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1	The importance of a small ephemeral tributary for fine sediment dynamics
2	in a main-stem river

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25 Abstract

26 Studies of ephemeral streams have focused mainly in arid and semi-arid regions. Such streams also occur widely in temperate regions, but much less is known about their influence on fluvial 27 processes in main-stem rivers here. In this paper we present evidence of the importance of a 28 29 small ephemeral temperate stream for main-stem fine sediment dynamics. The paper focuses on 30 a restoration project (River Ehen, NW England) which involved the reconnection of a headwater tributary to the main-stem river. We present data on suspended sediment transport 31 32 two years prior to and two years following the reconnection. Despite the small size and nonperennial flow of the tributary, its reconnection resulted in an increase of 65% in the main-stem 33 sediment yield. During both the pre- and post-reconnection periods, a higher proportion of the 34 annual yield was conveyed during short events with relatively high suspended sediment 35 concentrations. Following the reconnection, the magnitude and frequency of such events 36 increased, primarily due to sediment being delivered from the tributary at times when main-37 stem flows were not elevated. Overall, the main-stem remains supply limited and so is highly 38 39 dependent on sediment delivered from the tributary. The study helps stress that even nonperennial tributaries yielding only a small increase in catchment size (+1.2% in this case) can 40 have a major influence on main-stem fluvial dynamics. Their role as sediment sources may be 41 especially important where, as in the case of the Ehen, the main-stem is regulated and the 42 system is otherwise starved of sediments. 43

Keywords: Ephemeral stream, fine sediment, suspended load, channel reconnection, riverrestoration, temperate region, regulated river, River Ehen.

46 1. INTRODUCTION

47 The transport dynamics of the finer fraction of river sediment loads (i.e. material finer than 2 mm diameter) have been studied intensively. Fine sediment generally represents the most 48 important part of the sediment budget of a river (Walling and Webb, 1987; Vericat and Batalla, 49 50 2006) and so is quantitatively significant. Fine sediment is also important functionally, because 51 of the role it plays in habitat formation. For example, fine particles play an important role as architects of riverbed structure, and help strengthen the banks, encourage the establishment of 52 53 vegetation, enhance bed compactness and clog gravel interstices (Parker, 2003; Church, 2006). Fine sediment also has important implications for the entrainment of coarser bed material 54 (Dudill et al., 2016 and references therein) and may have negative effects on benthic organisms 55 when present in excessive amounts (Wood and Armitage, 1997; Jones et al., 2012). Interest in 56 the effects of fine sediment on aquatic organisms was triggered primarily by concerns over 57 human activities such as agriculture, deforestation and mining (Rabení et al., 2005). However, 58 some rivers carry naturally high fine sediment loads, whether as a result of glacial processes 59 (e.g. Gurnell et al., 1996) or loss of material highly erodible surfaces (e.g. badlands; Buendía et 60 al., 2011). Irrespective of whether causes are natural or anthropogenic, increased fine sediment 61 loads generally lead to reductions in the diversity of aquatic organisms (Buendía et al., 2013). 62 63 Nonetheless, the exact response of organisms remains difficult to predict because effects depend on the interaction of factors such as concentration, duration of exposure, particle-size 64 65 distribution and chemical composition (Bilotta and Brazier, 2008).

The variety of effects of fine sediment in rivers reflects differences in sediment sources and 66 characteristics (Sear et al., 2016), and the processes involved in its production, transport and 67 deposition through the channel network (Wood and Armitage, 1997). Primary sediment 68 production areas are confined largely to upper (i.e. headwater) parts of catchments (Charlton, 69 2008). Tributaries can have a major influence on the delivery of fine material to main-stem 70 channels (Webb et al., 2000; Collins and Walling, 2006), although this can vary over short 71 72 temporal and small spatial scales, linked to hydro-climatic, hydrologic and hydraulic conditions 73 (Buendía et al., 2014; Piqué et al., 2014). Some of this variability stems from spatial variation in the relative availability of fine sediment sources, and how local variation in precipitation 74 interacts to switch different tributaries on-and-off at different times (López-Tarazón et al., 75 2011; Tena and Batalla, 2013). 76

Interest in tributaries and their confluences has increased since the 1980s, with work focusingon the effects of tributary sediment delivery on downstream morphology (Rice and Church,

79 2001), sedimentary conditions (Rice and Church, 1998) and ecology (Rice et al., 2001, 2008). Most emphasis has been on the role of relatively large, perennial tributaries in supplying coarse 80 material to main-stem reaches (Benda et al., 2004; Ferguson et al., 2006), with a particular 81 focus on downstream fining and the effects of tributary inputs on the fluvial equilibrium of the 82 receiving river (Pizzuto, 1995; Rice, 1998). Less work has been conducted on fine sediment 83 delivery from small, low-order tributaries, although exceptions include studies on the Colorado 84 River, USA (Webb et al., 2000; Griffiths and Topping, 2015) and the River Isábena, Spain 85 86 (Francke et al., 2014).

Historically, catchment-scale studies have relied on traditional mapping techniques (i.e. aerial 87 88 photographs, satellite imagery and survey maps) to provide information on river channel characteristics that are relevant for helping to understand sediment fluxes (e.g. drainage 89 density, length of channel network, slope). However, these techniques lack the resolution to 90 characterise low-order streams (i.e. smaller headwater tributaries; Benstead and Leigh, 2012) 91 and, consequently, the extent of such streams may be underestimated (Meyer and Wallace, 92 2001). For the most part this has not been seen as problematic, as the influence of small 93 tributaries on main-stem river reaches has been considered inconsequential (sediment 94 contribution thought to be simply a function of size; Rhoads, 1987; Benda et al., 2004). This 95 view is reinforced by the fact that many small tributaries are intermittent and so deliver 96 97 material infrequently (Datry et al., 2014). However, others have argued that the role of these 98 small systems has been under-estimated (Benstead and Leigh, 2012). Tena et al. (2012) found 99 that the sediment contribution from intermittent tributaries increased the maximum suspended sediment concentration of a main-stem river three-fold. However, like many studies of 100 101 intermittent or ephemeral streams, this work was undertaken in a dryer region (the Mediterranean); studies of the importance of such streams in other regions (e.g. temperate 102 103 ones) remain scarce.

In this paper we present evidence of the importance of small, ephemeral tributaries for fine 104 105 sediment dynamics in main-stem rivers located in temperate regions. The paper is focused on a 106 headwater tributary of the River Ehen in NW England. Flows in the main-stem Ehen are regulated by a lake and associated weir. A tributary (Ben Gill) that enters the Ehen just 107 108 downstream from the weir was diverted in the 1970s as part of the water supply network, such that for more than 40 years it no longer delivered its sediment and water to the Ehen. However, 109 it was reconnected in autumn 2014. We demonstrate the importance of this tributary by 110 presenting data on the suspended sediment load of the Ehen two years before and two years 111 after the reconnection. We also discuss the timing and magnitude of fine sediment loads in the 112

Ehen in relation to hydrological conditions. Specific objectives of the paper are to: (i) characterise variation in fine sediment transport across a variety of temporal scales (event, annual, and pre- vs. post-reconnection), (ii) assess contribution of the tributary to the fine sediment load of the Ehen, and (iii) assess the links between fine sediment dynamics and the flow regime.

118 2. STUDY AREA

The River Ehen flows south-westwards and discharges to the Irish Sea (Figure 1A & B). It has 119 a total catchment area of 155.8 km². The hydrological regime of the Ehen is regulated by 120 121 Ennerdale Water, although because of the water abstractions and the design and management of the weir, impacts are limited mainly to modification of low flow percentiles. The lake is an 122 important drinking water supply for West Cumbria. It is a natural water body (occupying a 123 formally glaciated valley), although its storage capacity was increased by the construction of a 124 1.3 m high weir (in 1902) and the diversion of Ben Gill (in the 1970s, Figure 1C). Ben Gill is a 125 first order ephemeral headwater tributary, with a small (0.55 km²), steep (mean catchment 126 slope: 25%) mountainous and responsive catchment. It is considered to be ephemeral (as 127 128 opposed to intermittent) as it flows for less time than it is dry, and usually in response to rainfall (Uys and O'Keeffe, 1997). When flow recedes, Ben Gill is left dry along most of its 129 130 length. Although it is not gauged, previous estimates suggest that it flows for approximately ¹/₄ 131 of the time (Quinlan et al., 2015a).

The upper section of Ben Gill flows over a series of waterfalls and step-pool sections, where it 132 forms a steep gully. This upper section represents 85% of the total length of the Ben Gill and 133 has always remained highly dynamic due to its steep gradient. Dominant vegetation here 134 consists of shallow acid grassland with heather and bracken. When it reaches the valley floor, 135 the channel flattens out. Consequently, prior to its diversion, sediment transported from the 136 upper section of Ben Gill deposited to form an alluvial fan in the 300 m long lower section. 137 Average gradient here is 9% and landcover is rough pasture. Originally, Ben Gill discharged to 138 the Ehen approximately 40 m downstream from the lake outlet (i.e. weir). In the 1970s it was 139 140 diverted into the lake through an underground culvert positioned at the marked break in slope between the upper and lower sections (Figure 1C). Thus, the relatively long upper section has 141 142 remained a functional channel, while the short section (~15% of total length) below the diversion point, where it crosses the fan, was filled in and has terrestrialised. Since the 143 144 diversion, sediment supplied from the upper section accumulated around the culvert, and was periodically removed and used locally as building material. 145

- 146 Discharge (hereafter Q) in the River Ehen is gauged at Bleach Green (Figure 1C). The catchment area here is 44.5 km². Although this is only 28% of the total catchment of the River 147 Ehen, this upper area contributes 45% of the catchment's 1800 mm long term mean annual 148 rainfall (Alvarez-Codesal and Sweeting, 2015). The river at Bleach Green has a long term mean 149 daily Q of 2.70 m³ s⁻¹ (1973-2016 data) with minimum and maximum daily Q of 0.124 and 150 80.2 $\text{m}^3 \text{s}^{-1}$ respectively. The compensation flow released from the weir (via a fish-pass) has 151 varied over time; it was 0.37 m³ s⁻¹ until 2012 but is currently 0.92 m³ s⁻¹, sometimes phased 152 down to 0.69 $\text{m}^3 \text{s}^{-1}$ depending on lake level. 153
- Ennerdale Water acts as a sediment trap, with limited sediment transfer to the section immediately downstream (Quinlan *et al.*, 2015a). Further downstream, the river meanders through argillaceous rocks of the Skiddaw group and sandstones (Brown *et al.*, 2008). Here, important sediment contributions come from bank erosion, tributary inputs and diffuse agricultural runoff.
- 159 The Ehen was designated as a Special Area of Conservation (SAC) in 1995 as it supports an estimated 550,000 freshwater pearl mussels Margaritifera margaritifera, L. (Killeen and 160 161 Moorkens, 2013), the largest remaining population in England. As part of work to help conserve this important population, Ben Gill was reconnected to the Ehen in October 2014, in 162 163 an attempt to reactivate the delivery of coarse sediment. The diversion culvert was disabled and a new 300 m long section of channel was engineered over the alluvial fan, following the 164 approximate course of the original stream. The bed of the new section was lined with cobble-165 size material, with some larger (boulder-size) clasts along the banks (see Marteau et al., 2016 166 for more details). In an attempt to limit the first flush delivery of fine sediment to the main-167 stem, the bed was thoroughly washed, section-by-section, before the most downstream point 168 169 was excavated and opened to connect to the Ehen. The wash-water was stored in temporary offchannel settlement ponds; settled fine material was removed from site, with remaining wash-170 171 water pumped to the lake.
- 172 *Figure 1.*

173 **3. METHODS**

174 **3.1. Rainfall and discharge**

The current study is focused on a 4-year period, covering the two hydrological years immediately before the reconnection of Ben Gill (i.e. October 2012 – September 2014) and the first two years after (i.e. October 2014- September 2016). Daily precipitation was recorded by the Environment Agency at Ennerdale Bridge, 1.8 km downstream from the Ehen-Ben Gill confluence. The River Ehen is gauged by the Environment Agency at Bleach Green (Figure 1C; see Quinlan *et al.*, (2015a) for more details). Discharge data from Bleach Green (15-min interval) were used to produce time-series for the study period. Additionally, mean daily values for the 1974-2016 period were used to compute flow percentiles and values of water yield, to set the study period within a longer-term perspective.

184 **3.2. Suspended sediment**

Turbidity (NTU) was measured in the Ehen at Bleach Green using a YSI® 6600 probe with 185 186 self-cleaning wipers. The manufacturer reports a 0.1 NTU resolution for this instrument, with 187 an accuracy of $\pm 2\%$ or 0.3 NTU (whichever is greater). Turbidity was recorded at 15-min intervals over the 4-year study period. The probe was maintained by the Environment Agency, 188 and retrieved for cleaning and calibration every 2 to 3 months. Quinlan et al. (2015a) generated 189 an NTU-Suspended Sediment Concentration (SSC) calibration prior to the reconnection of Ben 190 191 Gill. This calibration was produced by sequentially adding fine sediment (collected from the bed at Bleach Green) to a bucket of water to create known concentrations, with turbidity 192 measured for each increment in sediment (further details in Quinlan et al., 2015a). The present 193 study uses the pre-reconnection data produced by these authors, except that for the calibration 194 195 curve the regression was forced through the origin. This calibration is used to derive SSC values and compute sediment loads for the pre-reconnection period. Because of the very low 196 197 values of turbidity recorded by Quinlan et al. (2015a) (a maximum of 8.6 NTU), this 198 calibration only encompassed the lower end of the probe's range (0-400 NTU). A second calibration was produced for the post-reconnection period, using the same procedure but 199 200 covering the entire range of the probe (0-1000 NTU) to capture the greater turbidity values recorded post-reconnection; this was used to estimate SSC and loads for this period. The 201 202 difference in range covered by the two calibrations does not impact interpretation of the results 203 since each curve is used only to compute SSC and load within its own range (i.e. the ranges 204 recorded within respective periods).

The slope of the NTU-SSC relationship prior to the reconnection was 2.06 (regression $r^2 = 0.99$, P < 0.001; Figure 2) while that for the post-reconnection period was 1.66 ($r^2 = 0.99$, P < 0.001). These slope values are significantly different (Ancova, df = 81, F = 229.19, P < 0.001).

Organic content of fine sediment remained low (below 10% on average), with no apparent seasonal or annual variations. The highest values of organic content were measured at very low SSC, and could not be differentiated from uncertainties associated with the probe accuracy and laboratory processing procedures. Thus, no attempt was made to correct SSC values for organiccontent.

Suspended sediment load (SSL) and water yield were computed from 15-min data. SSL was calculated by multiplying SSC by Q for 15-min time steps. Values were then summed to compute loads at the monthly and annual timescales.

216 *Figure 2.*

217

218 **4. RESULTS**

219 **4.1. Hydrological context**

220 Over the 4-year study period, precipitation averaged just under 2000 mm per year. Annual precipitation values were 1799 mm in 2012-2013, 1901 mm in 2013-2014, 1921 mm in 2014-221 2015 and 2329 mm in 2015-2016. Most events were less than 20 mm per day, with a total of 9 222 events exceeding 50 mm (Figure 3A). An exceptional rainfall event, the highest recorded 223 during the 4 years, occurred on the first day of the reconnection: in total, 104 mm fell within 224 225 the 24 hour period, with impacts on the morphology of the new channel (Marteau *et al.*, 2016) 226 and implications for fine sediment delivery to the main-stem (detailed in Section 4.2). The 227 2014-2015 hydrological year was the wettest within the study period, with precipitation 26% 228 greater than the two pre-reconnection years.

- 229 Despite being regulated by Ennerdale Water and its weir, the Ehen remains relatively flashy and regularly experiences high flows (Figure 3A). Its flow regime follows typical patterns for 230 the NW of England, with lower flows in late spring and summer and higher flows in the winter, 231 but with some high events also occurring in late summer. The median discharge (Q_{50} , the 232 discharge exceeded for 50% of the time) for the study period was 1.98 m³ s⁻¹, which is greater 233 than the long-term median value $(1974-2016 = 1.38 \text{ m}^3 \text{ s}^{-1})$. Minimum mean daily Q was 0.71 234 $m^3 s^{-1}$ (30/07/2013) while minimum instantaneous Q was 0.31 $m^3 s^{-1}$ (11/02/2015). Maximum 235 mean daily Q was 44.5 m³ s⁻¹ (15/11/2015, $Q_{0.02}$), with the instantaneous maximum value being 236 54.0 m³ s⁻¹. This maximum has only been exceeded twice over the 42-year period of record 237 (CEH, National Flow Archive website, AMAX dataset). 238
- 239 *Figure 3*.

Flow duration curves (Figure 4) indicate that the 2015-2016 hydrological year was substantially

241 wetter than the 3 previous years, with higher median, mean and maximum Qs. Low flows were

242 similar for each year of the study period, with most of the differences observed at higher flows (approximately Q_{10} and higher); for example, Q in 2015-2016 was above 10 m³ s⁻¹ for almost 243 10% of the time, markedly higher than the 3 other years (between 4 and 5% of the time). The 244 flow duration curve for year immediately preceding reconnection (2013-2014) was very similar 245 to the years before and after, differing only for the highest range of discharges, which were 246 247 exceeded only around 0.2% of the time. The occurrence of both similar and rather different hydrological regimes pre- and post-reconnection provides a useful basis for assessing the 248 effects of the reconnection on suspended sediment transport. 249

250 *Figure 4*.

4.2. Variations in suspended sediment transport

252 Episodes of high SSC were generally scarce during the pre-reconnection period (Figure 3B). The two most important periods of fine sediment transport were in summer 2013. These 253 occurred during floods that followed a prolonged period of low flow; they peaked at 190 mg l⁻¹ 254 255 but were short-lived (max 24 hours). The high rainfall event on the first day of the reconnection 256 generated visible erosion in the newly created Ben Gill channel, and was responsible for a plume of fine sediment entering the main-stem of the River Ehen. Turbidity exceeded the 257 258 probe's maximum value (1000 NTU) for 15 minutes during the day, and so the calculated SSC of 1700 mg l⁻¹ is probably an underestimate of the true instantaneous value. This value 259 represents a nine-fold increase in maximum instantaneous SSC compared to the maximum 260 recorded pre-reconnection. Although such an extreme value has not been recorded again (as of 261 September 2016), high SSC values have proven to be more frequent after the reconnection of 262 Ben Gill; for instance, the maximum pre-reconnection SSC of 190 mg l^{-1} has been exceeded 263 seven times since October 2014, including some long-lasting events (Figure 3B). 264

The relationship between Q and SSC has been affected by the reconnection, as indicated by the 265 266 difference between Figure 5 A and B. The relationship prior to the reconnection shows little 267 scatter, with the majority of the highest SSC events confined to low discharges (Figure 5A). The difference post-reconnection is most evident at low and medium discharges (Figure 5B). 268 While patterns remain unchanged at high flows (green square, Figure 5B), the scatter in the 269 relationship is considerably greater below 20 m³ s⁻¹; this is particularly visible for flows below 270 5 m³ s⁻¹ (blue square, Figure 5B). Overall, Figure 5 illustrates how the magnitude of SSCs 271 increased following the reconnection, and how the reconnection has altered the basic hydraulic 272 and sedimentary dynamics of the Ehen. 273

274 *Figure 5.*

275 Despite the increased frequency and magnitude of high SSC events following the reconnection,

it is notable that there is no marked difference in the respective mean and median values (Table

- 1). Note also that maximum SSCs in 2015-2016 coincided with very high flows ($Q_{0.02}$) which
- lead to appreciable volumes of sediment being transported through the channel (between 57
- and 60 t per month, in November and December 2015; Figure 6).
- 280 *Table 1.*

4.3. Contribution of the tributary to main-stem sediment loads

Water yield followed a similar pattern each year (Figure 6), with low values in early summer 282 (June) and high values in early to mid-winter (November to January). Maximum (26.84 hm³) 283 and minimum (2.45 hm³) monthly water yields were recorded in December 2015 and June 284 285 2014 respectively. Prior to the reconnection, monthly suspended sediment load (SSL) tended to follow the same pattern as water yield, with greater volumes of water leading to higher 286 sediment loads. In the month that the reconnection took place (October 2014), SSL was the 287 highest recorded during the study period (65.4 t); notably, this high value followed on the back 288 of the lowest SSL value recorded (September 2014, 1.81 t). Patterns of monthly SSL in 2015-289 2016 were more difficult to explain solely by water yield. For instance, floods in November 290 and December triggered monthly SSLs similar to October 2014, but water yields were 291 appreciably higher (around 25 hm³ in November and December 2015 compared to only 13 hm³ 292 293 in October 2014). Additionally, similar amounts of sediment were transported in January 2014 294 and August 2016, although water yields were different between these months.

295 *Figure 6.*

Annual water yield was generally similar for the first three years of the study (ranging between 296 93 and 105 hm³), but increased markedly in the final year (132 hm³; Figure 7A). Overall, these 297 values sit slightly above the long-term average of 85.4 hm³ (1974-2016 data). Sediment yield 298 was similar for the two pre-reconnection years (153.1 and 149.6 t, Figure 7A) but post-299 reconnection values increased by 65% on average (i.e. 250.9 and 251.2 t, Figure 7B), 300 highlighting the role of Ben Gill in supplying sediment. Post-reconnection, water yields were 301 also slightly higher (7% in 2014-2015, and 36% in 2015-2016), reflecting the higher 302 precipitation values (+4% and +26% respectively). 303

304 *Figure 7.*

4.4. Links between fine sediment dynamics and flow regime

306 The cumulative frequency curves (Figure 8) provide an insight in the transport duration of both water and sediment yields. Despite sitting on either side of the reconnection, transport durations 307 308 of the water yield for the years 2012-2013 and 2014-2015 were similar, as were the years 2013-309 2014 and 2015-2016. Overall, 50% of the water yield was transported within 20% (2012-2013 310 and 2014-2015) to 25% (2013-2014 and 2015-2016) of the time. The similarity suggests that the reconnection of Ben Gill did not create a shift in time concentration patterns for water 311 312 yields. However, time-concentration for the sediment loads clearly shifted after the reconnection, with a higher proportion of sediment transported in a much shorter amount of 313 time in the post-reconnection period. For instance, 1% of the time concentrated 17 to 23% more 314 of the sediment yield after the reconnection. This was true for both of the post-reconnection 315 years, regardless of differences in their hydrology and the magnitude of the sediment yield. The 316 higher proportion of sediment now being transported in a shorter amount of time reflects the 317 increased importance of intense but short-lived SSC events (Figure 3B). 318

319 *Figure 8.*

320 5. DISCUSSION

321 **5.1. Context**

322 Non-perennial water courses compose a substantial proportion of the total length, number and 323 discharge of the world's streams and rivers (Datry et al., 2014). They are diverse (hydraulically, geomorphologically and ecologically) and widespread, being found in most 324 325 terrestrial biomes (Larned et al., 2010). Temperate regions support many non-perennial streams which, just like their dryland counterparts, are experiencing altered hydrological regimes 326 327 related to global change (Stanley et al., 1997). Studies designed to understand their importance for sediment supply are crucial to assess the likely impacts of future changes in climate, land 328 329 cover or water use on river integrity. Ben Gill is an example of a non-perennial stream in a 330 temperate region; it is notable in being ephemeral despite being located in the wettest region (the NW) of England. 331

Though not grossly different, there were a number of differences in the flow regimes of the study years, with corresponding differences in water yield. Most of the variability related to the major floods of winter 2015; these resulted in higher water yields but had no impact on the time concentration of transport (Figure 8). Moreover, the higher water yield in 2015-2016 was found to be a simple response to increase in precipitation (+26% compared to pre-reconnection period) rather than any potential effect of the reconnection. Although we did not measure turbidity or SSC within Ben Gill itself, no changes other than the reconnection occurred in the upper part of the catchment over the study period; thus, we attribute this major change in fine sediment yield to a small (0.55 km^2), headwater tributary which only flows for approximately ¹/₄ of the time.

5.2. Sedimentary effects of the reconnection in the Ehen

343 Temporal variation in fine sediment transport

Ben Gill has experienced much erosion since it was reconnected, and this has resulted in the delivery of both fine and coarse sediment to the Ehen. Marteau *et al.* (2016) estimated that a minimum of 150 m³ of sediment was delivered to the Ehen in the first six months after the reconnection. Data presented in the current paper indicate that large volumes of fine material are also now being delivered as a result of the reconnection.

The very high SSC recorded on the day following the reconnection coincided with an unusually 349 high local rainfall event. This coincidence of timing was unfortunate from a management 350 perspective, given the sensitivity of aquatic organisms to fine sediment. Despite efforts by the 351 engineering company to remove fine particles from the newly created channel immediately 352 prior to the day of the reconnection, it is possible that a small part of the plume of sediment was 353 linked to the flushing of fine material remaining on the bed surface. Over 35.7 t of fine entered 354 the Ehen from Ben Gill over 48h, representing 55% of the month's sediment yield and 355 approximately 14% of the annual yield. We conclude that, given the scale of the rainfall event 356 357 and the magnitude of the erosion it generated, most of the plume originated from the erosion of subsurface fine material. 358

Maximum SSC values in the Ehen have increased post-reconnection, but this is not the case for 359 minimum and mean values, and the quartiles. This difference indicates that fluvial dynamics in 360 the Ehen at base-flow remain largely unaffected by the reconnection. Moreover, the time 361 concentration of suspended sediment yield has changed since the reconnection, with a higher 362 proportion of the sediment yield now being transported through the channel in a shorter period 363 of time. This supports the conclusion that the influence of Ben Gill on annual fine sediment 364 yields comes through large volumes of material being transported during short-lived events, 365 when Ben Gill is flowing. 366

367 Contribution of Ben Gill to the River Ehen fine sediment yield

- Suspended sediment loads in the Ehen following the reconnection increased by 65% on average. This major change is evident despite the fact that Ben Gill increased catchment size at the confluence by only 1.2%. The increased load equates to an increase in specific sediment yield from 3.39 t km² year⁻¹ pre-reconnection to 5.56 t km² year⁻¹ post-reconnection. If we consider the average increase of 100 t y⁻¹ to be eroded from Ben Gill catchment, then the specific yield from this tributary can be estimated at around 181 t km⁻² year⁻¹.
- Specific yields for the Ehen catchment are rather low when compared to other catchments, 374 while those for Ben Gill are closer to the higher values reported in the literature. For example, 375 Worrall *et al.* (2013) reported a long-term average sediment flux of 22.2 t km⁻² y⁻¹ for the UK 376 (5th percentile and 95th percentile of 5.4 and 107.7 t km⁻² year⁻¹ respectively). Foster and Lees 377 (1999) reported long-term sediment yields of 7 to 86 t km⁻² year⁻¹ from their own research in 378 the North of England, set against published values for the region ranging from 0.8 to 488 t km⁻² 379 year⁻¹ (see references therein). They argue that the higher values can be attributed to human 380 alterations to catchments, including agriculture and heather burning (Foster and Lees, 1999). 381 The estimated specific sediment yield of over 180 t km⁻² year⁻¹ for Ben Gill falls close to the 382 range of yields recorded in ephemeral Mediterranean basins (50 to 200 t km⁻² year⁻¹, Walling 383 and Webb, 1996; Rovira and Batalla, 2006). This highlights the potential for small ephemeral 384 tributaries to deliver large volumes of sediment regardless of their size and hydrology. 385

386 *Links between fine sediment dynamics and flow regime*

In general, flows in the Ehen and Ben Gill are rather synchronous (Quinlan et al., 2015a). 387 However, they are occasionally out of phase and maximum SSCs in the Ehen occur during the 388 rare times when Ben Gill is flowing but flows in the Ehen are not elevated much beyond base-389 flow. When sediment delivered from Ben Gill coincides with high Q in the Ehen, it is diluted 390 and quickly conveyed downstream; exhaustion occurs once Ben Gill again ceases to flow, 391 which is typically rather soon. Thus, hydraulically speaking the Ehen could carry more 392 sediment, but remains limited by the supply during floods; i.e. it will transport sediment as long 393 as material is available. This and the ongoing adjustment in sediment dynamics after the 394 395 reconnection are reflected in the Q-SSC relation observed in the Ehen, which contains much scatter; less than 0.01% of the variation in SSC can be explained by variation in Q (Figure 5). 396 397 Fluvial dynamics at low flows are largely controlled by the timing of sediment supply from Ben Gill, with potentially very high SSC events occurring (blue square, Figure 5B). Material 398 399 from previous high SSC events temporarily stored in the bed of the Ehen becomes available for 400 transport on the rising limb of hydrographs, but is quickly exhausted. The scatter shows the

401 variability in the amount of sediment available in the channel (red square), which remains very 402 limited. Subsequent higher Q have no influence on SSCs, because all the material has already 403 been exhausted, or inputs from Ben Gill are diluted by the large volumes of water (green 404 square, Figure 5B). Thus, the influence that the reconnection is having on the Q-SSC 405 relationship in the Ehen remains limited to low-intermediate discharges. This indicates that 406 despite its small contributing area, Ben Gill is affecting the basic hydraulic-sediment transport 407 relations in the Ehen for a certain range of Qs.

408 **5.3. Implications**

409 *Potential ecological consequences for the River Ehen*

410 The reconnection of Ben Gill forms part of catchment-wide initiative in the Ehen focused on conservation of freshwater mussels. The reconnection aimed to help re-naturalise the 411 hydrological regime of the Ehen and supply the coarser sediment which is an important part of 412 413 the habitat required by mussels. New coarse sediment is now delivered to the Ehen (Marteau et al., 2016), so one of the objectives of the reconnection is already being achieved. However, it is 414 415 also clear that Ben Gill is now delivering much fine sediment; indeed, data indicate that it has 416 become the main driver of suspended sediment dynamics in the section of the Ehen 417 immediately downstream from the confluence. This has potential implications for biota, not just 418 because of the absolute volumes involved but because temporal mismatch between sediment released from Ben Gill and high flows in the Ehen can lead to high SSC events at relatively low 419 discharges, facilitating in-channel sedimentation. The effects of this sedimentation on biota can 420 be direct (abrasion, clogging of gills) and indirect (deposition and subsequent consequences for 421 benthic habitat), causing, for instance, changes in macroinvertebrate drift patterns (Béjar et al., 422 423 2017), and reduced survival of salmonid embryos (Sear et al., 2016) and freshwater pearl 424 mussels (reviewed by Quinlan et al., 2015b).

425 Effects of the reconnection on fine sediment in the Ehen are not limited to changes in 426 concentration and load. The empirical calibration produced for the post-reconnection period yielded a regression coefficient which was significantly different to that for the pre-427 reconnection period (Figure 2). This shift in the NTU-SSC relationship can be interpreted as a 428 change in the quality of suspended sediment; material found in suspension now differs in 429 composition (particle size, shape, colour, organic content etc.) compared to before the 430 reconnection. This change may be critical ecologically (see for example Sear et al. (2016) in 431 relation to fish, and Österling *et al.* (2010) in relation to pearl mussels). Thus, understanding 432 433 how this new source of fine sediment is affecting in-channel fine sediment patterns, both

quantitatively and qualitatively, as well as its effects on biota, will be key for assessing theoverall effects of the reconnection.

436 *Wider repercussions*

Climate models suggest that the number of non-perennial streams will increase globally in the 437 near future, particularly in regions where water appropriation is occurring (Larned et al., 2010). 438 While arid and semi-arid regions will see patterns of intermittency shift towards a reduction in 439 the number of days of flow (e.g. Garcia et al., 2016), temperate regions are predicted to 440 experience increased seasonality in flows, with increased high flow magnitudes and reduced 441 442 low flows (van Vliet et al., 2013). In some areas, the latter may result in small perennial streams becoming intermittent or even ephemeral. The significant influence of Ben Gill on 443 sediment dynamics in the Ehen helps stress the functional implications of tributaries becoming 444 445 disconnected from their main-stems due to changes in flow.

446 Globally, the erosion and fluxes of fine sediment have been altered dramatically by human 447 activities. Land clearance, mining and agriculture are important causes of larger volumes of soil 448 and fine sediment now being washed into river networks (Trimble and Crosson, 2000; Walling, 449 2006), while dams trap a substantial fraction of fine material and so reduce loads (e.g. 60%, 450 Yellow River, Walling, 2006; around 90%, River Ebro, Vericat and Batalla, 2006). Our study 451 of the Ehen indicates that the disconnection of headwater tributaries may have a major influence on fine sediment fluxes (e.g. Zhang et al., 2015). However, it also shows that 452 reconnection of such tributaries can help restore hydro-sedimentary dynamics, and that the 453 reconnection of even small watercourses can play an important role in river rehabilitation 454 455 efforts.

456 6. FINAL REMARKS

457 The Ehen system is regulated and, as a whole, remains supply limited (as per Quinlan et al., 2015a) and highly dependent on sediment delivered from Ben Gill. Our results indicate that the 458 transport of fine sediment in the Ehen is not hydraulically driven (i.e. not controlled solely by 459 increases in discharge) but relies greatly on the ephemeral characteristics of Ben Gill. Despite 460 461 its limited influence on the hydrology of the Ehen, Ben Gill's impacts include quantitative and qualitative aspects of the fine sediment flux, as well as the temporal dynamics of this flux. The 462 work shows that small ephemeral headwater tributaries can play a crucial role in driving main-463 stem sediment dynamics, even in temperate regions, and may be particularly important in 464 catchments where main-stem rivers are regulated. Appreciation of this role is important, given 465

466 climate change and related water scarcity, and the likely societal pressures for flow regulation467 to provide water for human needs.

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478 8. CONFLICT OF INTEREST

479 The authors declare no conflict of interest.

480 9. **REFERENCE LIST**

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607 FIGURES

Figure 1: Details of the study area and site: (A) Location of the study area within the UK. (B)
The Ehen catchment, including the Ben Gill and upper Ehen sub-catchments. (C) A detailed
map of the study area showing key features discussed in the text. The red dot shows location of
the turbidity meter.



Figure 2: Calibration information for the turbidity probe, showing NTU-SSC relationships pre-(black dots) and post-reconnection (white dots) based on empirical calibration (see text for further details). Note that the starred value was found to have a high leverage on the prereconnection regression curve (Cook's distance > 1) and so was not used for the line fitting.



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Figure 3: (A) Discharge of the River Ehen and local daily rainfall. (B) Suspended sediment
concentration in the River Ehen. Discharge and suspended sediment concentration measured at
Bleach Green at 15-min intervals. Rainfall was recorded at Ennerdale Bridge. Black arrow
shows the day of Ben Gill reconnection.



- 624 Figure 4: Flow duration curves of the study years expressed as the percentage of time a given
- discharge is equalled or exceeded. Data are for Bleach Green gauging station, measured at 15min intervals. The inset table summarises key hydrological statistics for each year.



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Figure 5: Relationship between discharge and suspended sediment concentration in the River
Ehen, for the pre- reconnection (A) and post-reconnection (B) periods. Coloured rectangles in
(B) highlight parts of the graph that are further described in the text. Data were recorded at
Bleach Green at 15-min interval.





634 Figure 6: Monthly water and sediment yield for the study period.

Figure 7: (A) Water and sediment yield for each of the hydrological years of the study period.
(B) Change in water and suspended sediment yield following the reconnection. Changes are
assessed in respective years relative to the pre-reconnection period.



Figure 8: Cumulative frequency curves of water and suspended sediment yield for each of thehydrological years. Years 2012-2013 and 2013-2014 represent pre-reconnection data, while

years 2014-2015 and 2015-2016 represent post-reconnection data. Inset tables summarise some
statistics for each of the years (i.e. key percentiles of water and sediment yield (WY and SY
respectively) transported for a given proportion of time).



648 TABLES

649 Table 1: Statistics of suspended sediment concentration computed from 15-min data (Bleach

650 Green gauging station) for the River Ehen. Note that 1^{st} and 3^{rd} Qt. indicate the first and the

651 third quartile of the SSC data set.

Suspended Sediment Concentration $(mg l^{-1})$								
Year	Min.	1st Qt.	Median	Mean	3rd Qt.	Max.		
2012-2013	0.206	0.883	1.029	1.86	1.44	190		
2013-2014	0.206	0.617	0.823	1.08	1.23	33.9		
2014-2015	0.166	0.498	0.664	2.00	1.16	1702		
2015-2016	0.166	0.498	0.664	1.37	1.00	357		