. 1978. The Dynamics of a Drainage Network. *Nordic Hydrology* **9**: 293-
6
7 833 306.
8
9
10 834
11
12 835 Holden J. 2006. Sediment and particulate carbon removal by pipe erosion increase
13
14 836 over time in blanket peats as a consequence of land drainage. *Journal of*
15
16 837 *Geophysical Research* **111** (F2) F02010. DOI: 10.1029/2005JF000386
17
18 838
19
20
21 839 Holden J, Burt, TP. 2002. Piping and pipeflow in a deep peat catchment. *Catena* **48**:
22
23 840 163-199. DOI: 10.1016/S0341-8162(01)00189-8
24
25 841
26
27 842 Holden J, Burt TP. 2003. Runoff production in blanket peat covered catchments.
28
29 843 *Water Resources Research* **39**: 1191, DOI: 10.1029/2002WR001956
30
31 844
32
33
34 845 Holden J, Evans MG, Burt TP, Horton M. 2006. Impact of land drainage on peatland
35
36 846 hydrology. *Journal of Environmental Quality* **35** (5): 1764–1778. DOI:
37
38 847 10.2134/jeq2005.0477
39
40 848
41
42
43 849 Kirkby MJ. 1975. Hydrograph modelling strategies. In *Processes in physical and*
44
45 850 *human geography*. Peel R, Chisholm M, Haggett P (eds). Heinemann: London; 69-
46
47 851 90.
48
49 852
50
51
52 853 Lane SN, Brookes CJ, Kirkby MJ, Holden J. 2004. A network-index-based version of
53
54 854 TOPMODEL for use with high resolution digital topographic data. *Hydrological*
55
56 855 *Processes* **18**: 191-201. DOI: 10.1002/hyp.5208
57
58
59
60

- 856
- 857 Lexartza-Artza I, Wainwright J. 2009. Hydrological connectivity: linking concepts with
858 practical implications. *Catena* **79**: 146–152. DOI: 10.1016/j.catena.2009.07.001
- 859
- 860 Lindsay JB. 2005. The Terrain Analysis System: A tool for hydro-geomorphic
861 applications. *Hydrological Processes* **19**: 1123–1130. DOI: 10.1002/hyp.5818
- 862
- 863 McGuire KJ, McDonnell JJ. 2010. Hydrological connectivity of hillslopes and
864 streams: Characteristic time scales and nonlinearities. *Water Resources Research*
865 **46** (10): W10543. DOI: 10.1029/2010WR009341
- 866
- 867 Morgan RPC. 1972. Observations on Factors Affecting the Behaviour of a First-
868 Order Stream. *Transactions of the Institute of British Geographers* **56**: 171–185.
- 869
- 870 Pawson RR, Evans MG, Allott TEH. 2012. Fluvial carbon flux from headwater
871 peatland streams: significance of particulate carbon flux. *Earth Surface Processes*
872 *and Landforms* **37**: 1203–1212. DOI: 10.1002/esp.3257
- 873
- 874 Ramchunder SJ, Brown LE, Holden J, 2009. Environmental effects of drainage,
875 drain-blocking and prescribed vegetation burning in UK upland peatlands. *Progress*
876 *in Physical Geography* **33** (1): 49–79. DOI: 10.1177/0309133309105245
- 877
- 878 Reaney SM, Bracken LJ, Kirkby MJ. 2013. The importance of surface controls on
879 overland flow connectivity in semi-arid environments: results from a numerical
880 experimental approach. *Hydrological Processes*. DOI: 10.1002/hyp.9769

881

882 Roberts MC, Klingeman PC. 1972. The relationship of drainage net fluctuation and
883 discharge. Paper presented at 22 International Geographical Congress, Canada.

884

885 Rothwell JJ, Evans MG, Daniels SM, Allott TEH. 2007. Baseflow and stormflow
886 metal concentrations in streams draining contaminated peat moorlands in the Peak
887 District National Park (UK). *Journal of Hydrology* **341**: 90– 104. DOI:
888 10.1016/j.jhydrol.2007.05.004

889

890 Rothwell JJ, Robinson SG, Evans MG, Yang J, Allott TEH. 2005. Heavy metal
891 release by peat erosion in the Peak District, southern Pennines, UK. *Hydrological*
892 *Processes* **19**: 2973-2989. DOI: 10.1002/hyp.5811

893

894 Smart RP, Holden J, Dinsmore KJ, Baird AJ, Billet MF, Chapman PJ, Grayson R.
895 2013. The dynamics of natural pipe hydrological behaviour in blanket peat.
896 *Hydrological Processes* **27**: 1523-1534. DOI: 10.1002/hyp.9242

897

898 Wainwright J, Turnbull L, Ibrahim TG, Lexartza-Artza I, Thornton SF, Brazier RE.
899 2011. Linking environmental régimes, space and time: Interpretations of structural
900 and functional connectivity. *Geomorphology* **126** (3-4): 387-404. DOI:
901 10.1016/j.geomorph.2010.07.027

902

903 Wallett CV. 2004. *The Importance of Pipeflow to the Flux of Carbon from an Upland*
904 *Peat*. Unpublished M.Sc. Thesis, The University of Manchester.

905

- 1
2
3 906 Wharton G. 1994. Progress in the use of drainage network indices for rainfall-runoff
4
5 907 modelling and runoff prediction. *Progress in Physical Geography* **18**: 539-557. DOI:
6
7 908 10.1177/030913339401800404
8
9 909
10
11 910 Wigington PJ Jr., Moser T J, Lindeman DR. 2005. Stream network expansion: A
12
13 911 riparian water quality factor. *Hydrological Processes* **19**: 1715– 1721. DOI:
14
15 912 10.1002/hyp.5866
16
17 913
18
19 914 Worrall F, Burt TP, Jaeban RY, Warburton J, Shedden R. 2002. Release of
20
21 915 dissolved organic carbon from upland peat. *Hydrological Processes* **16**: 3486-3504.
22
23 916 DOI: 10.1002/hyp.1111
24
25 917
26
27 918 Worrall F, Reed M, Warburton J, Burt T. 2003. Carbon budget for a British upland
28
29 919 peat catchment. *Science of the Total Environment* **312**: 133-146. DOI:
30
31 920 10.1016/S0048-9697(03)00226-2
32
33
34
35
36
37
38
39
40
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TABLES

Drainage Density, (km/km ²)	Size of Basin (km ²)	Comments	Source
0.8 - 3.5	0.08	1 year of observation; Devon England	Gregory and Walling (1968)
0.9 - 6.5	0.16		
0.6 - 3.7	0.10	2 years of observations; Oregon, U.S.A.	Roberts and Klingeman (1972)
1.2 - 10.9	0.01		
3.1 - 4.2	0.26		
1.5 - 3.4	0.23		
0.8 - 2.7	18.56	1 year of observations; Buckinghamshire, England	Blyth and Rodda, (1973)
3.9 - 5.8	0.26	3 years of observation; preurbanisation, Devon, England	Gregory (1976)
5.0 - 17.6	0.26	1 year of observation; posturbanisation, Devon, England	
0.7 - 5.4	0.12	2 storms; New South Wales, Australia	Day (1978)
0.0 - 3.4	0.15	1 year of observation; New South Wales, Australia	Day (1980)
0.5 - 5.2	0.20		
0.0 - 1.8	0.07		
0.0 - 7.5	0.08		
0.0 - 7.7	0.10		
0.0 - 16.7	0.02		
0.2 - 8.0	47.8	Summer and Winter (aerial photography); Western Oregon, USA	Wingington <i>et al.</i> (2005)
0.6 - 4.7	23.6		
0.4 - 3.3	37.3		
0.5 - 2.9	37.1		
0.66 - 3.23	21.6		

Table 1. Variations in drainage density found by previous studies.

Data Source	Site/ Catchment	Characteristic
Field Data	Site specific	Gully Depth (m)
		Gully Top Width (m)
		Gully Floor Width (m)
LiDAR Data	Site specific	Elevation (m)
		Network Wetness Index
		Gully Depth (m)
		Channel Slope (one, two, three and four grid-cells either side of site) (%)
	Catchment of each site	Area of Catchment (m ²)
		Mean Slope of Catchment (%)
		Mean Wetness Index of Catchment
		Proportion of catchment area occupied by gullies (%)*
		Average gully depth in catchment (m)*
	Catchment of each site excluding gullies	Area of Catchment (m ²)
		Mean Slope of Catchment (%)
		Mean Water Table Depth of Catchment (mm)**
		Mean Wetness Index of Catchment

Table 2. Spatial data collected for each site.

* Extracted from the gully map of the catchment (Evans and Lindsay, 2010)

** Extracted from the water table model for the catchment (Allott *et al.*, 2009)

19/09/07 <i>n</i> =23	R=0.58 Sig. 0.08 <i>n</i> =10						
20/09/07 <i>n</i> =18	<i>n</i> =1	<i>n</i> =3					
03/10/07 <i>n</i> =10	<i>n</i> =0	<i>n</i> =2	<i>n</i> =8				
08/10/07 <i>n</i> =11	<i>n</i> =4	R=0.71 Sig. 0.02 <i>n</i> =10	<i>n</i> =2	<i>n</i> =2			
09/10/07 <i>n</i> =19	<i>n</i> =0	<i>n</i> =3	R=0.54 Sig. 0.04 <i>n</i> =15	R=0.84 Sig. 0.00 <i>n</i> =10	<i>n</i> =2		
28/10/07 <i>n</i> =19	<i>n</i> =0	<i>n</i> =4	R=0.63 Sig. 0.01 <i>n</i> =15	<i>n</i> =8	<i>n</i> =4	R=0.85 Sig. 0.00 <i>n</i> =16	
05/11/07 <i>n</i> =13	<i>n</i> =0	<i>n</i> =1	R=0.11 Sig. 0.75 <i>n</i> =11	<i>n</i> =6	<i>n</i> =0	R=-0.07 Sig. 0.83 <i>n</i> =12	R=-0.07 Sig. 0.82 <i>n</i> =13
	10/0/07 <i>n</i> =10	19/09/07 <i>n</i> =23	20/09/07 <i>n</i> =18	03/10/07 <i>n</i> =10	08/10/07 <i>n</i> =11	09/10/07 <i>n</i> =19	28/10/07 <i>n</i> =19

Table 3. Results of Spearman's rank correlation analysis for network expansion events in the 2007 dataset. The order in which sites went from dry to wet was compared for pairs of events where ten or more sites responded to both events.

30/07/08 <i>n</i> =10	R=0.60 Sig. 0.07 <i>n</i> =10				
31/07/08 <i>n</i> =17	R=0.22 Sig. 0.40 <i>n</i> =17	<i>n</i> =4			
01/08/08 <i>n</i> =18	R=0.70 0.00 <i>n</i> =17	<i>n</i> =7	<i>n</i> =2		
03/08/08 <i>n</i> =12	R=0.35 Sig. 0.27 <i>n</i> =12	<i>n</i> =6	<i>n</i> =2	R=0.66 Sig. 0.04 <i>n</i> =10	
16/08/08 <i>n</i> =19	R=0.43 Sig. 0.07 <i>n</i> =19	<i>n</i> =6	<i>n</i> =7	R=0.79 Sig. 0.00 <i>n</i> =12	R=0.58 Sig. 0.08 <i>n</i> =10
	29/07/08 <i>n</i> =39	30/07/08 <i>n</i> =10	31/07/08 <i>n</i> =17	01/08/08 <i>n</i> =18	03/08/08 <i>n</i> =12

Table 4. Results of Spearman’s rank correlation analysis for network expansion events in the 2008 dataset. The order in which sites went from dry to wet was compared for pairs of events where ten or more sites responded to both events.

Date of Event	Number of sites which respond to event	Cumulative sites wet (% of total which respond)				
		Hour 1	Hour 2	Hour 3	Hour 4	Hour 5
09/10/07	19	4 (21%)	7 (37%)	17 (89%)	19 (100%)	
28/10/07	19	5 (26%)	14 (74%)	19 (100%)		
05/11/07	13	13 (100%)				
31/07/08	17	0 (0%)	13 (76%)	15 (88%)	17 (100%)	
01/08/08	18	12 (67%)	17 (94%)	18 (100%)		
16/08/08	19	13 (68%)	14 (74%)	16 (84%)	17 (89%)	19 (100%)

Table 5. The timing of streamflow initiation for large events. Events represent the occasions during the study period on which the highest number of sites went from dry to wet, with the exception of the examples shown in Figures 2 and 3.

88x45mm (300 x 300 DPI)

Figure 2. The pattern and timing of streamflow initiation during a large event on 19-20 Sept 2007. The white circles represent dry sites; the black circles represent wet sites. (A) 19/09/07 13:00; (B) 19/09/07 15:30; (C) 19/09/07 18:00; (D) 19/09/07 20:30; (E) 20/09/07 02:45; (F) 20/09/07 03:30.
168x160mm (300 x 300 DPI)

Figure 3. The pattern and timing of streamflow initiation during a large event on 29 July 2008. The white circles represent dry sites; the black circles represent wet sites. (A) 04:00; (B) 05:00; (C) 06:00; (D) 07:00; (E) 08:00.
122x84mm (300 x 300 DPI)

Figure 4. The relationships between water table depth and descriptors of network extent during the 2007 and 2008 study periods.
130x196mm (300 x 300 DPI)

Figure 5. The variation in network extent and water table depth over the 2007 monitoring period.
114x142mm (300 x 300 DPI)

Figure 6. Observed (top) and modelled (centre) flow at one site, 2007. Water table depth (bottom) shows a critical threshold of 22.6 mm, above which flow was registered at the site.
68x50mm (300 x 300 DPI)

Figure 7. Modelled flow at one site, 2008 (top) and water table depth (bottom), showing the degree of uncertainty in critical water table depth at this site.
49x26mm (300 x 300 DPI)

Figure 8. The spatial distribution of critical water table depth. Larger circles represent wetter sites.
88x93mm (300 x 300 DPI)

Figure 9. (A) The variation in network extent with water table depth; (B) The frequency at which these network extents are observed.

111x147mm (300 x 300 DPI)

Figure 10. The distribution of water table depths during the 2007 and 2008 study periods and the longer term distribution of water table depths, using data from July 2007 to June 2010.
63x48mm (300 x 300 DPI)

Figure 11. The relationship between drainage density and discharge at hourly intervals, in (A) 2007 (n=1549), and (B) 2008 (n=1081).
38x17mm (300 x 300 DPI)

Figure 12. The variation in network extent, water table and discharge over the course of a storm on 19–20 September 2007.
152x256mm (300 x 300 DPI)