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

3

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25 **Abstract**

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

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

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

77 Interest in tributaries and their confluences has increased since the 1980s, with work focusing  
78 on 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).  
80 Most emphasis has been on the role of relatively large, perennial tributaries in supplying coarse  
81 material to main-stem reaches (Benda *et al.*, 2004; Ferguson *et al.*, 2006), with a particular  
82 focus on downstream fining and the effects of tributary inputs on the fluvial equilibrium of the  
83 receiving river (Pizzuto, 1995; Rice, 1998). Less work has been conducted on fine sediment  
84 delivery from small, low-order tributaries, although exceptions include studies on the Colorado  
85 River, USA (Webb *et al.*, 2000; Griffiths and Topping, 2015) and the River Isábena, Spain  
86 (Francke *et al.*, 2014).

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

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

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

## 118 **2. STUDY AREA**

119 The River Ehen flows south-westwards and discharges to the Irish Sea (Figure 1A & B). It has  
120 a total catchment area of 155.8 km<sup>2</sup>. The hydrological regime of the Ehen is regulated by  
121 Ennerdale Water, although because of the water abstractions and the design and management of  
122 the weir, impacts are limited mainly to modification of low flow percentiles. The lake is an  
123 important drinking water supply for West Cumbria. It is a natural water body (occupying a  
124 formally glaciated valley), although its storage capacity was increased by the construction of a  
125 1.3 m high weir (in 1902) and the diversion of Ben Gill (in the 1970s, Figure 1C). Ben Gill is a  
126 first order ephemeral headwater tributary, with a small (0.55 km<sup>2</sup>), steep (mean catchment  
127 slope: 25%) mountainous and responsive catchment. It is considered to be ephemeral (as  
128 opposed to intermittent) as it flows for less time than it is dry, and usually in response to  
129 rainfall (Uys and O’Keeffe, 1997). When flow recedes, Ben Gill is left dry along most of its  
130 length. Although it is not gauged, previous estimates suggest that it flows for approximately ¼  
131 of the time (Quinlan *et al.*, 2015a).

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

146 Discharge (hereafter  $Q$ ) in the River Ehen is gauged at Bleach Green (Figure 1C). The  
147 catchment area here is 44.5 km<sup>2</sup>. Although this is only 28% of the total catchment of the River  
148 Ehen, this upper area contributes 45% of the catchment's 1800 mm long term mean annual  
149 rainfall (Alvarez-Codesal and Sweeting, 2015). The river at Bleach Green has a long term mean  
150 daily  $Q$  of 2.70 m<sup>3</sup> s<sup>-1</sup> (1973-2016 data) with minimum and maximum daily  $Q$  of 0.124 and  
151 80.2 m<sup>3</sup> s<sup>-1</sup> respectively. The compensation flow released from the weir (via a fish-pass) has  
152 varied over time; it was 0.37 m<sup>3</sup> s<sup>-1</sup> until 2012 but is currently 0.92 m<sup>3</sup> s<sup>-1</sup>, sometimes phased  
153 down to 0.69 m<sup>3</sup> s<sup>-1</sup> depending on lake level.

154 Ennerdale Water acts as a sediment trap, with limited sediment transfer to the section  
155 immediately downstream (Quinlan *et al.*, 2015a). Further downstream, the river meanders  
156 through argillaceous rocks of the Skiddaw group and sandstones (Brown *et al.*, 2008). Here,  
157 important sediment contributions come from bank erosion, tributary inputs and diffuse  
158 agricultural runoff.

159 The Ehen was designated as a Special Area of Conservation (SAC) in 1995 as it supports an  
160 estimated 550,000 freshwater pearl mussels *Margaritifera margaritifera*, L. (Killeen and  
161 Moorkens, 2013), the largest remaining population in England. As part of work to help  
162 conserve this important population, Ben Gill was reconnected to the Ehen in October 2014, in  
163 an attempt to reactivate the delivery of coarse sediment. The diversion culvert was disabled and  
164 a new 300 m long section of channel was engineered over the alluvial fan, following the  
165 approximate course of the original stream. The bed of the new section was lined with cobble-  
166 size material, with some larger (boulder-size) clasts along the banks (see Marteau *et al.*, 2016  
167 for more details). In an attempt to limit the first flush delivery of fine sediment to the main-  
168 stem, the bed was thoroughly washed, section-by-section, before the most downstream point  
169 was excavated and opened to connect to the Ehen. The wash-water was stored in temporary off-  
170 channel settlement ponds; settled fine material was removed from site, with remaining wash-  
171 water pumped to the lake.

172 *Figure 1.*

### 173 3. METHODS

#### 174 3.1. Rainfall and discharge

175 The current study is focused on a 4-year period, covering the two hydrological years  
176 immediately before the reconnection of Ben Gill (i.e. October 2012 – September 2014) and the  
177 first two years after (i.e. October 2014- September 2016). Daily precipitation was recorded by

178 the Environment Agency at Ennerdale Bridge, 1.8 km downstream from the Ehen-Ben Gill  
179 confluence. The River Ehen is gauged by the Environment Agency at Bleach Green (Figure  
180 1C; see Quinlan *et al.*, (2015a) for more details). Discharge data from Bleach Green (15-min  
181 interval) were used to produce time-series for the study period. Additionally, mean daily values  
182 for the 1974-2016 period were used to compute flow percentiles and values of water yield, to  
183 set the study period within a longer-term perspective.

### 184 **3.2. Suspended sediment**

185 Turbidity (NTU) was measured in the Ehen at Bleach Green using a YSI® 6600 probe with  
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  
188 intervals over the 4-year study period. The probe was maintained by the Environment Agency,  
189 and retrieved for cleaning and calibration every 2 to 3 months. Quinlan *et al.* (2015a) generated  
190 an NTU-Suspended Sediment Concentration (SSC) calibration prior to the reconnection of Ben  
191 Gill. This calibration was produced by sequentially adding fine sediment (collected from the  
192 bed at Bleach Green) to a bucket of water to create known concentrations, with turbidity  
193 measured for each increment in sediment (further details in Quinlan *et al.*, 2015a). The present  
194 study uses the pre-reconnection data produced by these authors, except that for the calibration  
195 curve the regression was forced through the origin. This calibration is used to derive SSC  
196 values and compute sediment loads for the pre-reconnection period. Because of the very low  
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  
199 calibration was produced for the post-reconnection period, using the same procedure but  
200 covering the entire range of the probe (0-1000 NTU) to capture the greater turbidity values  
201 recorded post-reconnection; this was used to estimate SSC and loads for this period. The  
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).

205 The slope of the NTU-SSC relationship prior to the reconnection was 2.06 (regression  $r^2 =$   
206  $0.99$ ,  $P < 0.001$ ; Figure 2) while that for the post-reconnection period was 1.66 ( $r^2 = 0.99$ ,  $P <$   
207  $0.001$ ). These slope values are significantly different (Ancova,  $df = 81$ ,  $F = 229.19$ ,  $P < 0.001$ ).

208 Organic content of fine sediment remained low (below 10% on average), with no apparent  
209 seasonal or annual variations. The highest values of organic content were measured at very low  
210 SSC, and could not be differentiated from uncertainties associated with the probe accuracy and



211 laboratory processing procedures. Thus, no attempt was made to correct SSC values for organic  
212 content.

213 Suspended sediment load (SSL) and water yield were computed from 15-min data. SSL was  
214 calculated by multiplying SSC by  $Q$  for 15-min time steps. Values were then summed to  
215 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  
221 precipitation values were 1799 mm in 2012-2013, 1901 mm in 2013-2014, 1921 mm in 2014-  
222 2015 and 2329 mm in 2015-2016. Most events were less than 20 mm per day, with a total of 9  
223 events exceeding 50 mm (Figure 3A). An exceptional rainfall event, the highest recorded  
224 during the 4 years, occurred on the first day of the reconnection: in total, 104 mm fell within  
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  
230 and regularly experiences high flows (Figure 3A). Its flow regime follows typical patterns for  
231 the NW of England, with lower flows in late spring and summer and higher flows in the winter,  
232 but with some high events also occurring in late summer. The median discharge ( $Q_{50}$ , the  
233 discharge exceeded for 50% of the time) for the study period was  $1.98 \text{ m}^3 \text{ s}^{-1}$ , which is greater  
234 than the long-term median value (1974-2016 =  $1.38 \text{ m}^3 \text{ s}^{-1}$ ). Minimum mean daily  $Q$  was  $0.71$   
235  $\text{m}^3 \text{ s}^{-1}$  (30/07/2013) while minimum instantaneous  $Q$  was  $0.31 \text{ m}^3 \text{ s}^{-1}$  (11/02/2015). Maximum  
236 mean daily  $Q$  was  $44.5 \text{ m}^3 \text{ s}^{-1}$  (15/11/2015,  $Q_{0.02}$ ), with the instantaneous maximum value being  
237  $54.0 \text{ m}^3 \text{ s}^{-1}$ . This maximum has only been exceeded twice over the 42-year period of record  
238 (CEH, National Flow Archive website, AMAX dataset).

239 *Figure 3.*

240 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  $Q$ s. Low flows were

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

250 *Figure 4.*

#### 251 **4.2. Variations in suspended sediment transport**

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

265 The relationship between  $Q$  and SSC has been affected by the reconnection, as indicated by the  
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).  
268 The difference post-reconnection is most evident at low and medium discharges (Figure 5B).  
269 While patterns remain unchanged at high flows (green square, Figure 5B), the scatter in the  
270 relationship is considerably greater below  $20 \text{ m}^3 \text{ s}^{-1}$ ; this is particularly visible for flows below  
271  $5 \text{ m}^3 \text{ s}^{-1}$  (blue square, Figure 5B). Overall, Figure 5 illustrates how the magnitude of SSCs  
272 increased following the reconnection, and how the reconnection has altered the basic hydraulic  
273 and sedimentary dynamics of the Ehen.

274 *Figure 5.*

275 Despite the increased frequency and magnitude of high SSC events following the reconnection,  
276 it is notable that there is no marked difference in the respective mean and median values (Table  
277 1). Note also that maximum SSCs in 2015-2016 coincided with very high flows ( $Q_{0.02}$ ) which  
278 lead to appreciable volumes of sediment being transported through the channel (between 57  
279 and 60 t per month, in November and December 2015; Figure 6).

280 *Table 1.*

### 281 **4.3. Contribution of the tributary to main-stem sediment loads**

282 Water yield followed a similar pattern each year (Figure 6), with low values in early summer  
283 (June) and high values in early to mid-winter (November to January). Maximum ( $26.84 \text{ hm}^3$ )  
284 and minimum ( $2.45 \text{ hm}^3$ ) monthly water yields were recorded in December 2015 and June  
285 2014 respectively. Prior to the reconnection, monthly suspended sediment load (SSL) tended to  
286 follow the same pattern as water yield, with greater volumes of water leading to higher  
287 sediment loads. In the month that the reconnection took place (October 2014), SSL was the  
288 highest recorded during the study period (65.4 t); notably, this high value followed on the back  
289 of the lowest SSL value recorded (September 2014, 1.81 t). Patterns of monthly SSL in 2015-  
290 2016 were more difficult to explain solely by water yield. For instance, floods in November  
291 and December triggered monthly SSLs similar to October 2014, but water yields were  
292 appreciably higher (around  $25 \text{ hm}^3$  in November and December 2015 compared to only  $13 \text{ hm}^3$   
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.*

296 Annual water yield was generally similar for the first three years of the study (ranging between  
297  $93$  and  $105 \text{ hm}^3$ ), but increased markedly in the final year ( $132 \text{ hm}^3$ ; Figure 7A). Overall, these  
298 values sit slightly above the long-term average of  $85.4 \text{ hm}^3$  (1974-2016 data). Sediment yield  
299 was similar for the two pre-reconnection years (153.1 and 149.6 t, Figure 7A) but post-  
300 reconnection values increased by 65% on average (i.e. 250.9 and 251.2 t, Figure 7B),  
301 highlighting the role of Ben Gill in supplying sediment. Post-reconnection, water yields were  
302 also slightly higher (7% in 2014-2015, and 36% in 2015-2016), reflecting the higher  
303 precipitation values (+4% and +26% respectively).

304 *Figure 7.*

#### 305 **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  
307 water and sediment yields. Despite sitting on either side of the reconnection, transport durations  
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  
311 the reconnection of Ben Gill did not create a shift in time concentration patterns for water  
312 yields. However, time-concentration for the sediment loads clearly shifted after the  
313 reconnection, with a higher proportion of sediment transported in a much shorter amount of  
314 time in the post-reconnection period. For instance, 1% of the time concentrated 17 to 23% more  
315 of the sediment yield after the reconnection. This was true for both of the post-reconnection  
316 years, regardless of differences in their hydrology and the magnitude of the sediment yield. The  
317 higher proportion of sediment now being transported in a shorter amount of time reflects the  
318 increased importance of intense but short-lived SSC events (Figure 3B).

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  
324 (hydraulically, geomorphologically and ecologically) and widespread, being found in most  
325 terrestrial biomes (Larned *et al.*, 2010). Temperate regions support many non-perennial streams  
326 which, just like their dryland counterparts, are experiencing altered hydrological regimes  
327 related to global change (Stanley *et al.*, 1997). Studies designed to understand their importance  
328 for sediment supply are crucial to assess the likely impacts of future changes in climate, land  
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  
331 (the NW) of England.

332 Though not grossly different, there were a number of differences in the flow regimes of the  
333 study years, with corresponding differences in water yield. Most of the variability related to the  
334 major floods of winter 2015; these resulted in higher water yields but had no impact on the time  
335 concentration of transport (Figure 8). Moreover, the higher water yield in 2015-2016 was found  
336 to be a simple response to increase in precipitation (+26% compared to pre-reconnection

337 period) rather than any potential effect of the reconnection. Although we did not measure  
338 turbidity or SSC within Ben Gill itself, no changes other than the reconnection occurred in the  
339 upper part of the catchment over the study period; thus, we attribute this major change in fine  
340 sediment yield to a small (0.55 km<sup>2</sup>), headwater tributary which only flows for approximately  
341 ¼ of the time.

## 342 **5.2. Sedimentary effects of the reconnection in the Ehen**

### 343 *Temporal variation in fine sediment transport*

344 Ben Gill has experienced much erosion since it was reconnected, and this has resulted in the  
345 delivery of both fine and coarse sediment to the Ehen. Marteau *et al.* (2016) estimated that a  
346 minimum of 150 m<sup>3</sup> of sediment was delivered to the Ehen in the first six months after the  
347 reconnection. Data presented in the current paper indicate that large volumes of fine material  
348 are also now being delivered as a result of the reconnection.

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

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

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

368 Suspended sediment loads in the Ehen following the reconnection increased by 65% on  
369 average. This major change is evident despite the fact that Ben Gill increased catchment size at  
370 the confluence by only 1.2%. The increased load equates to an increase in specific sediment  
371 yield from  $3.39 \text{ t km}^2 \text{ year}^{-1}$  pre-reconnection to  $5.56 \text{ t km}^2 \text{ year}^{-1}$  post-reconnection. If we  
372 consider the average increase of  $100 \text{ t y}^{-1}$  to be eroded from Ben Gill catchment, then the  
373 specific yield from this tributary can be estimated at around  $181 \text{ t km}^{-2} \text{ year}^{-1}$ .

374 Specific yields for the Ehen catchment are rather low when compared to other catchments,  
375 while those for Ben Gill are closer to the higher values reported in the literature. For example,  
376 Worrall *et al.* (2013) reported a long-term average sediment flux of  $22.2 \text{ t km}^{-2} \text{ y}^{-1}$  for the UK  
377 (5<sup>th</sup> percentile and 95<sup>th</sup> percentile of  $5.4$  and  $107.7 \text{ t km}^{-2} \text{ year}^{-1}$  respectively). Foster and Lees  
378 (1999) reported long-term sediment yields of  $7$  to  $86 \text{ t km}^{-2} \text{ year}^{-1}$  from their own research in  
379 the North of England, set against published values for the region ranging from  $0.8$  to  $488 \text{ t km}^{-2}$   
380  $\text{year}^{-1}$  (see references therein). They argue that the higher values can be attributed to human  
381 alterations to catchments, including agriculture and heather burning (Foster and Lees, 1999).  
382 The estimated specific sediment yield of over  $180 \text{ t km}^{-2} \text{ year}^{-1}$  for Ben Gill falls close to the  
383 range of yields recorded in ephemeral Mediterranean basins ( $50$  to  $200 \text{ t km}^{-2} \text{ year}^{-1}$ , Walling  
384 and Webb, 1996; Rovira and Batalla, 2006). This highlights the potential for small ephemeral  
385 tributaries to deliver large volumes of sediment regardless of their size and hydrology.

#### 386 *Links between fine sediment dynamics and flow regime*

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

### 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  
411 conservation of freshwater mussels. The reconnection aimed to help re-naturalise the  
412 hydrological regime of the Ehen and supply the coarser sediment which is an important part of  
413 the habitat required by mussels. New coarse sediment is now delivered to the Ehen (Marteau *et*  
414 *al.*, 2016), so one of the objectives of the reconnection is already being achieved. However, it is  
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  
419 released from Ben Gill and high flows in the Ehen can lead to high SSC events at relatively low  
420 discharges, facilitating in-channel sedimentation. The effects of this sedimentation on biota can  
421 be direct (abrasion, clogging of gills) and indirect (deposition and subsequent consequences for  
422 benthic habitat), causing, for instance, changes in macroinvertebrate drift patterns (Béjar *et al.*,  
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  
427 yielded a regression coefficient which was significantly different to that for the pre-  
428 reconnection period (Figure 2). This shift in the NTU-SSC relationship can be interpreted as a  
429 change in the quality of suspended sediment; material found in suspension now differs in  
430 composition (particle size, shape, colour, organic content etc.) compared to before the  
431 reconnection. This change may be critical ecologically (see for example Sear *et al.* (2016) in  
432 relation to fish, and Österling *et al.* (2010) in relation to pearl mussels). Thus, understanding  
433 how this new source of fine sediment is affecting in-channel fine sediment patterns, both

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

#### 436 *Wider repercussions*

437 Climate models suggest that the number of non-perennial streams will increase globally in the  
438 near future, particularly in regions where water appropriation is occurring (Larned *et al.*, 2010).  
439 While arid and semi-arid regions will see patterns of intermittency shift towards a reduction in  
440 the number of days of flow (e.g. Garcia *et al.*, 2016), temperate regions are predicted to  
441 experience increased seasonality in flows, with increased high flow magnitudes and reduced  
442 low flows (van Vliet *et al.*, 2013). In some areas, the latter may result in small perennial  
443 streams becoming intermittent or even ephemeral. The significant influence of Ben Gill on  
444 sediment dynamics in the Ehen helps stress the functional implications of tributaries becoming  
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  
452 influence on fine sediment fluxes (e.g. Zhang *et al.*, 2015). However, it also shows that  
453 reconnection of such tributaries can help restore hydro-sedimentary dynamics, and that the  
454 reconnection of even small watercourses can play an important role in river rehabilitation  
455 efforts.

#### 456 **6. FINAL REMARKS**

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



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

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## 478 **8. CONFLICT OF INTEREST**

479 The authors declare no conflict of interest.

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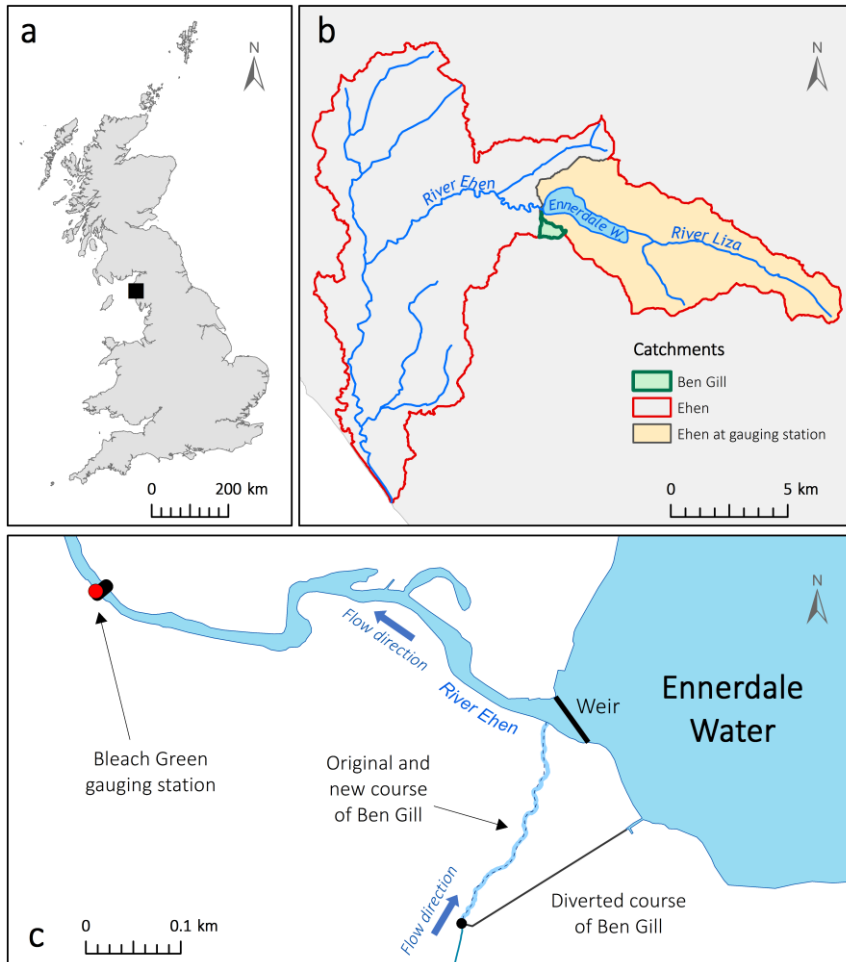
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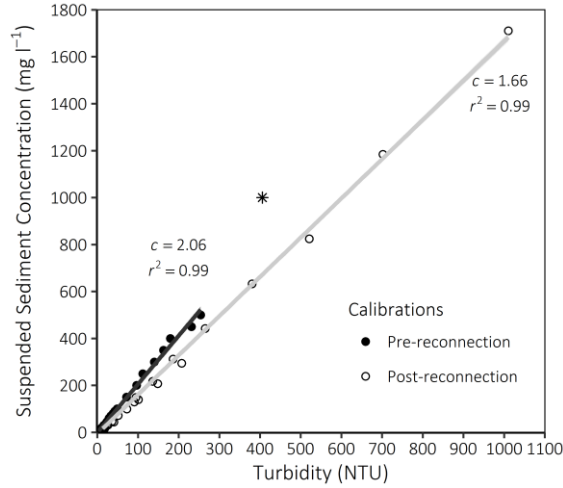
607 **FIGURES**

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



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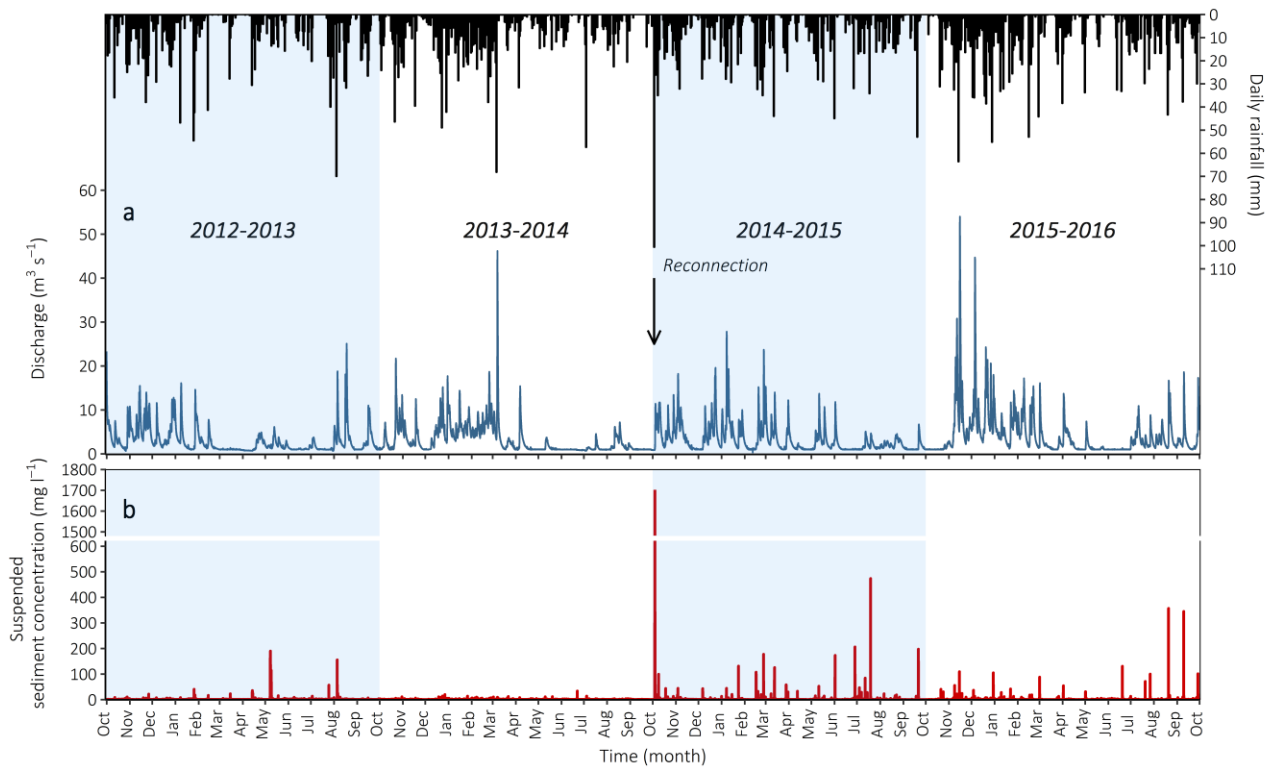
613 Figure 2: Calibration information for the turbidity probe, showing NTU-SSC relationships pre-  
 614 (black dots) and post-reconnection (white dots) based on empirical calibration (see text for  
 615 further details). Note that the starred value was found to have a high leverage on the pre-  
 616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



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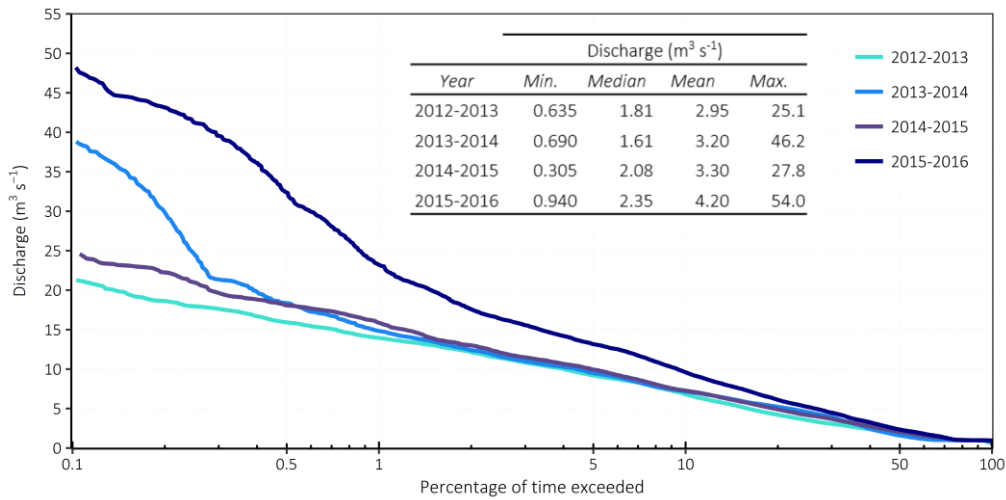
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619 Figure 3: (A) Discharge of the River Ehen and local daily rainfall. (B) Suspended sediment  
 620 concentration in the River Ehen. Discharge and suspended sediment concentration measured at  
 621 Bleach Green at 15-min intervals. Rainfall was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



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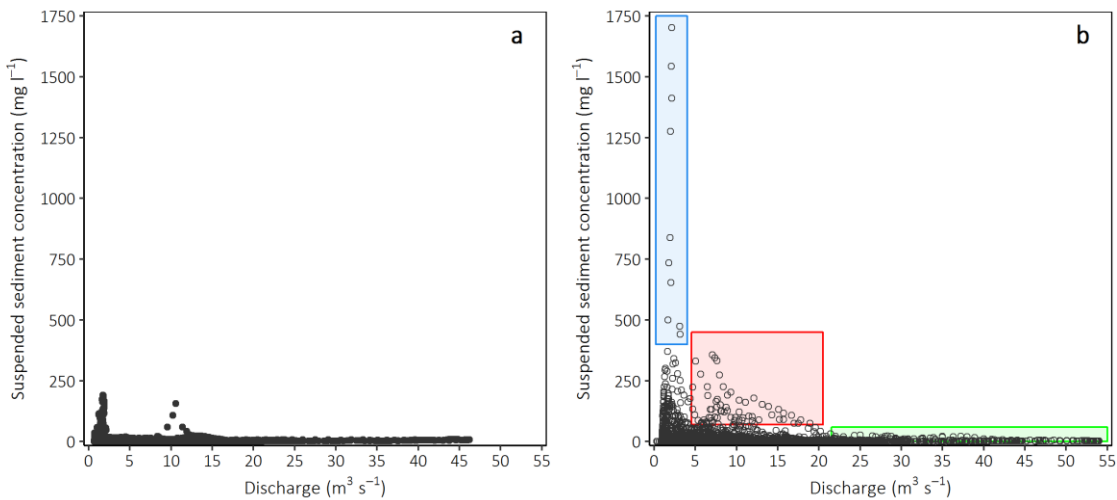
624 Figure 4: Flow duration curves of the study years expressed as the percentage of time a given  
 625 discharge is equalled or exceeded. Data are for Bleach Green gauging station, measured at 15-  
 626 min intervals. The inset table summarises key hydrological statistics for each year.



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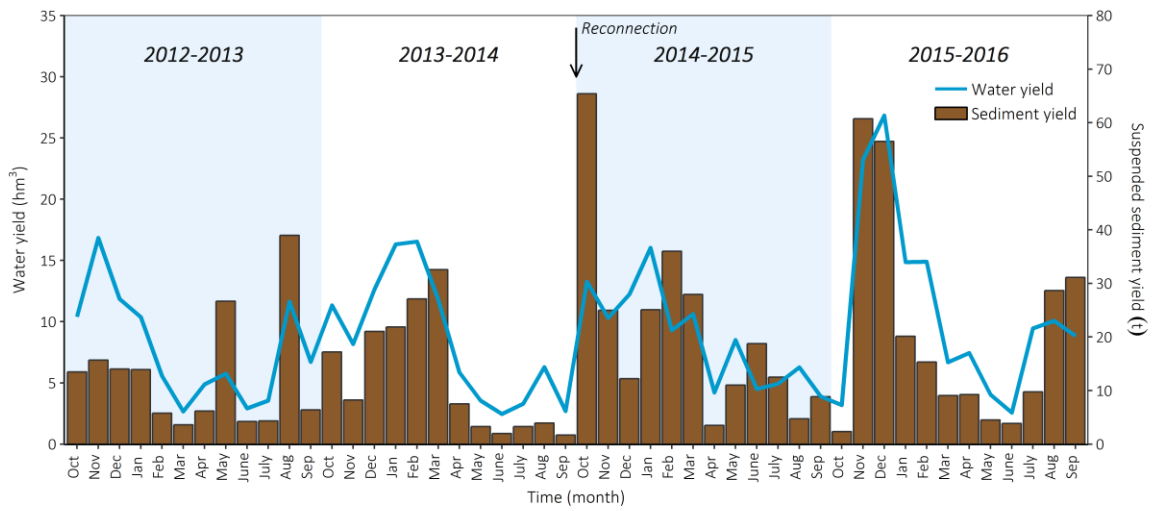
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629 Figure 5: Relationship between discharge and suspended sediment concentration in the River  
 630 Ehen, for the pre-reconnection (A) and post-reconnection (B) periods. Coloured rectangles in  
 631 (B) highlight parts of the graph that are further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



633

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



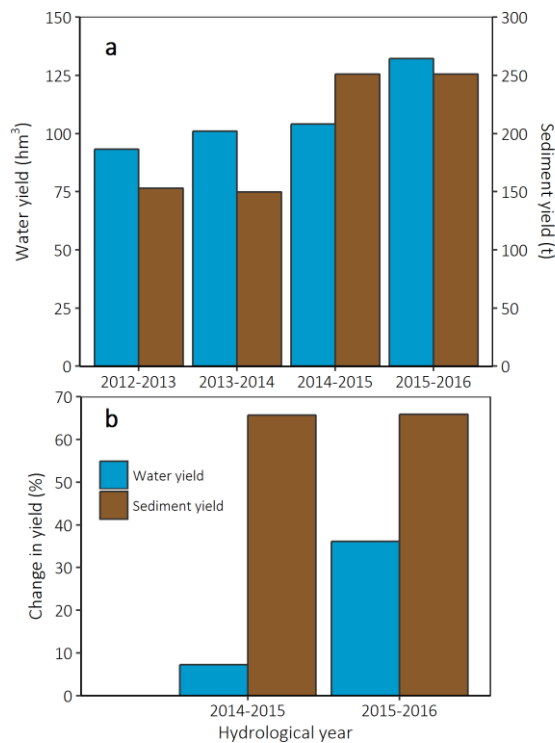
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636

637 Figure 7: (A) Water and sediment yield for each of the hydrological years of the study period.

638 (B) Change in water and suspended sediment yield following the reconnection. Changes are

639 assessed in respective years relative to the pre-reconnection period.



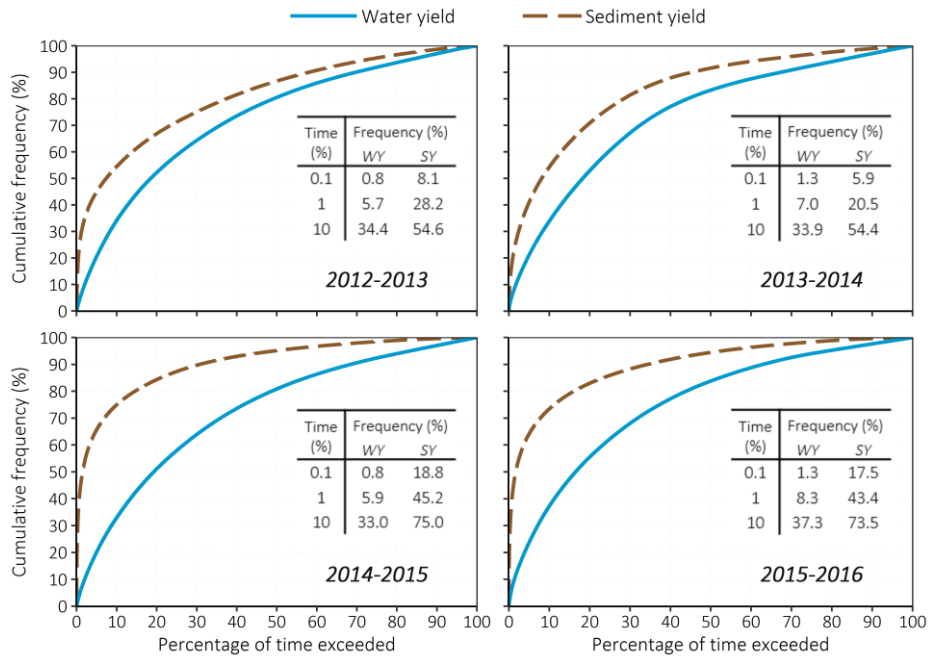
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642 Figure 8: Cumulative frequency curves of water and suspended sediment yield for each of the  
643 hydrological years. Years 2012-2013 and 2013-2014 represent pre-reconnection data, while



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



647

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<sup>st</sup> and 3<sup>rd</sup> Qt. indicate the first and the  
651 third quartile of the SSC data set.

<i>Year</i>	Suspended Sediment Concentration (mg l <sup>-1</sup> )					
	<i>Min.</i>	<i>1st Qt.</i>	<i>Median</i>	<i>Mean</i>	<i>3rd Qt.</i>	<i>Max.</i>
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

652