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RESEARCH ARTICLE

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Geomorphological response to system-scale river rehabilitation II: Main-stem channel adjustments following reconnection of an ephemeral tributary

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Abstract

This paper describes changes in bed morpho-dynamics and topography in the River Ehen, a regulated river in NW England (i.e., temperate climate) following a rehabilitation project that reconnected a formerly diverted headwater sub-catchment back to its main-stem. Sediment grain-size distributions in the Ehen changed subtly and in rather complex ways following the reconnection. Changes were most evident in the riffle morphological unit, where gravel-sized material accumulated in the first 2 years after the reconnection. All morphological units initially experienced an addition of fine sediment (size <8 mm) but by the end of the study the proportion of fine material in the bed matrix had returned to pre-reconnection levels. Topographic changes were evident in some units, with net aggradation in the riffle and scour in the plane bed; there was no detectable change in the pool. Albeit limited, there was evidence of an increase in bed mobility, with field observations indicating that the new sediment is moving over the top of the largely static existing pavement, rather than interacting with it. Despite numerous uncertainties related mainly to the ephemeral nature of the tributary and, consequently, how much sediment it would deliver, evidence suggests that the main project objective is being met: there is a renewed supply of sediment now being delivered to the main-stem Ehen at times and in quantities that are controlled by natural processes. Nevertheless, the river is still best considered to be in an adjustment phase, so assessment of its long term response to the reconnection requires continued monitoring.

KEYWORDS
bed mobility, geomorphological adjustments, grain size distribution, habitat, river Ehen, river rehabilitation

1 | INTRODUCTION

Recognition of the problems caused by the disconnection of rivers from their sediment sources has led to widespread river restoration or rehabilitation efforts that include gravel augmentation, dam removal and channel reconnection. Despite the prevalence of such efforts, river rehabilitation projects that fail to reactivate connectivity pathways have limited potential for success (see Fuller & Death, 2018 and references therein). The impacts of disconnectivity on river integrity can be observed at various spatial scales (Brierley, Fryirs, & Jain, 2006), and while they may not always be economically feasible, the greatest potential for effective river rehabilitation lies in catchment-scale initiatives (Shields, Copeland, Klingeman, Doyle, & Simon, 2003). Although this need for emphasis at the catchment scale has now been recognized for some time (Hillman & Brierley, 2005), the adaptive nature of objective-based river rehabilitation calls for a wider reporting of all types of initiatives, especially given the uncertain nature of river rehabilitation (Wheaton, Darby, & Sear, 2008).

When possible, reconnecting the affected river with its natural sediment sources appears a more desirable long-term solution than periodic artificial injections, as it allows material to be delivered at times and in quantities that are controlled by natural processes. Dam removal, for instance, recreates conditions in which both water and sediment fluxes are restored (assuming that the upstream sources remain) (Foley et al., 2017). Reconnecting previously diverted (disconnected) sub-catchments also has the potential to change sediment transport dynamics in the receiving system, as can be observed in confluence zones in natural systems (Brierley et al., 2006). Benefits of such reconnection may extend to improving other aspects of morpho-sedimentary conditions affected by the disconnection of sediment sources, such as reducing the degree of armouring (Parker, Dhamotharan, & Stefan, 1982). Thus, as the ongoing provision of material following reconnection is likely to generate long-lasting geomorphological adjustments, this approach is more sustainable than other practices. Indeed, one of the issues of river rehabilitation lies in the uncertainties of success and the potentially time-limited benefits (Brooks, Howell, Abbe, & Arthington, 2006; Wheaton et al., 2010), especially when all the causes of degradation are not removed (Hendry, Cragg-Hine, O'Grady, Sambrook, & Stephen, 2003), or when projects are designed without a long-term perspective (Alexander & Allan, 2007; Wohl, 2005). By focussing on reinstatement of processes, rehabilitation projects that involve reconnecting rivers to their sediment sources are also more consistent with the ecosystem-based approach than those that simply involve re-engineering or recreation of physical habitat.

The rehabilitation initiative in the River Ehen catchment aimed to improve habitat for the endangered freshwater pearl mussel (*M. margaritifera* L.) by reinstating fluvial processes through the reconnection of a formerly diverted tributary. From its inception, the initiative recognised that because of the lack of control over how sediment would be supplied by this tributary, the outcome would be uncertain and unpredictable. The River Ehen initiative therefore offers a unique opportunity to study and report on geomorphological adjustments in a main-stem river in response to tributary reconnection.

Initial monitoring of the Ehen (i.e., in the first 2 years post-reconnection) demonstrated how the small increase in catchment size (1.2%) stemming from the reconnection resulted in a 65% increase in main-stem suspended sediment yield (Marteau, Batalla, Vericat, & Gibbins, 2017). Other studies developed and applied methods to assess changes in the newly reconnected channel (Marteau, Vericat, Gibbins, Batalla, & Green, 2017) and the amount of material being supplied to the Ehen (Marteau, Gibbins, Vericat, & Batalla, 2020). The current paper focusses on assessing how this new situation affects main-stem morpho-dynamics. The overarching goal of the paper is to understand how this type of rehabilitation –that of reconnecting a sub-catchment– influences fluvial processes and geomorphic conditions in the main-stem Ehen. Specific objectives of the paper are: (a) to quantify adjustments to main-stem bed material dynamics (particle mobility) and sedimentary conditions (bed grain-size distributions), and (b) describe the nature and magnitude of topographic changes in the main-stem channel. Observed changes are used as a basis for discussing adjustments to geomorphic processes and the potential longer-term implications of the reconnection of the sub-catchment for riverbed mobility and channel dynamics in the Ehen. The discussion considers the lessons learnt from the tributary reconnection and their relevance for river rehabilitation projects elsewhere.

2 | STUDY AREA

2.1 | General context

The Ehen is a 24.6 km long river flowing south-westwards from Ennerdale Water (Figure 1(b)). Its entire catchment is 155.8 km^2 and comprises the River Liza (upstream from Ennerdale Water) and three major downstream tributaries (Croasdale Beck, River Keekle, and Kirk Beck). Flows in the Ehen are regulated by the (originally natural) lake and its associated weir, although the effects are primarily concentrated on high (reduced peak discharge) and very low flows (compensation flow higher than natural minimum flows). Compensation flow, which is released via a fish-pass, has varied over time (from 0.37 $\text{m}^3\ \text{s}^{-1}$ up until 2012 and currently 0.92 $\text{m}^3\ \text{s}^{-1}$). The Ehen is gauged by the Environment Agency at Bleach Green (550 m downstream from the lake outlet). Long-term (1973–2016) mean daily discharge here is 2.70 $\text{m}^3\ \text{s}^{-1}$, with minimum and maximum daily discharges of 0.124 and 80.2 $\text{m}^3\ \text{s}^{-1}$, respectively. Ennerdale Water is an important local supply of drinking water and actions were taken in the past to improve its storage capacity. These included the construction of a 1.3-m high weir (in 1902) and the diversion of Ben Gill (main headwater tributary of the Ehen) in the 1970s towards the lake. Further details of this initial diversion, along with the reconnection of Ben Gill in 2014, are given by Marteau, Vericat, et al. (2017) and Marteau, Batalla, Vericat, and Gibbins (2018).

The River Liza drains the higher parts of the catchment. However, the lake acts as a sediment trap and very little sediment from the Liza is transferred downstream (Quinlan, Gibbins, Batalla, & Vericat, 2015). This, in addition to the disruption of the natural input of water and sediment from Ben Gill (Figure 1), has resulted in the Ehen becoming increasingly stable and sediment-starved. In their preliminary study, Quinlan, Gibbins, Batalla, and Vericat (2015) and Quinlan (2014) described the riverbed of the upper Ehen as highly stable, heavily armoured, and immobile. The absence of topographic changes and marginal bed mobility, even following high flows, led Marteau, Batalla, et al. (2017) and Marteau, Vericat, et al. (2017) to describe the static coarse surface layer as pavement (sensu Sutherland, 1987).

Due to the requirements of both adult and juvenile mussels, the paved bed was considered limiting for mussel populations, especially because of its impact on recruitment (Quinlan, Gibbins, Malcolm, et al., 2015). Despite the flow regulation, the river has retained some hydrologic dynamism and flashiness and so, as per Bunte and Abt (2001), the pavement is more likely a result of sediment starvation (downstream winnowing of fines without replacement from upstream)

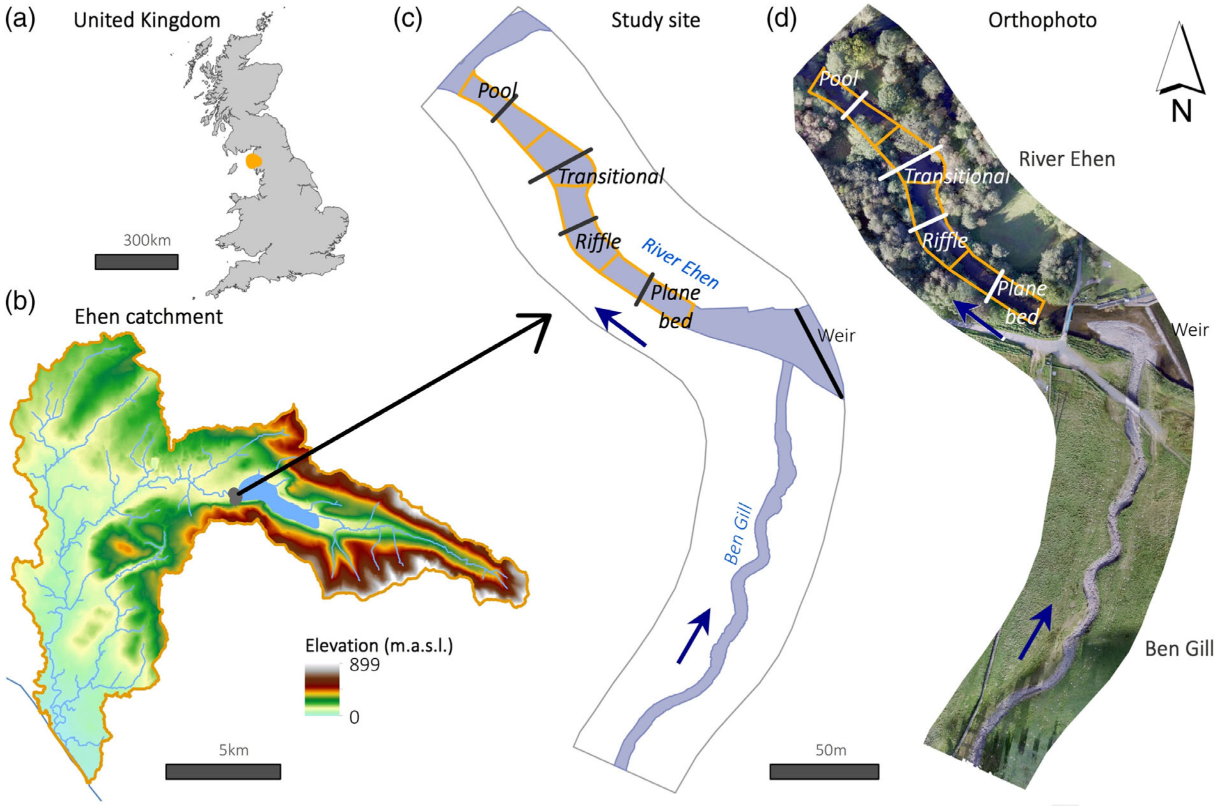


FIGURE 1 Details of the study catchment and site. (a) Location of Ehen catchment within the United Kingdom. (b) The River Ehen and its catchment. (c) Plan view and (d) orthophoto of study site. Morphological units are delimited in orange (c & d, see text). Bleach Green gauging station is located 500 m downstream from the confluence [Colour figure can be viewed at wileyonlinelibrary.com]

than a lack of competent flows. In such circumstances, restoring catchment-scale connectivity to yield a dynamic provision of sediment may help restore some habitat heterogeneity and potentially, in the long run, contribute to the (partial) breakup of the of the pavement. This provision formed the rationale for the reconnection of Ben Gill.

2.2 | Sediment inputs from Ben Gill

Analyses presented in Marteau et al. (2020) indicated that Ben Gill provided a minimum volume of 200 $m^3\ y^{-1}$ of bed material during the study period, of which only approximately 24% was readily available for transport in the Ehen. The tributary is capable of delivering a large variety of sediment clasts, but only pebbles to fine cobbles are present at the surface of the newly developed confluence bar (excluding fine sediments), and thus readily available for transport in the Ehen. According to field observations, most particles deposited in response to the reconnection are smaller than 64 mm. Changes in bed material fluxes from Ben Gill during the period September 2014 to October 2016 are fully described in Marteau et al. (2020).

3 | MATERIALS AND METHODS

This study builds on results from Quinlan (2014) and Quinlan, Gibbins, Batalla, and Vericat (2015) who reported on the state of the River Ehen prior to the reconnection. Post-reconnection bed stability and texture are compared to these earlier studies. Changes in suspended sediment transport and bed storage were also monitored and have been reported elsewhere (Marteau et al., 2018; Marteau, Batalla, et al., 2017). The volumes and characteristics of sediment delivered by Ben Gill following the reconnection are described in detail by Marteau et al. (2020). Only summary information on this source material is presented here, to provide a context for changes observed in the Ehen.

3.1 | Hydrological context

The gauging weir records discharge at 15-min intervals and these data are used to characterize the hydrological regime of the Ehen during the study period (July 2014 until October 2016; i.e., 2 months prior to and 24 months following the reconnection). Mean daily discharges for the 1974–2016 period are also used here for longer-term contextualisation of the study, including the assessment of discharge recurrence intervals.

3.2 | Flow hydraulics: Modelling and stream power data before and after reconnection

Key parameters to describe flow hydraulics were computed from 1D modelling using WinXSPro (Version 3.0, 2005, USDA Forest

Service). For each morphological unit present within the study reach, a hydraulic model was built with bed topography from the topographic surveys, along with the sediment D_{84} from the particle size surveys to determine roughness (Thorne & Zevenbergen method as provided by the model, Hardy, Panja, & Mathias, 2005). Results were validated with field observations on the day the surveys were performed and flow data from the nearby gauging station (see Figure 1). Modelling was repeated for each series of surveys in each unit. The discharge-shear stress (Q-τ) relationship was examined to compare flow hydraulics in relation to changes in topography. Since topographic differences between successive models did not prove significant (see results section), a single model per morphological unit was used for all simulations of hydraulics and bed mobility.

Model outputs were used to calculate discharge-related stream power, using Bagnold's (1966) formula:

$$\omega = \frac{\rho_w \cdot g \cdot Q \cdot S}{w} \tag{1}$$

where ω is the unit stream power (W m^{-2}), ρ_w is the density of water (kg m^{-3}), g is the gravitational acceleration (m s^{-2}), Q is discharge (m^3 s^{-1}), S is local slope (m m^{-1}) and w is the channel width at bankfull discharge (m). Once Q-ω relationships were defined, discharge data were used to compute time series of ω at 15-min intervals.

The relationship between maximum stream power recorded over a given period ($\omega_{\max}$) and the size of mobilized particles (in *b*-axis) was used to develop sediment mobility models for each morphological unit. These relations yielded information on the minimum stream power required to displace a given particle (i.e., critical stream power ω_{ci}). Then, following Hassan and Zimmerman (Hassan & Zimmermann, 2012), ω_{ci} was used to calculate total excess of stream power during a given period (ω_e):

$$\omega_e = \sum (\omega - \omega_{ci}), \text{ when } \omega > \omega ci \tag{2}$$

Values of ω_e were used to compare particle mobility before and after reconnection [i.e., comparison of current data with those of Quinlan, Gibbins, Batalla, and Vericat (2015)]. Direct comparison of the distance moved by tracers in relation to flow strength (e.g., ω_e) was not possible given the differences in hydraulic conditions experienced by the tracers in the two studies. Instead, total displacement of moved and recovered particles was divided by the total ω_e experienced by the tracers and plotted against their *b*-axis. This provided an estimate of the distance travelled per unit of ω_e for a particle of a given size. The purpose here was to provide an insight into gross changes in mobility of the bed following the reconnection; due to the relatively simple models and data used, speculation of the processes underpinning changes in mobility is avoided.

3.3 | Assessment of sedimentary changes in the Ehen

The assessment of sedimentary adjustments in the River Ehen downstream from the confluence of Ben Gill was based on changes in surface grain-size distributions (GSD), bed mobility and channel topography. Full details of these methods are provided below.

3.3.1 | Surface grain-size distributions

Bed surface texture was monitored in the Ehen using the pebble count method to derive GSDs (Wolman, 1954), which involves measuring pebbles along their *b*-axis (Bunte & Abt, 2001) and classifying them following the Wentworth scale. The lower limit of this technique is considered to be 8 mm, although particles <8 mm were still picked and counted to know their proportion. The three main morphological units present in the study reach (see Figure 1c,d) were sampled independently on seven occasions (Figure 2), with 200 particles collected in both the plane bed and riffle on each occasion, and 300 in the pool. Data collected by Quinlan, Gibbins, Batalla, and Vericat (2015) in 2011–2012 in the same units were used as a pre-reconnection reference (although only 100 particles were measured per unit by these authors).

No attempt was made to sample subsurface material due to (a) the absence of exposed gravel bars even during low flows, and (b) the risks associated with underwater subsurface sampling and the release of fine sediments, which are known to be present at rather high levels (Marteau et al., 2018) and which on release may impact freshwater pearl mussels.

3.3.2 | Bed surface mobility

The movement of bed particles was monitored using painted tracers. Each morphological unit was seeded with 100 particles (collected from Ben Gill and not directly from the Ehen in order to prevent the disruption of the bed). Tracers of different colours (one colour per unit) were placed in equally spaced lines of five to seven tracers, perpendicular to the flow, and spread over the entire unit. The sizes of tracers seeded covered the whole range of particles found in the respective units; tracers ranged between 8 and 181 mm (in *b*-axis) in the plane bed and the pool, and between 8 and 256 mm in the riffle. Tracers were seeded on July 31, 2014 and resurveyed on five occasions (Figure 2). The study design was selected to match that of Quinlan, Gibbins, Batalla, and Vericat (2015). Their results, collected from two resurveys under medium flows (return periods of 1.4 and 1.8 years), are used for comparison between pre- and post-reconnection mobility conditions and to study potential changes in mobility patterns. Particles that were not recovered were not included in analyses. No systematic data on particle burial were collected, although tracers were found under small gravel accumulations on numerous occasions. The plane bed and riffle units were expected to

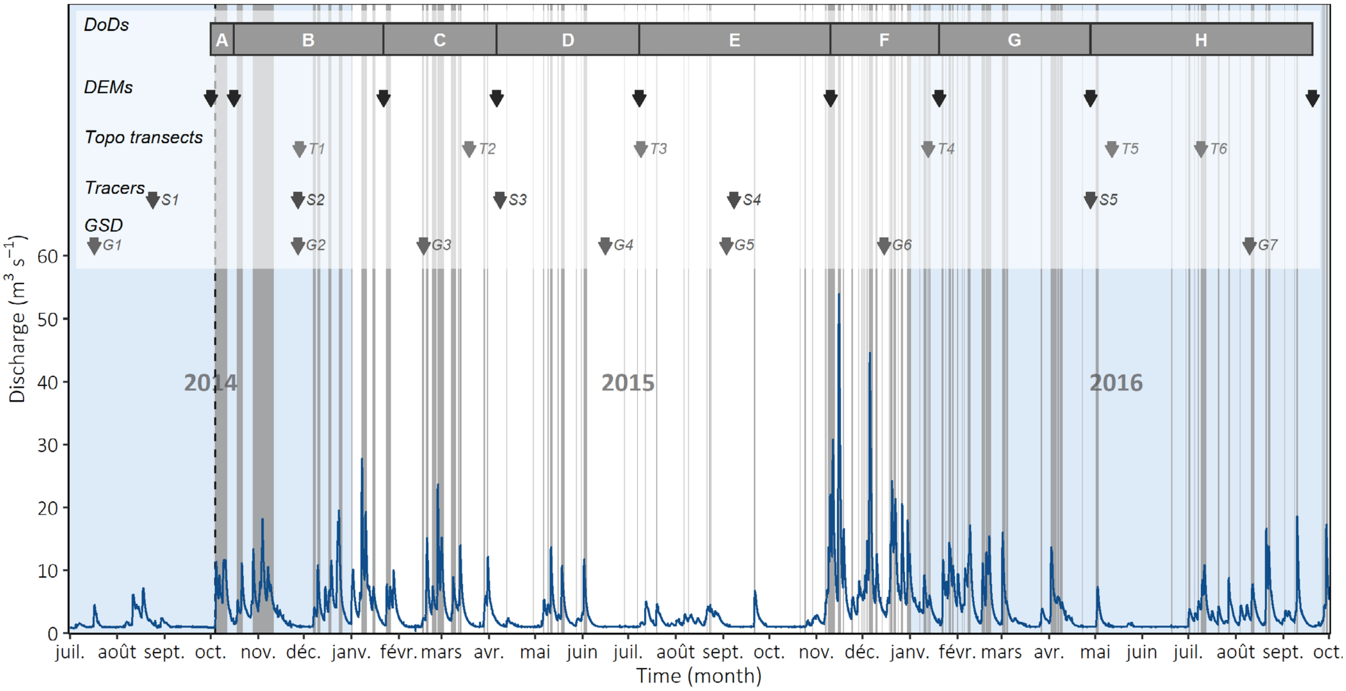


FIGURE 2 Hydrograph of the River Ehen (at Bleach Green gauging station), timing of flows in Ben Gill (grey bars) and frequency of the different field surveys undertaken for the study period (arrows). The dashed vertical line shows the day of the reconnection [Colour figure can be viewed at wileyonlinelibrary.com]

be the most active (Quinlan, Gibbins, Batalla, & Vericat, 2015), and since they are the closest to the confluence they were considered adequate for assessment of changes in bed surface mobility following the reconnection.

3.4 | Changes in bed topography

Bed topography was surveyed in each morphological unit across a fixed control transect using an Acoustic Doppler Current Profiler (ADCP) (StreamPro, Teletyne RD Instruments). An initial pre-reconnection baseline survey was performed over the entire study reach in July 2014, which showed that units possessed only minor topographic variability, justifying the use of a single transect per unit. Transects were located in the middle of each unit and surveyed on six occasions post-reconnection (see Figure 2). Top, face and bottom of bankside areas were surveyed with a Leica Viva GNSS differential rtk-GPS on the first post-reconnection survey (T1), and only areas where deposition would prevent access of the ADCP were re-surveyed. No other changes to the banks were observed throughout the study.

On each occasion (December 2014, March 2015, July 2015, Jan 2016, May 2016 and July 2016, see Figure 2 and Table S1), transects were resurveyed 2–4 times, with data used to determine the average bed elevation at points and a measure of uncertainty (i.e., standard deviation of bed elevations) at a spacing of 0.2 m (> D_{84} of coarsest unit). Similar to the procedure used to determine the minimum level of detection (minLoD) for successive Digital Elevation Models(DEMs, see the application of this in Marteau et al., 2020), difference in elevation (topographic change) was defined as certain only if change was higher than the minLoD:

$$\mathrm{minLoD} = t \cdot \sqrt{\mathrm{SD}_i^{\,2} + \mathrm{SD}_{i+1}^{\,2}} \tag{3}$$

with SD_i and SD_{i+1} the standard deviation of surveys *i* and *i+1* respectively (based on repeated surveys), and $t = 1$ (confidence interval = 64%).

3.5 | Data analysis

3.5.1 | Flow hydraulics

To determine if topographic changes had an impact of flow hydraulics (i.e., if a single 1D hydraulic modelling exercise was suitable for the entire study period), changes in the Q-τ relationship over time were assessed. To do so, the power-law regression of the Q-τ relationship was tested for change over time using ANCOVA (Andrade & Estévez-Pérez, 2014).

3.5.2 | Grain-size distributions

Differences in bed GSD were analysed using χ^2-homogeneity test. This test allows the comparison of entire distributions, rather than simply testing for differences in summary statistics such as mean or median particle size. It performs well for sampled particle size distributions of arbitrary shape and is suitable for comparing distributions of different size (Scheibelhofer, Besenhard, Piller, & Khinast, 2016).

3.5.3 | Bed mobility

Mobility models based on tracer and hydraulic data were expressed in the form $\omega_{ci}=aD_i^b$. Bagnold's (1980) formulation of

$$\omega_{ci} = 0.0971(D_i)^{1.5} \cdot \log(1200d/D_i) \tag{4}$$

led Costa (1983) to model particle mobility from a power regression of the form $a \cdot D_i^b$. Several authors have also applied regressions of this form for different types of river (Ferguson, 2005; Petit, Gob, Houbrechts, & Assani, 2005; Williams, 1983) and the same form of equation was used in this study. In order to identify the minimum ω required to entrain particles (i.e., critical stream power, ω_{ci}), the relationship between several particle size statistics (i.e., $D_{\max}$, D_{mean}, D_{84}) and $\omega_{\max}$, determined from the associated $Q_{\max}$ experienced prior to the resurvey of tracers, was analysed.

Tracer data were further investigated using limiting response (LR) regression models (Cade and Noon, Cade & Noon, 2003). LR models allow for heterogeneity in values of Y across the range of the X variable (something which would violate assumptions of standard, central response regression modelling) while also allowing for a focus on upper and lower limits of observed responses, in this instance of particle mobility to flow characteristics (e.g., peak discharge, $\omega_{\max}$, ω_e). The nature of the scatter in the Ehen tracer data meant that central response models were inappropriate. As well as negating this issue, the LR models provided insights into the maximum response in distance travelled that could be expected for a given value of particle size. The upper limit (T = 0.95) was modelled using Quantile Regression (QR); 95% of points sit below this modelled line. To describe the general trend, QR was fitted to the T = 0.5. Different regression models were tested, with the power relation $y = e^{ax}e^b$ (i.e., $\log_{10}[y] = ax + b$) providing the best fit for both levels of T (based on AIC values). QR models were fitted separately to pre- and post-reconnection data, allowing assessment of whether conditions have changed. All statistical tests were performed in R (R Core Team, 2017).

4 | RESULTS

4.1 | Hydrological regime

The hydrological regime of the Ehen reflects typical patterns for rivers in the NW of England - it experiences low flows in the summer and higher flows in the winter, with some high flow events observed intermittently in late spring. Thus, despite the regulation by Ennerdale Water and its associated weir, the Ehen's hydrological regime remains relatively flashy and variable. Flows for the study period ranged from 0.31 $m^3\ s^{-1}$ (11/02/2015) to 54.0 $m^3\ s^{-1}$ (November 15, 2015). Mean and median discharges (3.50 $m^3\ s^{-1}$ and 1.99 $m^3\ s^{-1}$, respectively) are slightly higher than long-term respective values (2.72 $m^3\ s^{-1}$ and 1.38 $m^3\ s^{-1}$, 1974–2016). Flows in November and December 2015 were particularly high, with a maximum discharge of 54.0 $m^3\ s^{-1}$ (estimated return period of 30 years).

4.2 | Flow hydraulics

The Q-τ relationship for each morphological unit did not change significantly over time (ANCOVA tests per unit, all $p > .05$). Thus, a single model was created per unit. The overall Root Mean Square Error (RMSE) of all modelled (Q_{mod}) versus observed (Q_{obs}) discharges was 0.41 $m^3\ s^{-1}$. Given the stable nature of the riverbed, the negligible changes observed in flow hydraulics, and because no topography data were available for the 2011–2012 period of study, this model was used for the pre-reconnection period as well.

Stream power (ω) associated with flow magnitude was calculated using Equation (1); ω was highest in the plane bed and lowest in the pool; $\omega_{\max}$ calculated in the entire reach was 119 W m^{-2} and was observed post-reconnection during the 30-year return-period flood of 2015 (S5 in Figure 2, Table 1). $\omega_{\max}$ pre-reconnection was 48.2 W m^{-2}, significantly lower than observed post-reconnection.

4.3 | Changes in the Ehen surface grain-size

The 7 GSD surveys indicated differences in sediment size between the morphological units as well as differences in the nature and extent of changes in each one following the reconnection (Figure 3a). No significant difference was found between the GSD just prior to the reconnection (G1) and that reported by Quinlan, Gibbins, Batalla, and Vericat (2015) (χ^2 test, p-values: plane bed = .35, riffle = .28, pool = .24). The GSD of the pool did not change significantly following the reconnection (i.e., no difference between G1 and any of the other six surveys; Table 2). In the plane bed, only G2 was significantly different from G1 (χ^2, $p < .05$). The riffle was the morphological unit where GSD was most variable over time, with G1 to G4 each significantly different from their preceding sampling occasion. Here, successive GSDs post-reconnection remained constantly different from G1, suggesting an effect of Ben Gill that persisted for the whole study period.

The change between G1 and G2 in the plane bed was towards an overall flattening of the GSD, apart from the sediment class 90.5–181 mm (Figure 3(b)), in which frequency almost doubled. The proportion of grains smaller than 11.3 mm also increased. In the riffle, the proportion of particles between 8 and 22.6 mm generally increased from G1 to G4 (Figure 3(c)). The proportion of coarse particles (>128 mm) did not change appreciably, but changes were observed in the proportion of material between 22.6 and 128 mm. The GSD at G4, from which successive GSDs were not significantly different, showed a higher sorting than G1, with more of the finer

TABLE 1 Summary table of discharge and hydraulics associated with tracers surveys in the River Ehen

	Discharge				Stream power			
	$m^3 s^{-1}$				Plane bed	Riffle	Pool	
Tracers survey	Q_{mean}	Q_{max}	Q_{SD}	Return period of Q_{max} Years	ω_{max} $W m^{-2}$	ω_{max} $W m^{-2}$	ω_{max} $W m^{-2}$	Number of flood events
S1	2.52	7.21	1.64	0.5	15.9	11.4	6.0	8
S2	3.28	18.20	3.12	1.3	40.3	28.8	15.3	14
S3	4.42	27.80	3.95	3.1	61.5	44.0	23.3	17
S4	2.07	13.70	1.62	0.9	30.3	21.7	11.5	11
S5	4.53	54.00	5.46	30	119.1	85.5	45.3	26

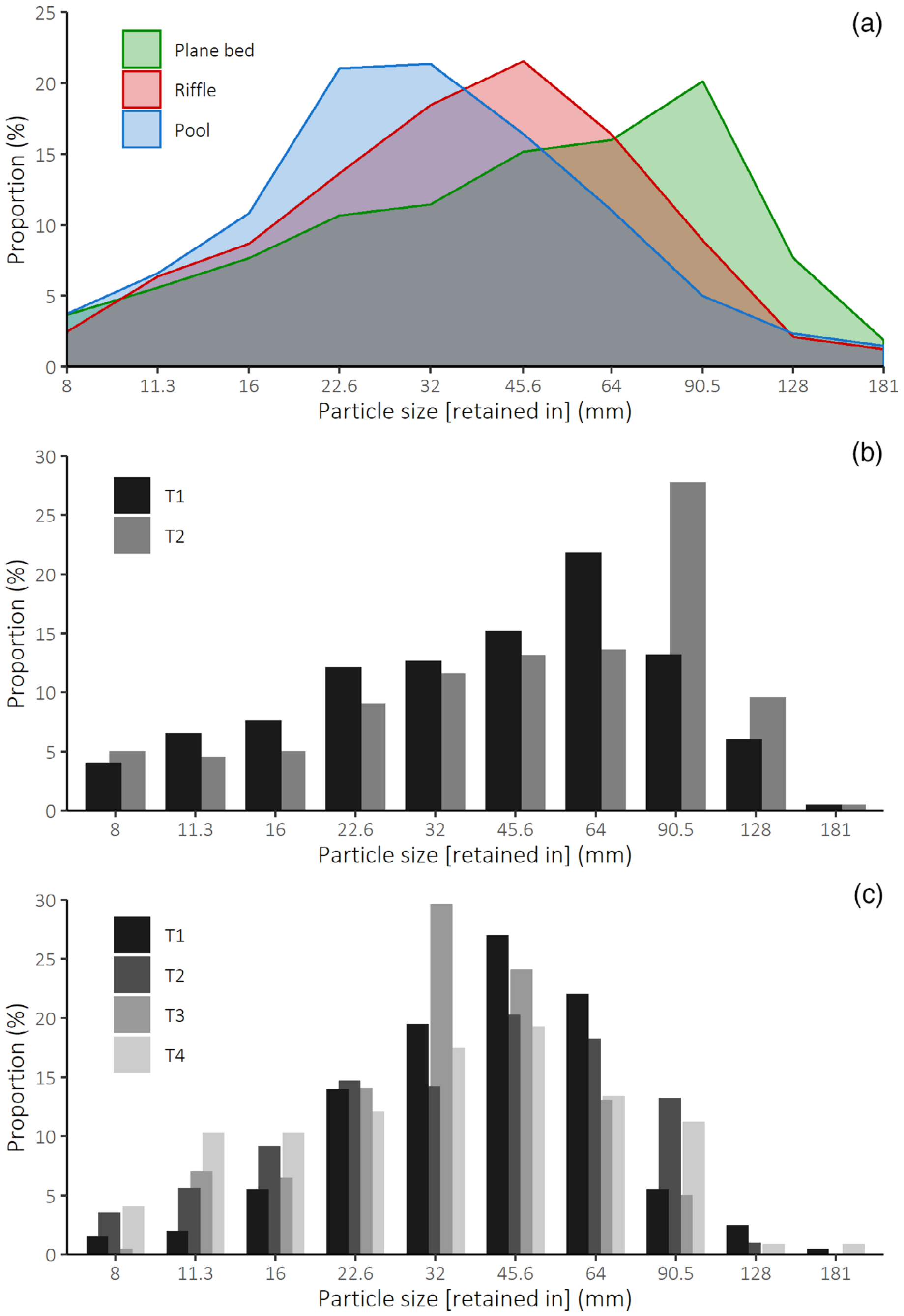


FIGURE 3 Histograms of GSD per morphological unit. (a) Average distributions for the entire study period. Changes on GSD fractions for the (b) plane bed and (c) riffle morphologies. Only GSD at sampling occasions that were found to be statistically different ($\chi 2$) are shown [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Results of the χ^2 test of homogeneity used for the comparison of bed texture

Plane bed	G1	G2	G3	G4	G5	G6	G7
G1	-	*	**	NS	NS	NS	NS
G2		-	NS	NS	NS	NS	NS
G3			-	NS	*	NS	**
G4				-	NS	NS	NS
G5		*$\chi2$ = 71.42, df = 48,*			-	NS	*
G6		*p = .0158*				-	NS
G7							-
Riffle	**G1**	**G2**	**G3**	**G4**	**G5**	**G6**	**G7**
G1	-	*	*	***	**	**	*
G2		-	***	NS	NS	NS	NS
G3			-	**	***	***	**
G4				-	NS	NS	NS
G5		*$\chi2$ = 75.45, df = 36,*			-	NS	NS
G6		*p = 7.32e-05*				-	NS
G7							-
Pool	**G1**	**G2**	**G3**	**G4**	**G5**	**G6**	**G7**
G1	-		NS	NS	NS	NS	NS
G2		-					
G3			-	NS	NS	NS	NS
G4				-	NS	NS	NS
G5		*$\chi2$ = 45.75 df = 40,*			-	NS	NS
G6		*p = .2456*				-	NS
G7							-

Note: ****p* < .001, ***p* < .001, **p* < .001.
Abbreviation: NS, Not significant.

fraction (<22.6 mm) and less coarser material. Similarly, the percentage of particles <8 mm increased in all morphological units following the reconnection and tended to decrease over time and return to levels similar to pre-reconnection by G7.

4.4 | Particle mobility

4.4.1 | Distance travelled and particle size of mobilized material

Of the 300 tracers seeded, 31% were recovered at the end of the study (Table S2). The periods between the five resurveys encompassed different peak flows (Figure 2), ranging between 7.2 and 54 $m^3\ s^{-1}$. Recovery rates were very high for the first two surveys (88–98%; annexe 1). Over the whole period, the pool showed the highest recovery rates (100% at S1 to 43% at S5) while the riffle showed the lowest rates (97% at S1 to 21% at S5). Recovery dropped markedly when preceded by high flows. Only two surveys were carried out by Quinlan, Gibbins, Batalla, and Vericat (2015) prior to the reconnection, capturing movement associated with peak flows of 21.8 and 18.6 $m^3\ s^{-1}$. Recovery rates were lower in their study for P1 (56%) but almost all of these were subsequently recovered (98%, P2).

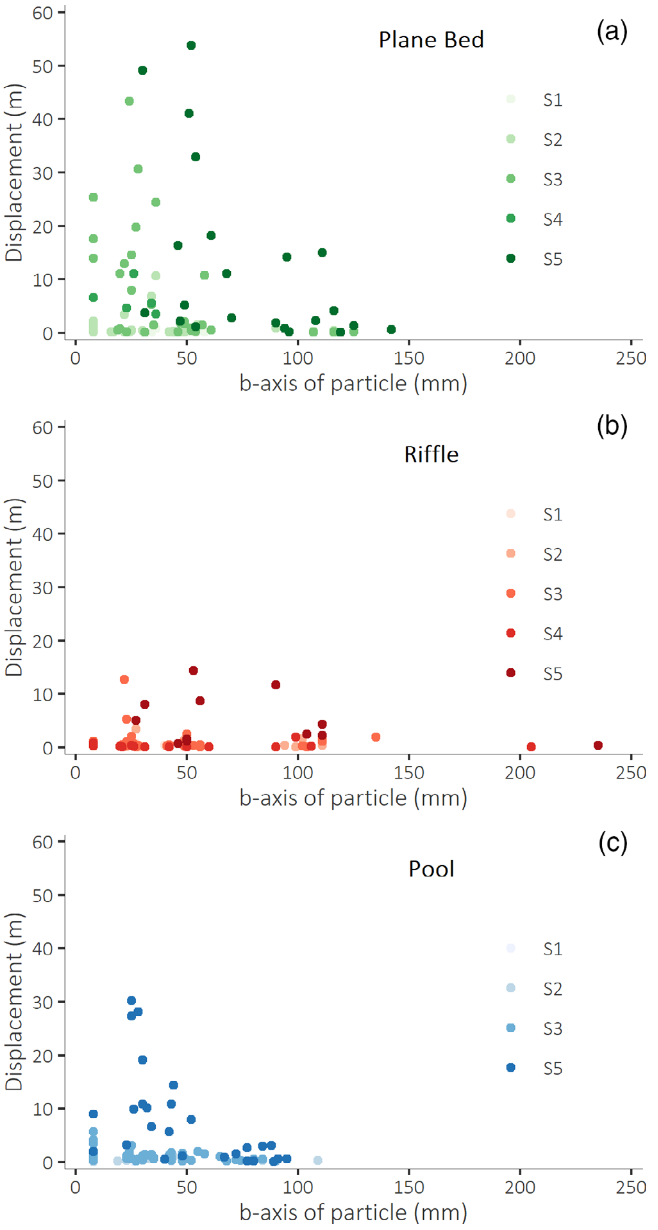


FIGURE 4 Displacement (m) against the b-axis of all tracers recovered for each survey (S1 to S5): (a) in the Plane Bed, (b) in the Riffle and (c) in the Pool. See Table S2 for the hydraulic data associated with each period [Colour figure can be viewed at wileyonlinelibrary.com]

The longest displacements (53.8 m, Figure 4a) of particles up to 150 mm were observed in the plane bed. However, as this corresponds to the largest seeded particle (reflecting local GSDs), it is possible that larger material may also have been mobilized. The largest particle moved was found in the riffle (235 mm, Figure 4b), which also corresponds to the largest clast seeded. In the pool, smaller tracers were displaced and distances were shorter (Figure 4c). In general the largest displacements were observed in S5, when the highest peak flow was observed (a 30-year return-period flood, Table S2).

Mobility of tracers in relation to the GSD of each unit shows that most flow events (see Figure 2, Table 2 and Table S2) were generally not able to mobilize particles coarser than the bed grain size distribution (Figure 5). The survey S3 had a maximum preceding discharge of *c*. 28 $m^3\ s^{-1}$ and was only capable of moving a distribution of particles within the envelop of GSD for the lower range of sizes (8–22.6 mm) in the plane bed (Figure 5a) and the riffle (Figure 5b). Only flows associated with S5 (Q_{max} = 54 $m^3\ s^{-1}$, 30-year flood) were able to mobilize particles over a distribution coarser than respective unit GSDs. When the pool data are excluded, patterns are different to those pre-reconnection (surveys "*p*," Figure 5). Mobility patterns in the plane bed and riffle were rather similar to the ones observed for S3, with a maximum discharge (27 $m^3\ s^{-1}$) slightly higher than those recorded at P1 and P2 (21.8 and 18.6 $m^3\ s^{-1}$ respectively).

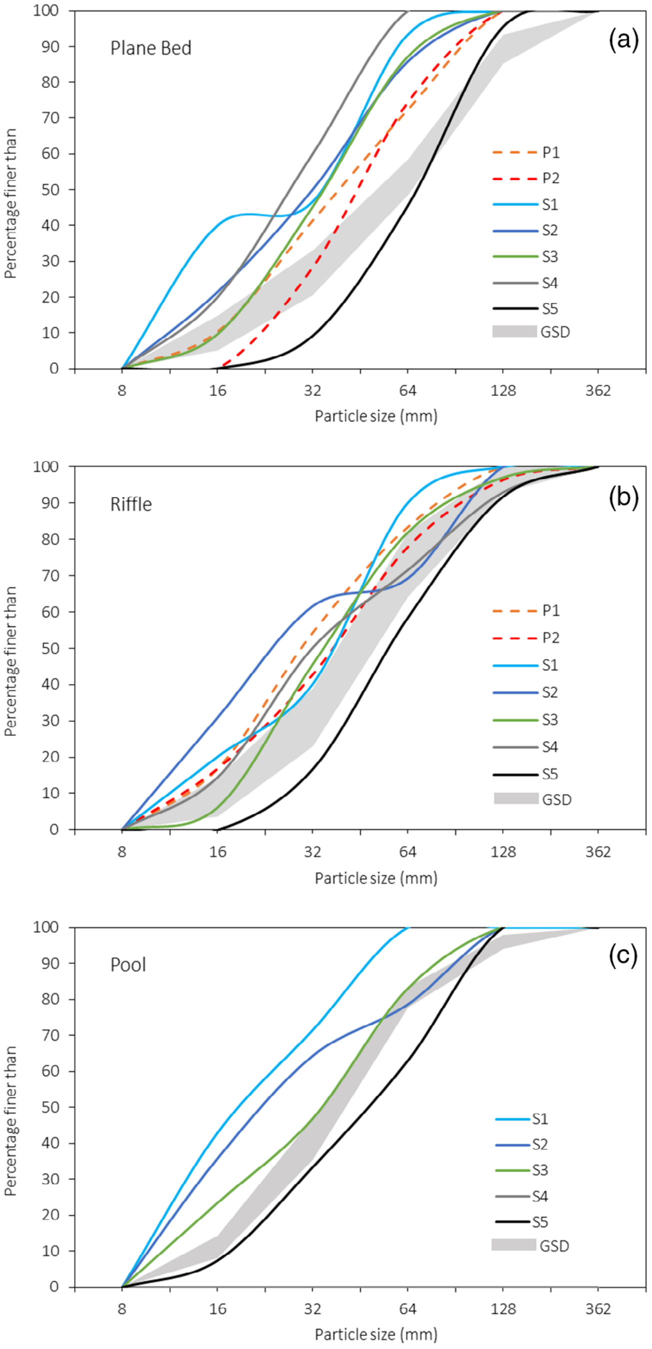


FIGURE 5 Grain size distribution of the mobilised tracers for each survey (S1 to S5) and these from Quinlan, Gibbins, Batalla, and Vericat (2015) and Quinlan, Gibbins, Malcolm, et al. (2015), P1 & P2: (a) plane bed, (b) riffle and (c) pool. The bed grain size distribution envelopes from the various GSDs surveys during the presents study are shown as grey areas. No data were used for the pool from Quinlan, Gibbins, Batalla, and Vericat (2015) (i.e. P1 & P2) [Colour figure can be viewed at wileyonlinelibrary.com]

4.4.2 | Excess stream power and mobility

The maximum particle size mobilized in the plane bed and in the riffle were the largest tracers seeded (Figure 4), restricting the use of D_{max} to understand particle mobility in the Ehen and yielding a rather weak relationship with ω_{max}. D_{mean} offered the best fit but is of limited utility to estimate ω_{ci} since it smooths the relationship and underestimates the critical value. The choice was made to use the relationship between D_{84} and ω_{max} for the analysis (Figure 6(a)), as used in previous studies (e.g., Petit et al., 2005).

The Ehen mobility model sits within other models found in the literature (Figure 6(b)). Using Equation (2), ω_e was computed for each survey period at 15-min intervals (Table S2). The flow data indicate that ω did not reach ω_{ci} prior to S1 in any morphological unit. ω_e was also 0 in the pool during S4, which coincides with the very limited movement observed in this unit during this period. Maximum ω_e was experienced during S5 throughout the entire reach, which can be explained partly by the length of time between S4 and S5, but also by the extended periods when ω was above ω_{ci}. ω_e experienced during the study by Quinlan, Gibbins, Batalla, and Vericat (2015) was relatively high at P1 and lower at P2, and no episode where ω_e = 0 was observed then.

For both periods considered, the scatter in the points representing the relationship between particle size of recovered tracers and displacement (riffle and plane bed) relative to ω_e showed a typical LR form (Figure 7), with a stronger trend (steeper slope) for the upper limit (T = 0.95) than the central trend (T = 0.5). The upper limit to displacement fell sharply across the sediment size range. Note also the high variability in displacement for small particles compared to large ones (as was also observed in Figure 4). In general, for the same relative level of ω_e, smaller particles were capable of travelling longer distances than larger ones.

The T = 0.95 model fits for both periods were significant (p < .005) but the T = 0.5 fit was significant only for the post-reconnection model. Analysis of model coefficients showed that the upper limit of the responses differed significantly between the periods (*b coefficient*: −3.23 pre-reconnection, −2.60 post-reconnection). Thus, the upper limit of the response, which is the maximum potential distance travelled by a particle, is now higher than it was under similar ω_e conditions before the reconnection. The relative positions of the data points and fitted lines indicate that particle mobility in the riffle and the plane bed has increased since the reconnection.

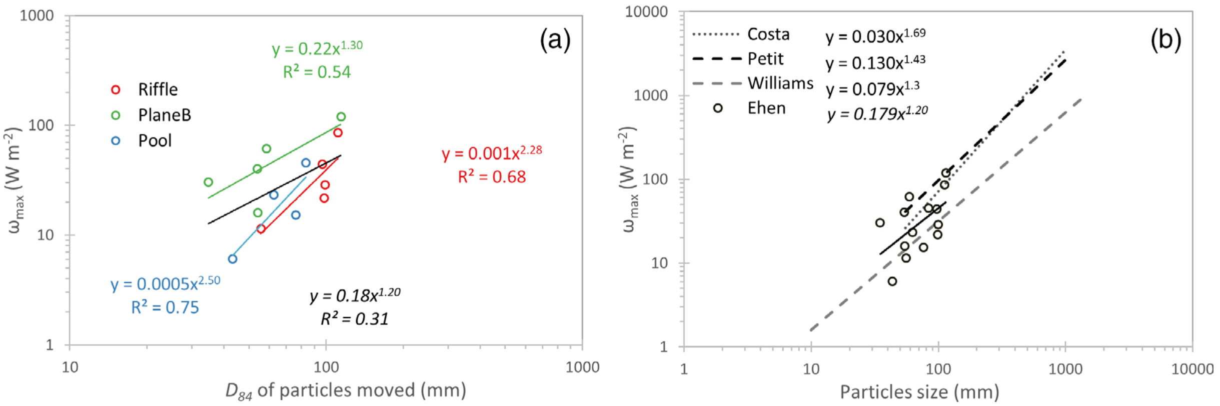
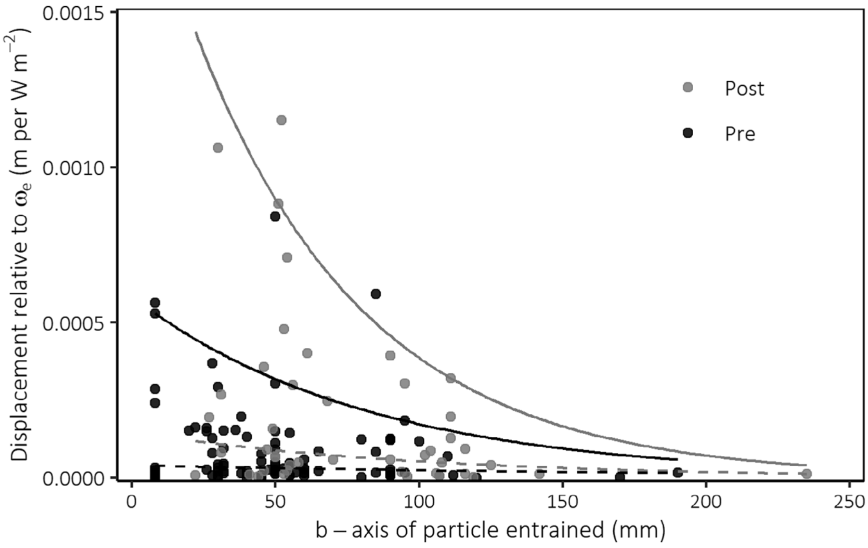


FIGURE 6 (a) Relationship between maximum stream power (ω_{max}) and D_{84} of grain size distribution. (b) Mobility model for this study (from D_{84} data) compared to formulae found in the literature (Costa, 1983; Petit et al., 2005; Williams, 1983) [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 7 Particle displacement relative to the excess stream power they experienced (all successive surveys and morphological units Plane Bed and Riffle merged together), in relation to the b-axis of particles, in the River Ehen, pre- (black dots) and post-reconnection (grey dots). Note that the full and dashed lines represent the 0.95 and 0.50 quantile regression models, respectively



4.5 | Topographic changes in the Ehen

There was no change in topography between the baseline survey and survey T1. The pool experienced little topographic change compared to the other morphological units (Figure 8). Overall topographic changes in the plane bed were negative (i.e., net scour of almost −5 m^3), with the floods of winter 2015 playing a significant role in generating an overall deepening of this unit. The riffle showed sedimentation of around 13 m^3, while the transitional area, only surveyed for topography, experienced mostly erosion (*c.* 10 m^3 in total). The limited deposition of gravel that occurred in the plane bed between T4 and T5 was insufficient to compensate for erosion at T4. Deposition happened in the riffle between T1 and T2 (*c.* 22 m^3), with this corresponding to the observed development of a gravel bar along the right bank that is composed mostly of fine to coarse pebbles (Figure S1). The large floods of winter 2015 (between T2 and T4) generated loss of material from the riffle. Further accumulation in this unit happened between T4 and T5, and the erosion observed between T5 and T6 can be identified as a deepening of the channel along the bank opposite to the gravel accumulation.

5 | DISCUSSION

5.1 | The Ehen rehabilitation initiative in context

The Ehen is a rare example not just of a basin-scale management initiative (i.e., reconnection of a whole sub-catchment, as opposed to artificial gravel augmentation) but one that also includes detailed pre- and post-project monitoring. Monitoring was particularly important in the Ehen because of the sensitivity of the freshwater pearl mussel to changes in geomorphic and sedimentary conditions and because of the uncertainty surrounding the magnitude and nature of any changes that might occur in response to the reconnection. Thus, monitoring was needed not just to assess whether the project was achieving its objectives but to ensure that no sudden and unforeseen changes

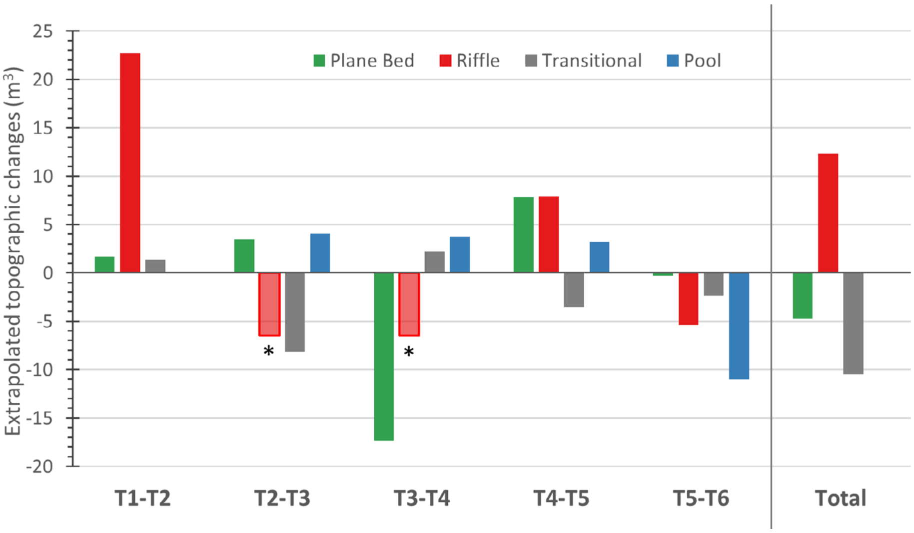


FIGURE 8 Extrapolated net topographic changes in the upper River Ehen, (only changes above the minimum level of detection have been considered, see methods). See Figure 1 for details on the morphological units. Note that there was no suitable topography data for T3 at the riffle, therefore for T2-T3 and T3-T4, the value of T2-T4 is divided between the (Indicated with *) [Colour figure can be viewed at wileyonlinelibrary.com]

resulted in the type of deterioration in benthic conditions that might necessitate intervention to protect mussels.

The current paper compared pre-reconnection geomorphic conditions (data collected over 3 years) to those in the first 2 years following the reconnection of Ben Gill to the main-stem Ehen. Given the potentially slow rate of environmental responses to management interventions and changes in the pace of responses over time (Charlton, 2008), there is a need to be cautious when evaluating the changes observed in the Ehen to date; that is, it is important to be circumspect when discussing the “success” of the rehabilitation initiative so early in its life.

Previous assessment of its former geomorphic character and activity (United Utilities, 2012) resulted in the expectation that renewed geomorphic activity in the Ehen would be triggered in Ben Gill as soon as the channel was offered the opportunity to recover its dynamics. Nevertheless, the magnitude of change in Ben Gill and the resulting development of a confluence bar (as discussed in Marteau et al., 2020) have proven to be more pronounced than expected. The following section discusses the key findings of the monitoring within this context, and is followed by some consideration of changes over longer timescales and responses to other management activity.

5.2 | A slow but visible recovery of sedimentary activity

Following 40 years of flow regulation by the weir and the associated diversion of Ben Gill, the Ehen displayed general signs typical of regulated rivers, with simple channel geometry, no well-established dynamic geomorphic features (i.e., no gravel bars) and with a wide and uniformly armoured channel to a level that can be considered a pavement (Church, 1995; Pitlick & Wilcock, 2001).

In the first 2 years following its reconnection, Ben Gill supplied sediment to the Ehen at an estimated (minimum) rate of just over 180 m^3 y^{-1} (Marteau et al., 2020). Even though the bar that has formed at the confluence of the Ehen and Ben Gill since the reconnection retains a large fraction of this sediment, part of the material is carried downstream (approximately 45 m^3 y^{-1} Marteau et al., 2020). This sediment supply is a situation that the river has not experienced for 40 years. Thus, the most fundamental objective of the project has been achieved.

By the end of the study period the confluence bar was well developed, and over a distance of approximately 100 m (in the plane bed unit) forced most of the flow to one side of the channel. This forcing has probably contributed to increased hydraulic heterogeneity within the reach, and it is probable that flow constriction applied by the confluence bar forced most of the flow over a limited width of the plane bed and generated higher velocities and shear stress, resulting in local erosion. Bed texture changed directly after the reconnection (G2 & G3), corresponding with some gravel deposition (T2 & T3), and changed again once all that material was washed away by the large floods of winter 2015 (G5, at T4). This increase in hydraulic heterogeneity is also responsible for the greatest mobility witnessed in the plane bed. Indeed, longer step-length and higher displacement rates were observed in the tracer data here than in the rest of the reach.

The riffle showed clear signs of deposition, mostly of fine to coarse pebbles (i.e., 4 to 32 mm in *b*-axis) evident along the right bank where a lateral bar developed (Figure S1). Deposition was expected here as it retained attributes of an old, pre-existing bar feature. Development of this bar is compelling evidence of geomorphic change, along with the general tendency of fining of the bed surface material in the riffle. This section of channel showed a similar frequency of larger particles being displaced compared to pre-reconnection, although not over long distances. This is the section where the coarsest particles were moved, though mean travel distances were shorter than in the plane bed. Estimates of mobility in the riffle were probably biassed by the low recovery rate for smaller particles (i.e., no measurement of displacement). Numerous tracers are likely to have been buried and trapped under the newly formed lateral bar, hence the apparent lower displacements (average step-length at highest peak flow = 5.5 m) and recovery rate (final survey = 21%).

The pool showed very limited activity. Particle mobility was low and overall changes in bed topography were null over the course of the study. The bed here is particularly paved and regularly covered with algae, factors which limit the interpretation of the topographic changes observed here. No change in GSD was found in the pool either, although field observations suggest that changes would be missed by the method used to sample GSD - local pockets of sand and fine gravel were observed in the reach in areas of preferential deposition (e.g., behind boulders, along the banks) but were not captured by the Wolman pebble count which only accounts for particles >8 mm.

5.3 | Changes remain limited but bode well for the future

The field observations of new pockets of sand in the pool, together with the fining trends identified in the riffle, support the hypothesis that only the smaller fraction of the material supplied by Ben Gill is transported downstream under the existing hydrological regime. Nonetheless, prospects for the further improvement of habitat conditions are good. Sediment exports from Ben Gill are not yet showing signs of a decrease so an ongoing supply of coarse material is expected. Although the sediments transported away from the confluence bar encompass only particles smaller than 64 mm, this represents the size fraction that was considered missing because of 40 years of sediment starvation, and critical for the establishment of suitable recruitment habitat for pearl mussels. Sediments delivered by Ben Gill are being pushed through the upper Ehen, with signs of aggradation and fining slowly migrating downstream from the plane bed (earliest signs of deposition) to the riffle (gravel bar growing throughout the study), the entrance of the transitional area (recent signs of break-up of the pavement) and soon reaching the pool (only pockets of fine and coarse sand so far). As more sediment is delivered to the river, at a pace and a frequency that is controlled by natural (or at least restored) processes, the sediment wave will continue to disperse downstream and help promote geomorphic and hydraulic diversity. Another critical change that might further enhance this dynamic is that the next phase of the Ehen rehabilitation work involves removal of the weir. The primary goal of this is the further re-naturalisation of the Ehen's flow regime, and it is hoped that this will increase the conveyance of material supplied by Ben Gill.

Comparison of the relative size of mobilized particles to the surface GSD confirmed the generally low mobility experienced in the River Ehen, even after the reconnection, with only high magnitude flood events (e.g., return period of 30 years) capable of entraining and transporting particles that encompass the entire surface GSD. The Ehen struggles to carry all the material supplied by Ben Gill, so changes within the study reach remain limited. Thus, the scale of change observed in Ben Gill is not yet matched with geomorphic adjustments of similar amplitude in the Ehen. Nevertheless, particle mobility has increased since the reconnection, with a lower amount of energy now required to move particles of the same size. Tracer data revealed that events of 1 to 2 year return period, such as experienced at P1, P2 and S3 for example, are capable of setting particles of sizes between 8 and 64 mm in motion (i.e., similar to particles found at the surface of the confluence bar, D_{50} between 35 and 65 mm, as described in Marteau et al., 2020). Moreover, although the reconnection has not altered the hydrological regime of the river (Marteau, Batalla, et al., 2017), it has increased bed mobility to a certain degree. These various pieces of evidence show that the Ehen is capable of re-distributing part of the bed material provided by Ben Gill and that, as discussed below (Section 5.4), this sediment so far moves as a bedload carpet on top of the existing pavement, with only limited interaction with the bed (apart from some local trapping of sand and small to medium sized gravels). With particles of a given size now displaced at lower energy, flow competence can be described as higher thanks to the entrainment of loose material now available in larger quantities.

5.4 | Predicting future directions based on results from flume experiments

While many examples exist of restoration or rehabilitation initiatives in both the scientific and grey literatures, these consist mainly of dam removal (Doyle et al., 2005; Major et al., 2012; Orr & Stanley, 2006), artificial gravel augmentation (e.g., Arnaud et al., 2017; Bunte, 2004; Merz & Chan, 2005), or channel re-meandering (e.g., Lorenz, Jähnig, & Hering, 2009; Pedersen, Kristensen, & Friberg, 2014; Rogiers, Lermytte, de Bie, & Batelaan, 2011). Projects that involve reconnecting sub-catchments remain scarce. Thus, one element of uncertainty in the Ehen project concerned the limited evidence from elsewhere that could be used to predict the likely outcomes of the reconnection. A particular element of the uncertainty concerned the fact that Ben Gill is ephemeral. Predicting and understanding geomorphic changes in, and the downstream effects of flows in such streams is very difficult (Williams, 2005), as demonstrated by the complex relationship between flows in the main-stem and those in Ben Gill (Marteau et al., 2018). Uncertainties surrounding Ben Gill are significant because the timing and magnitude of flows here drive the evolution of the newly reconnected channel and in turn the delivery of material to the Ehen, both fine (Marteau, Batalla, et al., 2017) and coarse (Marteau et al., 2020).

Evidence from experimental studies may help understanding of the process changes occurring following the reconnection. Flume experiments have confirmed field observations that a reduction in sediment supply can result in an increase in the D_{50} (Buffington & Montgomery, 1999; Dietrich, Kirchner, Ikeda, & Iseya, 1989; Lisle, Nelson, Pitlick, Madej, & Barkett, 2000) and in the surface layer becoming immobile (Dietrich et al., 1989; Nelson et al., 2009). Conversely, the addition of material to an armoured channel tends to increase bed surface mobility (Sklar et al., 2009; Venditti et al., 2010) and decrease bed surface particle size (Sklar et al., 2009). Despite the limited spatial (300 m-long reach) and temporal (2 years) extent of this study, the geomorphic adjustments observed in the Ehen are in line with the conclusions of these studies. The renewed provision of coarse material from Ben Gill has reactivated part of the lost geomorphic dynamism - material is being carried downstream and is starting to affect particle mobility and bed texture. The dispersion of coarse material is likely to be further enhanced once channel complexity is significantly improved (e.g., Lisle, Cui, Parker, Pizzuto, & Dodd, 2001).

In the Ehen study reach, the riffle and a riffle-pool transitional area immediately downstream are separated by a hydraulic jump (*c*. 0.5 m). This jump plays a role in trapping gravel in the riffle and generating higher velocities directly downstream from the jump. Early signs of break-up of the pavement have been observed downstream from this jump, with new sediment being deposited in its stead. In some experimental studies, the injection of sediment resulted in the mobilisation of part of the bed surface (e.g., Koll, Koll, & Dittrich, 2010; Venditti et al., 2010). This raises the possibility that reconnection of Ben Gill may further contribute to the break-up of the pavement of the River Ehen as, over time, more and more sediment moves on top of it. This is evidence that the system has some potential for (geomorphological) recovery, but also that this will only be achieved if specific conditions are met, that is, increased morphological complexity (e.g., hydraulic jumps, flow constriction) and high discharges (e.g., >25-year return period floods). In fact, most flume studies reporting this process have been undertaken over a freshly created armour layer, where the movement of particles is not impeded by some biological activity (e.g., macroinvertebrates; Johnson, Reid, Rice, & Wood, 2009; biofilm; Piqué, Vericat, Sabater, & Batalla, 2016) or imbrication and compactness (Houbrechts et al., 2012), so there are limitations in the extent to which flume studies can be used to understand potential adjustments in the Ehen. Conditions for a partial mobilisation of the pavement will require more time and/or more sediment and/or coarser particles which, because mixed sediments tend move not by translating but rather by dispersing (although the mode of the wave may seem to be translating, Lisle et al., 2001; Sklar et al., 2009), may require longer than the timeframe of this study to be realized.

One unexpected outcome of the reconnection that is potentially of great significance for freshwater pearl mussels is the delivery of large amounts of fine sediment (Marteau, Batalla, et al., 2017). Excessive volumes of fine sediment are considered problematic for mussels - they are rarely found in areas with dominant silt substrate (see review by Quinlan, Gibbins, Malcolm, et al., 2015). No formalized standards exist in the literature regarding the tolerance limits of mussels to fine sediments, so no direct conclusion can be drawn about the potential impacts on mussels of the increase in fine sediment storage observed in the Ehen following the reconnection. The high suspended loads observed so far since the reconnection may reduce over time (as availability in the engineered channel in Ben Gill decreases), but ongoing monitoring of fine sediment remains essential, with contingency plans (e.g., temporary diversion and storage of water) already considered if conditions become critical.

5.5 | Wider lessons and a call for objective-based rehabilitation

The reactivation of sediment connectivity in the Ehen is likely to generate a series of geomorphic adjustment phases that, while being intrinsically opposite, are akin to those outlined by Petts and Gurnell (2005) in relation to dam closure. These phases run from an accommodated regime state towards a new regime state, possibly (and ideally) closer to the natural or pre-modified one. As the Ehen moves from one state to another, the system will likely progress along a so-called "relaxation path," at a pace that will depend on the river characteristics (e.g., energy availability and expenditure, sensitivity to changes, hydrologic regime), the degree of alteration compared to its (estimated) "natural" state (e.g., shift in river type, degree of armouring and stabilisation) and the degree to which altered processes are being restored. Similar observations have been made in the case of dam removal. For dammed rivers, downstream channels experience a relaxation phase (adjusting to restored connectivity) overlapping with the reaction phase (i.e., still being perturbed by additional sediment eroding from the old reservoir) (Major et al., 2017). Although the first pulse of sediment observed after the opening of Ben Gill was major, it was much less than witnessed in rivers experiencing non-phased dam removal. The rehabilitation of the River Ehen also differs from dam removal in the fact that while sediment connectivity has been restored, flow effects of reconnecting the ephemeral Ben Gill are limited (Marteau, Batalla, et al., 2017). In turn, the ecological effects of reconnecting this tributary to the Ehen are very different to those associated with reconnecting up and downstream areas by dam removal.

Given that the reconnection has had no significant impact on flow regime, the Ehen example could be compared to (repeated) gravel augmentation. Such augmentation is now common-place in many parts of the world, particularly downstream from dams (Habersack & Piégay, 2008) and is increasingly implemented for geomorphic purposes, that is, maintaining channel complexity, substrate quality and habitat heterogeneity (Gaeuman, 2012). Nevertheless, significant differences lie in the fact that in the Ehen the frequency, timing, volume and sizes of material delivered are uncontrolled, and so more natural. It also differs in that these inputs are sustained by ongoing erosion and delivery process in the catchment rather than anthropogenic agency. The effects expected from gravel addition (e.g., bed fining, enhanced bed mobility) are most beneficial when they persist over a long period of time and affect long sections of river channel (Bunte, 2004; Harvey, McBain, Reiser, Rempel, & Sklar, 2005). Given that particle size and excess shear stress (reflected in changes in bedforms) adjust to both flow intensity and sediment supply (Buffington & Montgomery, 1999), and since Ben Gill shows no sign of reduction in its sedimentary activity as yet, geomorphological and sedimentary adjustments in the upper Ehen are anticipated to continue, associated with competent events in both Ben Gill and the Ehen, that are not always synchronized (Marteau et al., 2018).

The overall approach adopted for the Ehen is one of adaptive management. Much has been learnt from this project to date, particularly in relation to the significance of seemingly small tributaries that flow for only a small part of the year. Such a small sub-catchment (0.55 km^2 within a 156 km^2 catchment) would fall outside of what could be considered as a significant tributary (Benda, Andras, Miller, & Bigelow, 2004; Rice, 2017) but its role is magnified by its location and local context of its situation (e.g., Lisenby & Fryirs, 2017). The unexpected issue of increased fine sediment delivery in the Ehen has initiated further studies, focussing on the Quaternary alluvial fan that the lower section of Ben Gill cuts across. A study is being carried out to better understand the subsurface composition of the fan (and hence the amount of fine material potentially available for delivery to the Ehen) and the factors that influence how frequently it flows. This study, along with the ongoing monitoring of Ben Gill, will inform adaptation of the interventions in the Ehen to help ensure that, over longer timescales than reported here, project goals are achieved.

6 | CONCLUSIONS

The work presented here is a rare example of objective-based river rehabilitation designed to improve habitat by restoring catchment-scale connectivity. It was designed to reinstate sediment dynamics in an ecologically important river while limiting the need for invasive and repeated intervention. The reconnected tributary exerts an important control on coarse sediment supply and dynamics and has proven to be an important source of fine material. Within the 2-year post-reconnection period considered here as the *adjustment phase*, effects of this renewed sedimentary activity in downstream reaches of the Ehen remain limited to localized deposition (linked to the new supply of sediment) and scour (caused by the 30-year flood) in morphological units that are close to the confluence and where flow hydraulics are most diverse. Flow competence has increased thanks to the newly supplied sediment, and the bed shows some signs of increased mobility, with bedload (particularly the finer fraction) carried downstream as a sediment carpet overpassing the stable paved layer of coarser material. It is anticipated that over time, the continuous and uncontrolled supply of coarse sediment by Ben Gill disperses further downstream in the Ehen and interacts with the pavement; at this point the river may be considered to be reaching its new (quasi)equilibrium state. The river's mussel population might benefit from this rather slow process, since this species can be sensitive to abrupt changes in habitat and excessive disturbance of the riverbed. Further monitoring of the speed, nature and spatial extent of geomorphic changes in the Ehen, along with surveys of the mussel population, is necessary to ensure that these early signs of improvement are turned into a long term rehabilitation success story.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, BM, upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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