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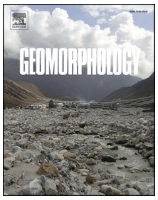

Long-term geomorphic adjustments following the recoupling of a tributary to its main-stem river

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ABSTRACT

River restoration and rehabilitation projects are widespread, but rarely include the data needed to fully evaluate if they are successful in achieving their goals or how long the process of readjustment takes before a new 'recovered' regime state is reached. Here we present a seven-year post-project dataset detailing the morpho-sedimentary responses of a river to the reconnection of a formerly diverted tributary, and relate observed changes to conditions in the river prior to the reconnection. We describe changes in the tributary and main-stem channels, including changes in channel planform, morphology, and the export of coarse and fine sediment from the tributary to the main-stem river. We use the data to develop a conceptual model of the system's response to the reconnection.

Marked geomorphic changes occurred within the first two years after the reconnection. Changes during this 'shock phase' included dramatic erosion and subsequent deepening and widening of the tributary channel, rapid development of a confluence bar and an increase in fine sediment delivered to the main-stem. After this shock phase, and despite the continued occurrence of high magnitude flow events, the rate of geomorphic change in the tributary began to decrease, and the rate of growth of the confluence bar slowed. Fine sediment volumes in the main-stem also decreased steadily. After an adjustment phase lasting a total of approximately 4.5 yr (including the initial 2-yr shock phase), the tributary to mainstem system appeared to reach a new dynamic equilibrium that we consider the adjusted regime state. This new regime state was characterised by, among other things, an increase in geomorphic heterogeneity in the tributary and main-stem channels.

Changes in both fluvial processes and forms indicate that within 4.5 yr the project was successful in achieving its goal of augmenting sediment and increasing geomorphic heterogeneity. Our conceptual model of adjustment mirrors that developed by Petts and Gurnell (2005), with the river passing through a complex and dynamic adjustment phase before reaching a new regime state. However, unlike the responses to impoundment represented by Petts and Gurnell, our model of river response to rehabilitation charts increases in dynamism and heterogeneity.

1. Introduction

Projects that aim to improve the physical and/or ecological integrity of river channels are increasing globally. Such projects include the development of e-flows (Schlatter et al., 2017), dam and weir removal (Sneddon et al., 2017; Thomas et al., 2015; Petts and Gurnell, 2005), and a variety of channel habitat restoration (Wohl et al., 2015) and gravel augmentation initiatives (Peirce et al., 2021; Gaeuman et al., 2017). Critiques of such projects reveal a common problem related to limited post-project monitoring, which constrains assessment of whether projects have achieved their objectives and, accordingly, whether they might be considered as being 'successful' (Klein et al., 2007). The issue is

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evident from the list of completed projects included in the River Restoration Centre (RRC) database, with only around 21 % of the 2800 projects including post-project monitoring (England et al., 2021; RRC, 2016). For those projects that include monitoring, timescales are often limited to only a few years, which may be insufficient to capture more gradual geomorphic and ecological adjustments (which may take up to 20 yr, depending on the restoration measure(s) involved (England et al., 2021; Erwin et al., 2016; Klein et al., 2007)). Thus, while longer-term monitoring is widely recognised as important (England et al., 2021; Erwin et al., 2016), examples of this good practice remain scarce.

For projects focussed on improving fluvio-geomorphic conditions, three system states need to be captured within monitoring timeframes: (i) the constrained state prior to the restoration, (ii) the immediate post-intervention or 'adjustment' state or phase, and (iii) the adjusted regime state where the system is considered to have reached a new dynamic equilibrium (Fischenich and Morrow, 2000). Geomorphic responses to restoration have been documented for dam removal (Petts and Gurnell, 2005; Magilligan et al., 2016), as well as floodplain (Fisher, 2018) and channel course restoration (Addy et al., 2012). Responses, in terms of types and timing of channel adjustments, vary depending on the nature of the restoration, channel characteristics such as slope, sediment supply, and the magnitude and frequency of flood events capable of eliciting geomorphic change (Groll, 2017; Petts and Gurnell, 2005; Reinfelds et al., 2004). Some responses, e.g., to dam and weir removal, include upstream changes such as incision and knick-point migration, along with downstream aggradation (Magilligan et al., 2016; Thomas et al., 2015). Sediment yields may dramatically increase after some types of habitat restoration, depending on the stability and composition of the bed and bank materials, but these elevated sediment yields typically reduce towards pre-restoration levels over time as the system stabilises (Sear et al., 1998). Increased geomorphic diversity often results from river restoration, when the river is given the freedom to adjust (Sear et al., 1998). The removal of embankments or other anthropogenic structures allows channel migration, evolution and bank erosion, enabling the formation of features such as point bars, lateral bars, riffles, etc. (Williams et al., 2020).

Ecological and geomorphological recovery often proceed at different rates following restoration, depending on the level of degradation, the type and scale of the restoration initiative, and wider catchment characteristics (Polvi et al., 2020). Tullos et al. (2014) found that following dam removal on the Calapooia and Rouge rivers in Oregon, recovery of macroinvertebrate assemblages occurred within a year, whilst geomorphological disturbance from the sediment pulse was still evident after two years. However, sometimes ecological recovery following restoration may take longer than geomorphological recovery, especially if the stream reach remains isolated from others (Fuchs and Statzner, 1990).

Artificial sediment augmentation to improve instream habitat is a widespread practice, notably in salmonid rivers experiencing sediment starvation (Sellheim et al., 2016; Pulg et al., 2022). However, as sediment is likely to be transported downstream, to be successful over the long-term the practice needs repeating (Chardon et al., 2018). A passive approach to augmentation by naturally re-establishing a sediment supply may be more sustainable since it negates the requirement for ongoing intervention (Groll, 2017). One example of passively restoring sediment (and water) supply is the reconnection of formally diverted or disconnected tributaries back to their main-stem rivers (Gilvear et al., 2013; Marteau et al., 2020a). By recoupling tributary to main-stem channels, such reconnections can be considered as system scale rehabilitation (Marteau et al., 2020b) and may have long-term benefits that extend beyond the restored reaches (Hillman and Brierley, 2005).

Marteau et al. (2020a & b) reported on a fluvial system rehabilitation project in the United Kingdom where the upper River Ehen's main sediment source, a tributary named Ben Gill, was reconnected. The project adopted the 'don't fight the site' philosophy of Brierley and Fryirs (2009) and focussed on process recovery rather than form-based management. However, while these traits meant that the project aligned with current notions of rehabilitation, they brought great uncertainty, both in terms of how much sediment might be delivered to the main-stem by the tributary and how long adjustment and 'recovery' might take.

Marteau et al. (2017, 2020a, b) analysed the changes that occurred in the first two years after the reconnection of Ben Gill. While the impacts of tributaries on their main-stem rivers generally increase with the size of the tributary relative to the main-stem (Benda et al., 2004), despite the small size of Ben Gill its reconnection had a major impact on the sediment budget of the Ehen over this initial two-year period (Marteau et al., 2017). This paper provides a longer-term perspective, and reports on the changes in the tributary and mainstem channels over an additional five-year period (i.e., total of seven years after the reconnection). Its aim is to describe the various morpho-sedimentary changes that have happened over this seven-year period, assess whether a new adjusted state has been reached, and describe the processes and forms that characterise this state. The paper integrates multiple lines of evidence from both the tributary channel and the main-stem river to address four objectives: (i) assess erosion, deposition and net volumetric changes and patterns within Ben Gill, (ii) assess the geomorphic evolution of the Ben Gill tributary channel (changes in width/depth, long profile, sinuosity, and the emergence of geomorphic units), (iii) describe the development and evolution of the Ben Gill - Ehen confluence bar, and (iv) quantify suspended sediment dynamics in the main-stem River Ehen. We use the data to discuss the advantages of rehabilitation projects that focus on geomorphic processes at the system scale, and to develop a conceptual model of adjustment to tributary reconnection.

2. Study area

The study site is located in the Lake District of NW England, where the River Ehen flows out of Ennerdale Water (Fig. 1). The Ehen has a catchment of 126 km^2 (Quinlan, 2014) and flows south-westwards to the Irish Sea.

Ben Gill is a first-order headwater tributary that naturally joined the Ehen immediately downstream from the outlet of Ennerdale Water. Ennerdale Water is a natural post-glacial lake, but its water level and storage capacity were increased by the construction of a 1.3 m high weir in 1902. In 1971 Ben Gill was diverted away from the Ehen so that it discharged directly into the lake, via an underground culvert (see Fig. 1). The original channel that flowed across the alluvial fan (a length of approximately 245 m; dashed blue line in Fig. 1) was infilled and over time terrestrialised. It existed in this modified state for 43 yr, with neither sediment nor water from Ben Gill being delivered directly to the Ehen.

The River Ehen is a designated Site of Special Scientific Interest (SSSI) and Special Area of Conservation (SAC), supporting England's largest remaining population of the endangered freshwater mussel *Margaritifera margaritifera*. Ecological studies showed a declining mussel population, with a lack of juvenile recruitment in the upper Ehen (Killeen and Moorkens, 2013; O'Leary, 2013). The decline was attributed to a lack of suitable sediment and geomorphic activity, resulting in an armoured bed. This important mussel population and the deteriorating habitat in the river provided the impetus to reconnect Ben Gill to the Ehen. The reconnection was considered crucial for the long-term geomorphic integrity of the river, delivering coarse sediment that underpins the development of ecologically important geomorphic units such as riffles and gravel bars, and which creates a looser and more porous bed that, in turn, improves groundwater-surface water exchange.

The reconnection involved blocking off the culvert and excavating a new Ben Gill channel across the alluvial fan, 245 m long and approximately following its original course (Fig. 1). The new channel was engineered to be 5 m wide and 0.5 m deep (mean values) with a semi-circular cross-sectional shape, and with an average gradient of 9.4 %; it was designed to convey a 1 in 100-yr flood (Marteau et al., 2017; Marteau et al., 2018). The engineered channel was lined with gravel and

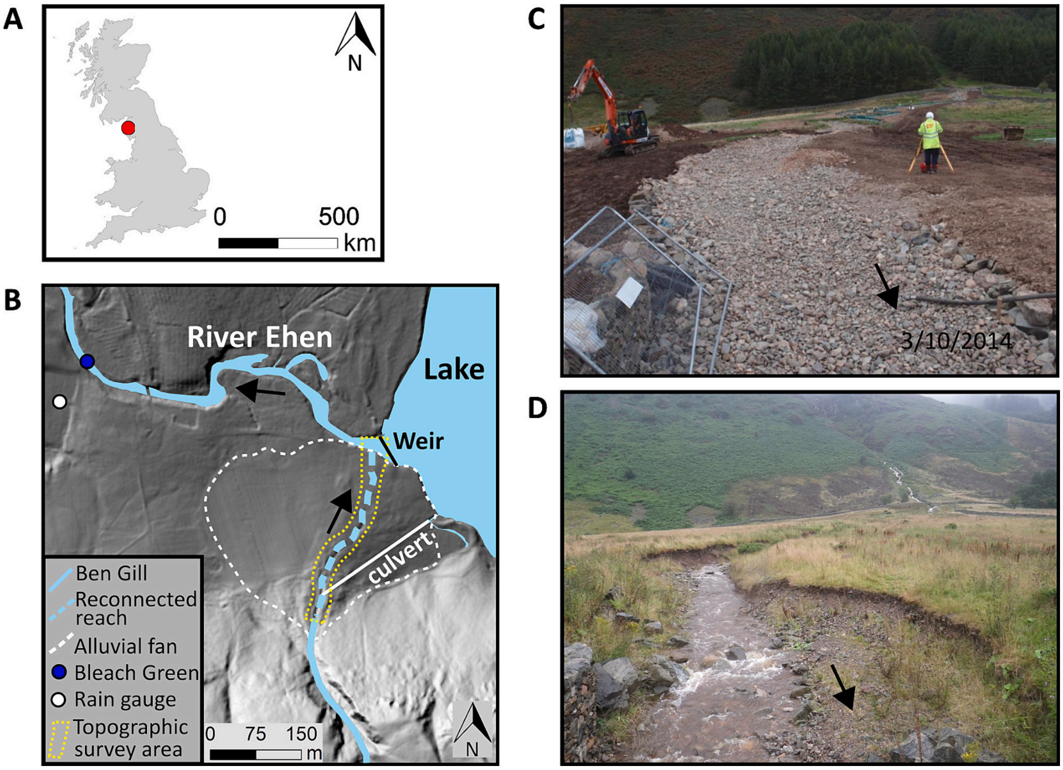

Fig. 1. **A**: Study location within the UK. **B**: Study site map showing the lake (Ennerdale Water), Ben Gill and the River Ehen and other key features. **C**: Restored Ben Gill channel on the day of the reconnection in October 2014. **D**: Same view of the channel in August 2021 during a flow event. Arrows indicate flow direction.

cobbles (20–256 mm b axis) and some boulders (up to 750 mm b axis) (Marteau et al., 2017). The lowermost 30 m of the channel was confined by stone walls (Fig. 6). The engineering works were undertaken in 2014, with the lowermost section completed on 3 October, at which point the Ben Gill sub-catchment was again connected to the Ehen. Beyond restoring a small tributary, this initiative reconnected a significant area of the Ehen's upper catchment which had been disconnected for 43 yr (Fig. 2) and which had created a sedimentary disequilibrium downstream (Quinlan, 2014).

Ben Gill has a steep, small catchment area (0.54 km^2), comprising of heathland, acid grassland and bog, which receives approximately 2000 mm of rain per year. Sediment sources in the Ben Gill catchment include in-channel deposits, alluvial fan deposits, colluvium and rockfall, while in the Ehen (i.e., upstream from the lake), sediment sources include glacial and river terrace deposits. The upper part of Ben Gill (85 % of Ben Gill's total length; henceforth ‘upper Ben Gill’) is perennial. However, during dry, baseflow conditions, all water discharging from the upper catchment infiltrates at the alluvial fan apex, leaving the lower part dry. Hence, the lower section (approximately 245 m) is ephemeral. Following heavy rainfall, this section flows and Ben Gill is able to discharge into the Ehen; both Quinlan (2014) and Marteau et al. (2017) estimated that the lower section of Ben Gill flows for 15–20 % of the time each year. Blackburn et al. (2021) developed a conceptual hydrogeological model of the Ben Gill alluvial fan that helped understand the controls on flow in the lower section of the channel. They estimated that the lower section starts flowing following rainfall events >11 mm and when discharge in upper Ben Gill exceeds 0.06 m^{3}s^{-1} (Blackburn et al., 2021).

Marteau et al. (2020a, b) reported changes in Ben Gill and the Ehen over the 2014–2016 period, during the first two years after the reconnection. Over this period Ben Gill predominantly experienced erosion, with up to 1.7 m of scour in places. The total estimated export of sediment from Ben Gill to the Ehen over this period was 384 m^3. Much of the coarse sediment was deposited at the confluence, forming a gravel bar

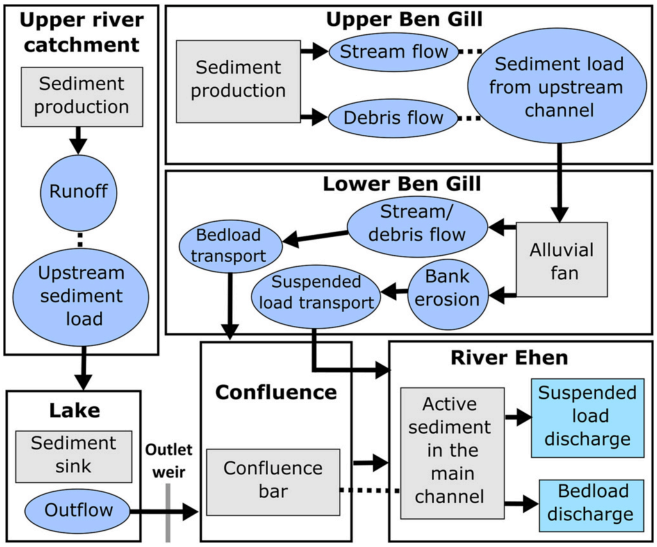

Fig. 2. Sediment budget for the Ben Gill - Ehen fluvial system. Each main system component is shown by a box. The ‘Upper river catchment’ refers to the Ehen upstream of Ennerdale Lake (known as the River Liza); other boxes show the lake, the two sections of Ben Gill (the perennial upper section, and the ephemeral lower section), the Ben Gill - Ehen confluence zone and the main-stem River Ehen. Grey rectangles represent storage; ovals represent transfer processes; solid arrows indicate mass transfer while dashed lines indicate basic links between processes and/or storages (adapted from Dietrich and Dunne, 1978). Note that, for simplicity, dissolved loads and processes such as weathering are not considered. Suspended load transport from the lake to the Ehen is considered marginal (see Quinlan et al., 2015).

that acted as a transient sediment storage unit (Fig. 2), with only the highest flows in the Ehen having the competence to entrain and convey this sediment downstream. Hence, the bar grew progressively over the two-year period. Suspended sediment loads (SSL) in the Ehen increased by 65 % compared to pre-reconnection, and there was evidence of the bed becoming more mobile and the development of new channel features such as gravel bars in the downstream reach (Marteau et al., 2017). Marteau et al. (2020b) concluded that two years after the reconnection Ben Gill and the Ehen were still adjusting to the renewed supply of water and sediment.

A schematic of the Ben Gill - Ehen fluvial system and its sediment budget is presented in Fig. 2. The figure shows the main components of and linkages within the system, and illustrates the key sediment sources, transport pathways and sinks. Note that it illustrates the system post-reconnection, and so the Ben Gill sub-catchment is shown as discharging its water and sediment to the Ehen. During the period 1971-September 2014 when Ben Gill had been diverted into the lake, there was no lower Ben Gill channel or confluence. Over the 43-year period of disconnection, sediment arriving at the fan apex from the upper Ben Gill catchment was retained in a grill located at the diversion point and was periodically removed, while fine material passed through the grill and was transported along the culvert and into the lake. Of the system components shown in Fig. 1, the lower section of Ben Gill, the confluence and the Ehen are those affected by the reconnection and are detailed in this paper. Note that the small larch plantation (area < 0.02 km^2) visible on the alluvial fan debris cone in 2014 (Fig. 1C) was felled and re-planted with native trees in summer 2020, near the end of the study period (Fig. 1D). The ground immediately surrounding the stream remained undisturbed during and after the felling, and there was no evidence of any change in channel after the felling. The rest of the Ben Gill catchment remained unchanged throughout the study period.

3. Materials and methods

3.1. Hydrological data

3.1.1. Rainfall

Daily and 15-min rainfall data from October 2014 onwards were obtained from the Meteorological Office's Ennerdale telemetry rain gauge (station number: 591642), situated 500 m west of the ephemeral part of Ben Gill stream (Fig. 1). Rainfall records were used to help interpret flow observations and to understand the controls on flows and subsequent geomorphic changes.

3.1.2. Streamflow and suspended sediment data

River Ehen discharge data (15-min intervals) from Bleach Green weir, located 550 m downstream from the confluence with Ben Gill (Fig. 1), were obtained from the Environment Agency (EA). These covered the seven-year study period (October 2014 to August 2021). Ben Gill was only gauged for one year out of the seven-year study period (detailed in Blackburn et al., 2021). A time-lapse camera located at the confluence, as reported by Quinlan et al. (2015) and Marteau et al. (2018), was used to assess the presence of flow in the lower (ephemeral) part of Ben Gill. This camera took images every 60 min from June 2015 to August 2021, providing visualisations that were used to estimate flow duration and magnitude. The one-year continuous gauged data and time-lapse imagery indicated that flow events in Ben Gill typically last around 24 h (range 3–96 h). The 60-min time-lapse interval was therefore considered suitable for capturing peak or near-peak discharges of the events, while not risking filling up memory cards and losing events as would have been the case if a shorter interval was used. Approximately 50,000 images were classified into flow categories that represented stream stage at respective points in time. The classification was: 0 = No flow, 1 = Low flow, 2 = Moderate flow, 3 = High flow, 4 = Very high flow, as used by Quinlan et al. (2015). Prior to the telemetry camera installation in June 2015, flow data was collated from a battery powered time-lapse camera and field observations (Marteau et al., 2020a, b).

Suspended Sediment Concentrations (SSC) in the Ehen were estimated using turbidity data from Bleach Green weir. Turbidity (NTU) was logged at 15-min intervals over the study period using a YSI® probe fitted with self-cleaning wipers. The probe has a 0.1 NTU resolution and a 2 % or 0.3 NTU accuracy (whichever is greater). The probe was maintained by EA and cleaned every 2 to 3 months (except during the COVID-19 pandemic). The empirical NTU-SSC relationship constructed by Marteau et al. (2017) was used to convert NTU values to SSC; see this paper for details. SSC data were manually checked and cleaned to ensure elevated SSC values were not artifacts caused by probe issues. The COVID-19 pandemic in 2020–2021 affected the cleaning regime of sondes and resulted in some extended periods of erroneous data. This limited the possibility of complete analysis of the SSC time-series.

3.2. Topographic surveys

Topographic surveys and all related analyses of Ben Gill focussed on assessing changes in the newly excavated section of the channel that cuts across the alluvial fan (Fig. 1). Thus, all subsequent references to 'Ben Gill' concern this section. Topographic surveys along this channel and downstream to the confluence of Ben Gill and Ehen were conducted by means of photogrammetry using aerial images captured with a drone. Data presented here include integration of images captures by Marteau et al. (2020a, b) in the first two years following reconnection (October 2014–November 2016), and those undertaken over the more recent period (November 2017–August 2021). In total, 22 flights were undertaken (8 over 2014–2016 and 14 over 2017–2021), allowing assessment of geomorphic changes in Ben Gill and the confluence zone over the seven-year period since the reconnection. Continuous heavy rainfall the day after the reconnection (4 October 2014) prevented a baseline 'time zero' aerial survey. An rtk-GPS based topographic survey (derived from 37 cross sections along the 245 m channel) undertaken by engineering contractors shortly before the reconnection was therefore used as the baseline. From this GPS survey, volumetric changes between the day of the reconnection and the first aerial survey (16 October) were calculated (see full details in Marteau et al., 2020a).

Full details of survey and workflow methods can be found in Marteau et al. (2017) and Marteau et al. (2020a). For the 2017–2021 surveys we used the same data processing workflow as these authors, though field survey methods differed slightly. For the 2017–2021 surveys a total of 43 fixed ground control points (GCPs) were installed along the restored Ben Gill channel, compared to 180 in the 2014–2016 surveys. The GCPs were surveyed in using a Leica Viva® GNSS (Lecia Geosystems) differential rtk-GPS with the same fixed base station point as 2014–2016. The smaller number of GCPs yielded reliable 3-D models (see error analysis below). The error in coordinates varied between 0.008 m and 0.018 m. A DJI Mavic Pro with a built-in 12.3 Mp camera was used for the 2017–2021 surveys. Images were taken at 15–20 m above ground level at 2 s intervals on a flight path up and down the channel; GCPs were easily visible in the images. This resulted in a total of 320–350 overlapping images per survey. Images were checked and out-of-focus ones were discarded before processing. Surveys were only undertaken when the channel was wholly or mostly dry.

3.2.1. Photogrammetry & error analysis

Images were processed using Agisoft® PhotoScan Professional (Version 1.4.0) (Agisoft LLC, 2018). Images were added then aligned, with the centre of each GCP marker identified and adjusted manually. Orthophotos and 3D dense point clouds were generated. Dense point clouds were regularised in ArcGIS 10.7 (Esri© Inc., USA) using the ToPCAT algorithm (Brasington et al., 2012). ToPCAT is freely available from the Geomorphic Change Detection (GCD) software as an ArcMap addin (see http://gcd.riverscapes.xyz/ or Wheaton et al., 2010) for the methodological developments). From this, regularised *Z*-minimum point clouds were generated with a 0.05 by 0.05 m grid cell format whereby the minimum value represents the elevation. Triangular Irregular Networks (TINs) were computed from these and then DEMs with 0.05 m cell size were created. This process follows Marteau et al. (2020a).

Twenty-one DEMs of Difference (DoDs) were produced to represent topographic changes occurring between successive surveys. These were calculated using ArcGIS by subtracting the topography of the previous DEM from the latest DEM. A minimum level of detection (minLoD) threshold of ±0.05 m was applied. This minloD was based upon the maximum error observed when comparing the differences between in-field rtk-GPS and DEM coordinates of 23 additional test GCPs used as control markers (not used in DEM creation). Mean residuals for these test GCPs $X = -0.002$ m, $Y = 0.017$ m, and $Z = 0.009$ m. Marteau et al. (2017) conducted rigorous error analysis for the 2014–2016 surveys and because of the low error associated with those surveys, a uniform minLoD threshold was deemed sufficient for the 2017–2021 ones. Changes below the minLoD were considered uncertain and not used for the computation of the DoDs. Areas within the channel where vegetation grew during the summer months were excluded from DEMs to prevent confusion between plant growth and deposition. All 2017–2021 surveys used the same fixed 43 GCPs to ensure consistency during data collection and to minimise error.

The gravel bar at the confluence of Ben Gill and Ehen increased in size over the study period (see Section 4) but during high flows was submerged under turbid water. These conditions prevented detailed analysis of area and volumetric changes in changes in the bar. Instead, the highest elevation on the bar was extracted from each DEM and used to assess changes in bar height since the reconnection.

3.2.2. Channel measurements

Bankfull area in Ben Gill was assessed by locating the edges of the bank top from orthophotos. Mean channel width for each survey was then calculated by dividing the total bankfull channel area by the length of the channel using orthophotos and DEMs. Channel bed elevations were determined to enable direct elevation comparisons along the channel profile over time, as thalweg lengths changed dramatically and therefore could not be directly compared. Mean channel elevation values were calculated by extracting the elevations of 243 fixed points (a point every metre along the channel) within the active channel from each DEM. For presentation of monthly bed elevation changes, the newly constructed channel was divided into lower, middle and upper sections, each 81 m in length and comprising 81 data points. These same subdivisions are also used for describing channel features and observed changes.

3.3. Geomorphic unit detection

The Geomorphic Unit detection Tool (GUT) developed by Wheaton et al. (2015) was used to analyse the geomorphological features within Ben Gill. The tool required inputs including channel DEMs, thalweg profiles, bankfull widths, low flow widths and channel centre lines; these were obtained from the topographic survey data. GUT runs in python with ESRI dependencies and uses a 3-tier framework to identify the channel margins (tier 1), geomorphic shapes and types (tier 2) and specific geomorphological units (tier 3) (see Wheaton et al. (2015) for further details). Geomorphic features identified by GUT were validated through field observations. The excavation of Ben Gen Gill did not include creation of any geomorphic units (i.e., channel slope was uniform and there was no purposeful longitudinal arrangement sediment grain sizes). GUT was therefore used to assess development of identifiable, water-worked morphological features in Ben Gill from this starting point.

4. Results

4.1. Ben Gill geomorphology

Based on analysis of hourly time-lapse images, Ben Gill flowed for 18 % of the time between its reconnection in October 2014 and August 2021. Over this period, 325 distinct flow events occurred; the longest event (in March 2019) lasted for 14.6 days, though most lasted between 3 and 96 h. Despite only experiencing intermittent flows, Ben Gill underwent appreciable geomorphic changes over the period, evident in various metrics extracted from the DEMs and DoDs. In the sections which follow we present data on each of these metrics.

4.1.1. Volumetric changes

Estimates of mean monthly volumetric change in Ben Gill (based on the DoDs), along with potential hydroclimatic drivers for the same time intervals, are given in Fig. 3. In the first two weeks following the reconnection (i.e., the difference estimated from the rtk-GPS survey and first aerial survey) there was an estimated net erosion of 29.2 m^3 (91.4 m^3 erosion, 62.2 m^3 deposition) (Marteau et al., 2020a). As this estimate is from a two-week period, we did not extrapolate up to compute mean monthly volumes, and so it is not so shown in Fig. 3.

The magnitude of volumetric changes (erosion and deposition) decreased substantially and progressively over the seven-year period. Erosion almost always greatly dominated over deposition, so the net change in Ben Gill has mostly been negative (Fig. 1 Inset B). The most recent two years, however, have seen generally lower and rather stable values of erosion and deposition, with net change close to zero. During the first two years of the reconnection the net export of sediment from Ben Gill was 384 m^3 (~192 m^3/yr) (Marteau et al., 2020a), whereas from November 2017 to August 2021 the net export of sediment was 135 m^3 (~29 m^3/yr). The exported sediment comes from within the new channel, essentially from erosion of the alluvial fan, and also material delivered from upper Ben Gill catchment, but our analyses do not allow us to assess the relative contribution of these two sources.

No long-term directional trends in maximum rainfall or flow were observed (upper panel in Fig. 3), so the general reduction in erosion and

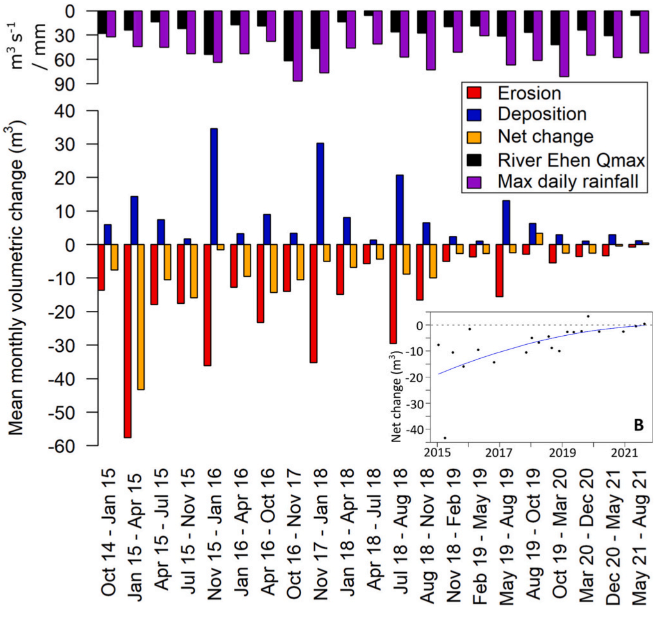

Fig. 3. Mean monthly volumetric changes within the lower reach of Ben Gill. The maximum Ehen discharge and maximum daily rainfall are also shown. Inset **B** shows the net mean monthly volumetric changes between each period where the X-axis represents continuous time. A smooth spline regression trend line was fitted ($P < 0.05$, $R^2 = 0.4$).

deposition occurred independently of these potential external drivers. Some variability in rainfall totals and intensities and flow magnitude between survey periods occurred, which may explain differences in the magnitude of volumetric change between respective periods, but the lack of any trends in the hydroclimatic data indicate that the consistent trajectory of the geomorphic activity was being controlled by intrinsic factors.

4.1.2. Channel elevation and width

Concurrent changes in channel elevation and width were modelled from October 2014 to August 2021 using a piecewise regression (Fig. 4). The regression ($R^2 = 0.97$) was fitted in R using the segmented package (Muggeo, 2008). Mean channel elevation decreased by 0.27 m in the first two years after the reconnection, but subsequent changes were negligible (as indicated by the break in slope of the regression). Mean channel width increased from 5 m (the width of the new engineered channel) to 6.2 m over the seven-year period. Most of this increase happened in the first three years (5.0 to 5.7 m = 0.7 m) with more modest rates of change in the following four years (5.7 to 6.2 m = 0.5 m).

The estimated mean monthly bed elevation change (Fig. 5) was generally negative in the first 3–4 yr following reconnection (i.e., bed elevation was lowering). However, the general trend (central black line in Fig. 5) was of a reduction in the rate of negative change, and by late 2018 values were close to zero. The dashed lines bounding the distribution plot the maximum and minimum values and help illustrate a trend of reduced variability over time - vertical spread is much reduced in 2019–2021 compared to the 2014–2018 period. In particular, the lower line has a steep slope, indicating that the maximum reductions on bed elevation have reduced dramatically over time. The magnitude of bed elevation change differed between the upper, middle and lower subsections of the channel. The mid-channel subsection typically experienced the greatest decreases in elevation, whilst the upper subsection exhibited values closer to zero or even positive (i.e., an increase in elevation). The dynamics of the lower subsection changed little over the period, switching between minor increases and minor decreases in elevation (Fig. 5).

Some of the differences between subsections are also evident from plots of channel bed elevations over time (Fig. 6A). These mean elevations are based on the values extracted from 243 fixed points along the channel. The major change that occurred in the middle and part of the lower subsections (100–180 m from upstream end) in the first couple of years after the reconnection is evident from the position of the red line. Another smaller decrease in bed elevations in the upper channel over the 35–60 m distance (Fig. 6A) occurred during the first year following the reconnection. These changes represent two knick-points that migrated upstream before fading out. Channel bed elevation changes were predominantly negative and at their greatest during the first three years of the reconnection, with a drop in elevation observed along much of the channel between 2014 and 2017 (Fig. 6A). Elevation changes between 2017 and 2021 were minor in comparison.

4.1.3. Planform changes

Ben Gill became progressively more sinuous over time, with two points are notable from Fig. 6B. The first is the presence of an outlier in April 2015. The high sinuosity on this date resulted from an increase in channel length of 25 m compared to the previous survey. However, by the following survey (July 2015) channel length was shorter (by 17 m) and correspondingly the sinuosity was reduced. This change is indicative of the dynamism in the first months following the reconnection. The second point to note is that the overall trend was non-linear. The modelled line indicates that while channel sinuosity increased up until the end of the survey period, the rate of change reduced latterly.

Some examples of thalweg lines and channel migration are shown in Fig. 7A. The middle subsection experienced the clearest increases in sinuosity from October 2014 to August 2021. Change in the upper subsection mainly involved a westward migration of part of the channel, while (ignoring the area constrained by the wall) the lower subsection remained relatively straight, with changes mainly in the position of meanders rather than an increase in sinuosity.

4.1.4. Development of geomorphological units

Ben Gill channel was 5 m wide and 0.5 m deep when excavated in 2014. It was lined with coarse gravel and cobbles, with some boulders

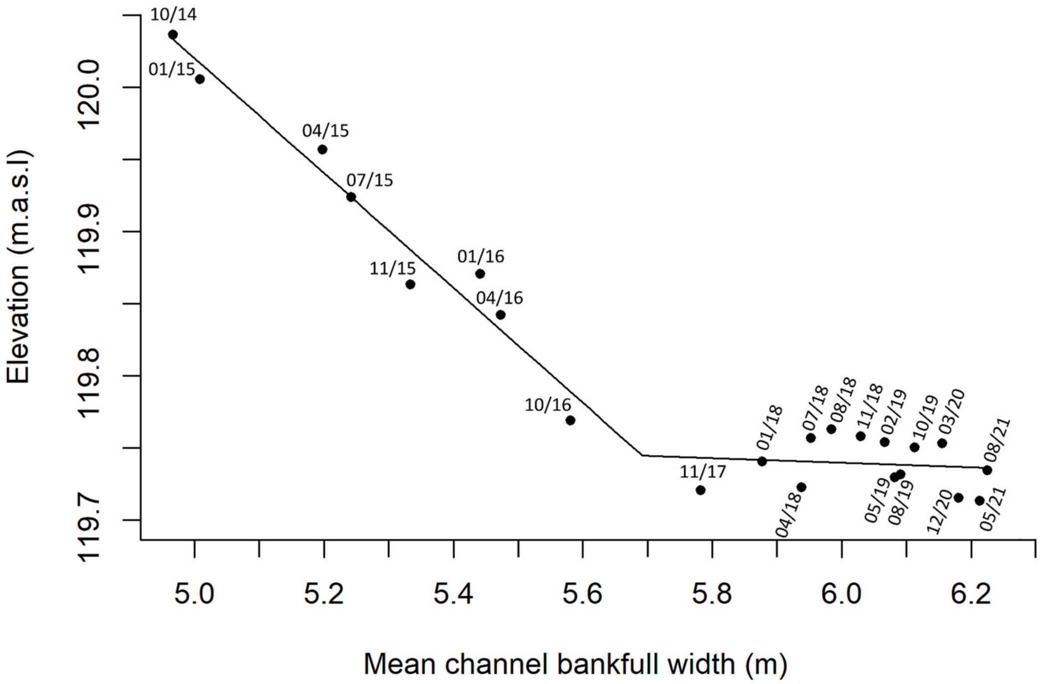

Fig. 4. Changes in mean channel bed elevations and channel bankfull width in Ben Gill from 2014 to 2021. Survey dates included are in the format MM/YY. The line is a piecewise regression model ($R^2 = 0.97$).

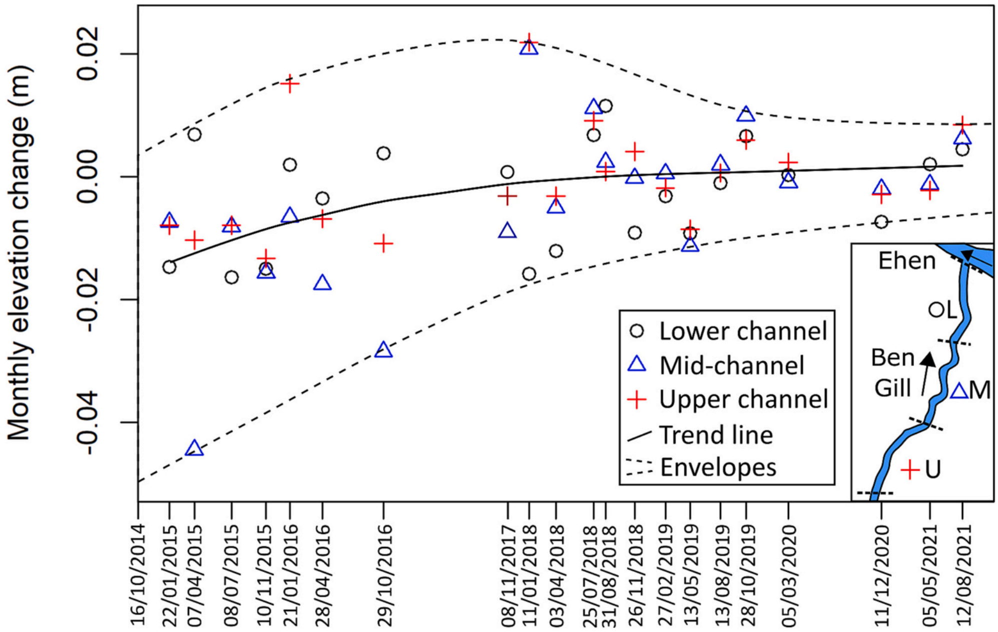

Fig. 5. Mean monthly bed elevation changes for the lower, middle, and upper subsections of the Ben Gill channel. Each set of three points represent elevation changes from the previous survey (22/01/2015 points represent elevation changes from the first survey in October 2014). The map in the lower right indicates the locations of these subsections; arrows show flow direction. Data was fitted with a smooth spline regression trend line ($P < 0.05$, $R^2 = 0.4$).

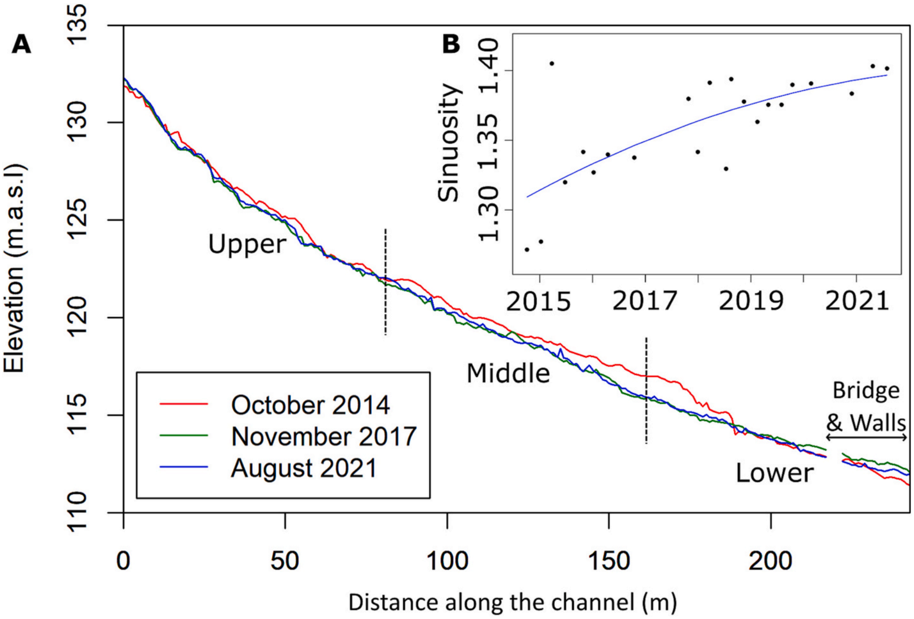

Fig. 6. **A**: Channel bed elevations in Ben Gill derived from 243 fixed points, one every metre within the active channel, extracted from DEMs. The gap at 220–226 m is where an access bridge crosses. **B**: Ben Gill channel sinuosity October 2014–August 2021 measured along the channel thalweg. The data was fitted with a smooth spline regression trend line ($P < 0.05$, $R^2 = 0.53$).

along the channel edge, and no attempt was made to create geomorphic units or introduce geomorphic heterogeneity along the channel. As reported previously (Marteau, 2017; Marteau et al., 2018), the completion and opening of the channel coincided with a period of extremely high rainfall which resulted in major and immediate changes, as the channel responded to its first wetting. The first full aerial survey was undertaken two weeks after this, so captured the first water-worked conditions in the channel. Fig. 7 compares geomorphic units on this date (October 2014) with the most recent survey (August 2021).

Even though the result of a single flow event, the October 2014 channel exhibited a step-pool, step-step and cascade morphology whilst numerous incipient lateral bars, channel banks and proto-terraces had developed following incision and reworking of the coarse gravel and cobbles that were used to line the channel. Parts of the middle and lower channel - interpreted as transition zones by the GUT tool - represented areas where little geomorphic reworking had occurred and so the engineered channel bed remained largely intact. Rapids had formed within sections of the newly incised, narrow channel as a result of this first flow event.

By 2021, step-step, cascade and step-pool morphologies dominated the channel, though the frequency of step-pools had decreased. Cascades were predominantly located in the upper subsection, whilst the middle

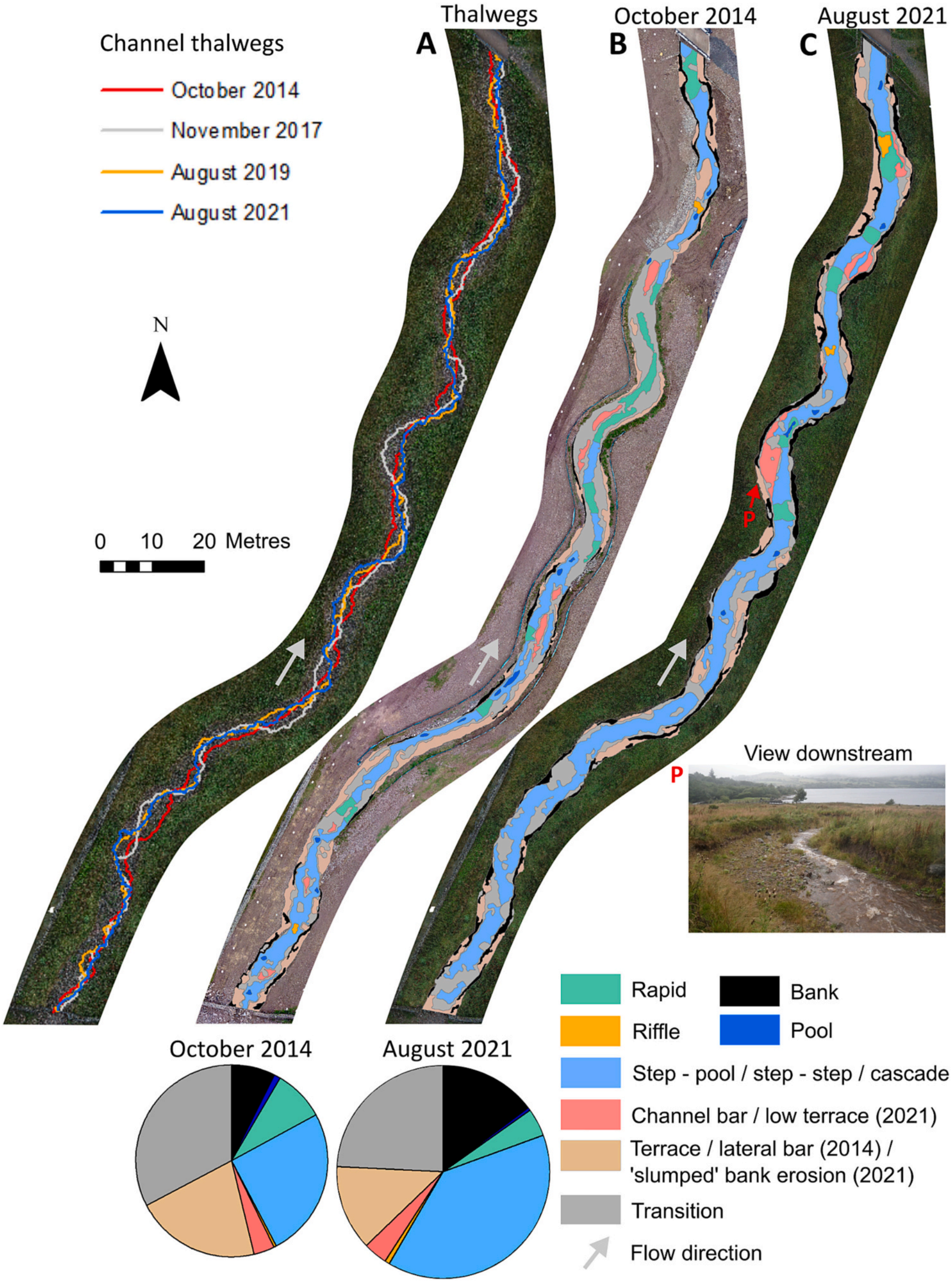

Fig. 7. **A**: Channel thalwegs for Ben Gill derived from four DEMs (2014, 2017, 2019 and 2021), highlighting changes in thalweg positions and channel sinuosity (excludes the lowermost 30 m where the channel goes under a bridge and is confined by walls). **B**: Geomorphic features within Ben Gill in October 2014 two weeks after the reconnection. **C**: Geomorphic features in August 2021, almost seven years later. Features were identified using the geomorphic unit tool software (GUT) developed by Wheaton et al. (2015) and were further interpreted based on field surveys. Some bar features were interpreted as terraces or slumped/collapsed bank material, commonly resulting from lateral erosion. The inset photo (P) in Fig. 7 depicts a low terrace feature in 2021. Pie charts summarising the geomorphic unit coverage are proportionally sized to the total channel area.

and lower subsections exhibited a greater degree of morphological heterogeneity, containing step-steps, step-pools, rapids, bars, terraces, and a riffle. Low terraces forming floodplains developed where channel widening had occurred (Inset photo in Fig. 7), whilst high terraces (up to 1 m above the bed level) colonised with grasses and shrubs formed where incision had resulted in the abandonment of the original channel bed.

4.1.5. *Ben Gill sediment sources*

The Ben Gill alluvial fan contains a large volume of sediment, which became newly available for transport once the culvert was blocked off and water flowed down the engineered section of channel. Other sources of sediment include the material used to line the channel, and material delivered from the upper catchment (see Fig. 2). These sediments are predominantly coarse, comprising sands, gravels, cobbles and boulders, though silt and small amounts of clay are present in the alluvial fan and upper catchment till deposits (Blackburn et al., 2021). The following sections describe how this material has influenced the Ehen.

4.2. *Impacts on the River Ehen*

4.2.1. *Confluence bar*

Much of the coarse sediment transported by Ben Gill was deposited at its confluence with the Ehen, forming a large gravel bar. This bar was not present prior to the reconnection, though old images show that it existed before the original diversion of Ben Gill to the lake. It developed very quickly following the reconnection, and within the first two weeks was 1 m deep in places. As detailed by Marteau et al. (2020a), net deposition occurred in the first two years and so the bar continued to grow.

Fig. 8 shows the evolution of the bar between 2014 and 2021, using its maximum elevation as an index. Prior to the reconnection there was no bar, so the elevation of this area equated to bed level (horizontal line in Fig. 8). Following the reconnection, the maximum bar thickness has remained consistently at least 1 m higher than the original bed

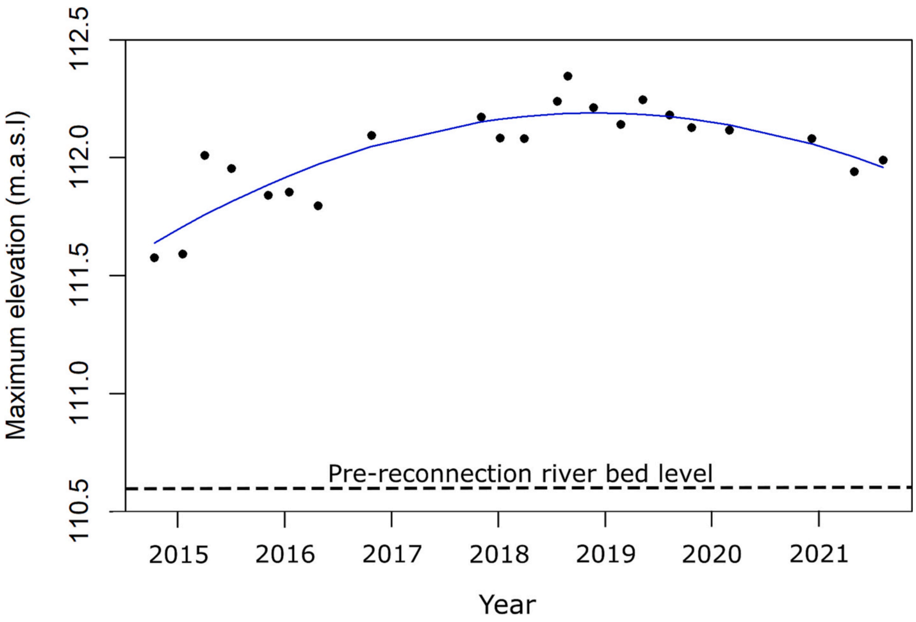

Fig. 8. Maximum elevation of the confluence bar, measured from successive DEMs, from the first aerial survey in October 2014 to August 2021. The pre-reconnection riverbed level was approximately 110.6 m ASL. The graph shows a smooth spline regression trend line ($P < 0.005$, $R^2 = 0.766$).

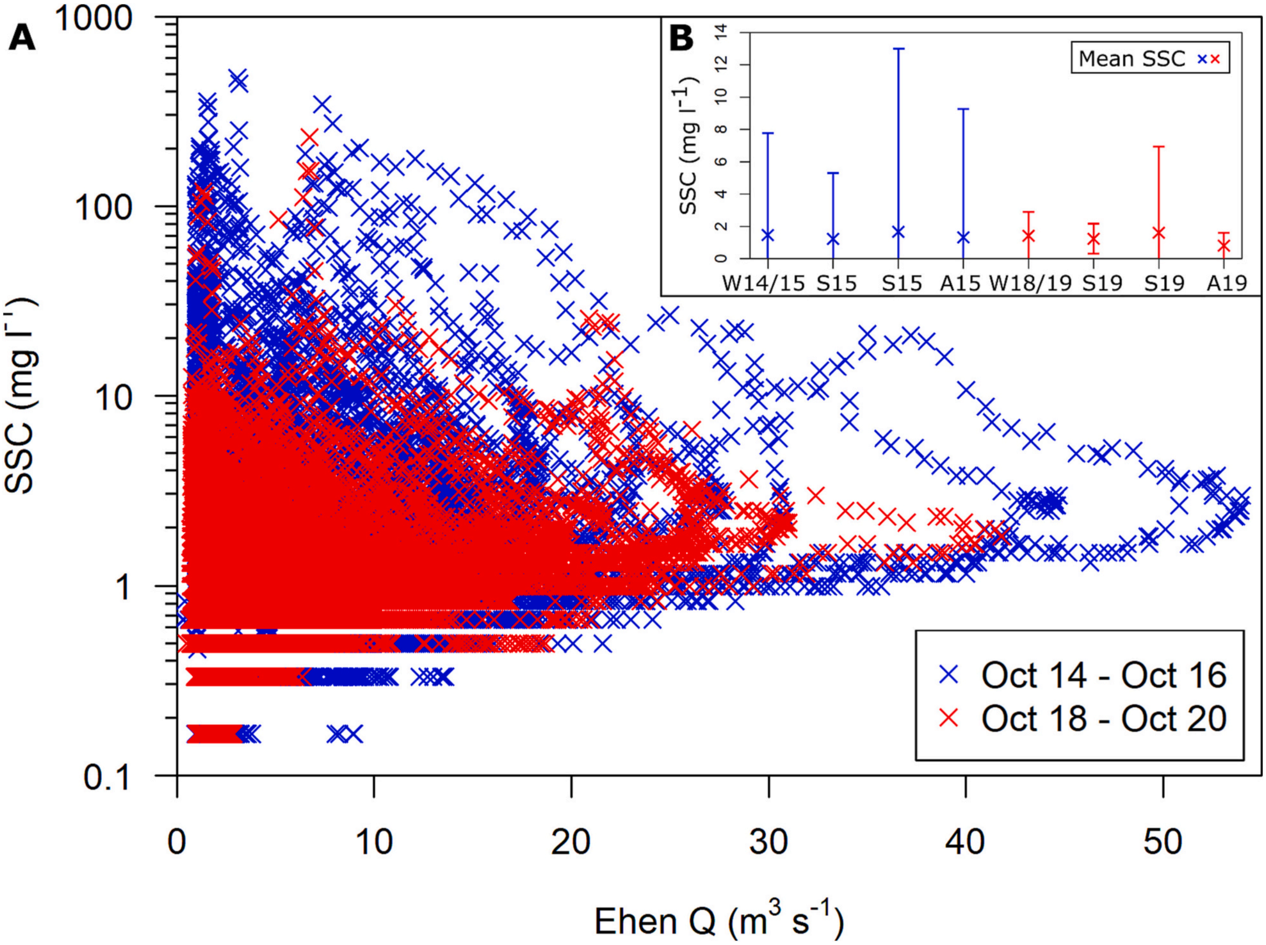

Fig. 9. A: Suspended sediment values plotted against discharge for the upper River Ehen at Bleach Green, situated 550 m downstream of the confluence. Blue crosses represent values during the first two years of the reconnection while red crosses represent SSC values 4–6 yr after the reconnection. **B**: Comparison of seasonal mean and standard deviation SSC values for the 2014–2015 and 2018–2019 seasons; W = Winter, S = spring, S = Summer, A = Autumn, using Northern Hemisphere meteorological seasons.

elevation. However, following progressive heightening between 2015 and late 2017, the rate of change slowed and there was little change evident over the period 2018–2019. Surveys since 2019 indicate that the maximum height of the bar is lowering, with the height in August 2021 being approximately 0.3 m lower than the peak attained in mid-2018.

4.2.2. Suspended sediment dynamics

The reconnection of Ben Gill re-established a sediment (and water) supply to the upper Ehen, with large volumes of fine material transported into the river during periods when the channel was flowing (detailed in Marteau et al., 2020b). This section focuses on fine sediment dynamics in the Ehen, with emphasis on assessing whether these dynamics have changed since the reconnection. Fine sediment is used as a measure of wider geomorphic activity in the Ehen.

Prior to the reconnection of Ben Gill SSCs in the Ehen were very low, with a peak value of 190 mg l^{-1} over the period 2011 - September 2014 (Marteau et al., 2017; Quinlan et al., 2015), as the only sources of fine sediment were the limited inputs from the lake and riverbanks. Following the reconnection, as detailed by Marteau et al. (2017), peak SSCs increased dramatically, with the first flow event (October 2014) resulting in SSC values exceeding 1700 mg l^{-1}, 900 % greater than peak pre-reconnection ones. However, as Ben Gill was dry for 82 % of the time, SSCs in the Ehen remained low throughout these lengthy zero flow periods, and therefore mean SSCs change little following the reconnection.

Fig. 9 compares discharge-SSC relations for the first two years following the reconnection with the most recent complete two-year SSC dataset (because of COVID, not all years had continuous data; see Section 3). In line with Ben Gill volumetric change data (Fig. 3), Fig. 9 compares SSC data from 16 October 2014 onwards, therefore excluding the initial period within which the exceptional >1700 mg l^{-1} value occurred. Data relate to values recorded at Bleach Green weir on the Ehen. Mean and minimum SSCs in the two periods were similar. However, peak SSCs decreased across the whole of the flow range, causing the constellation of data values for the most recent period to occupy a lower position and cover a more restricted area on the scatterplot than the initial 2-yr period. The inset (Fig. 9B) shows that the magnitude of variability also reduced over time. Season by season, SD values were lower in the more recent period than immediately post-reconnection.

5. Discussion

5.1. Main findings

Long-term monitoring of the system revealed the nature of geomorphic evolution within Ben Gill, sediment export, the development of the confluence bar and changes to fine sediment dynamics within the Ehen. All lines of evidence indicated high magnitude geomorphic changes in the newly reconnected system within the first two years following the reconnection. Major changes included erosion and subsequent deepening and widening of the Ben Gill channel, the rapid development of a confluence bar and an increase in fine sediment loads in the Ehen. After this initial period, the rate of geomorphic change in Ben Gill began to decrease and the rate of growth of the confluence bar slowed. Fine sediment volumes in the Ehen also decreased steadily. Overall, the trajectories suggest that approximately 4.5 yr after the reconnection the Ben Gill - Ehen system has reached a new, adjusted regime state.

Fig. 10 conceptualises geomorphic changes in Ben Gill (planform changes, changes in channel elevation and width; empirical details in Figs. 4-6), sediment export from Ben Gill (details in Fig. 3), evolution of the confluence bar (details in Fig. 8) and changes in the fine sediment flux in the Ehen (details in Fig. 9). As described below, evidence suggests that the system has moved through a series of distinct stages and is now, seven years after the reconnection, in what we have termed a new 'adjusted state'. The nature of the changes, in terms of their rates and magnitude, reflect the peculiarities of the Ehen system, and so the trajectories plotted in Fig. 10 are best interpreted within the context of Fig. 2, which shows the key components of the Ben Gill - Ehen system. Note that the perennial upper part of the Ben Gill catchment was not affected by the reconnection (Fig. 10), so the figure represents only the lower (engineered) section, along with the Ehen. The following sections discuss these changes and their implications, based around the generalised trajectories shown in Fig. 10.

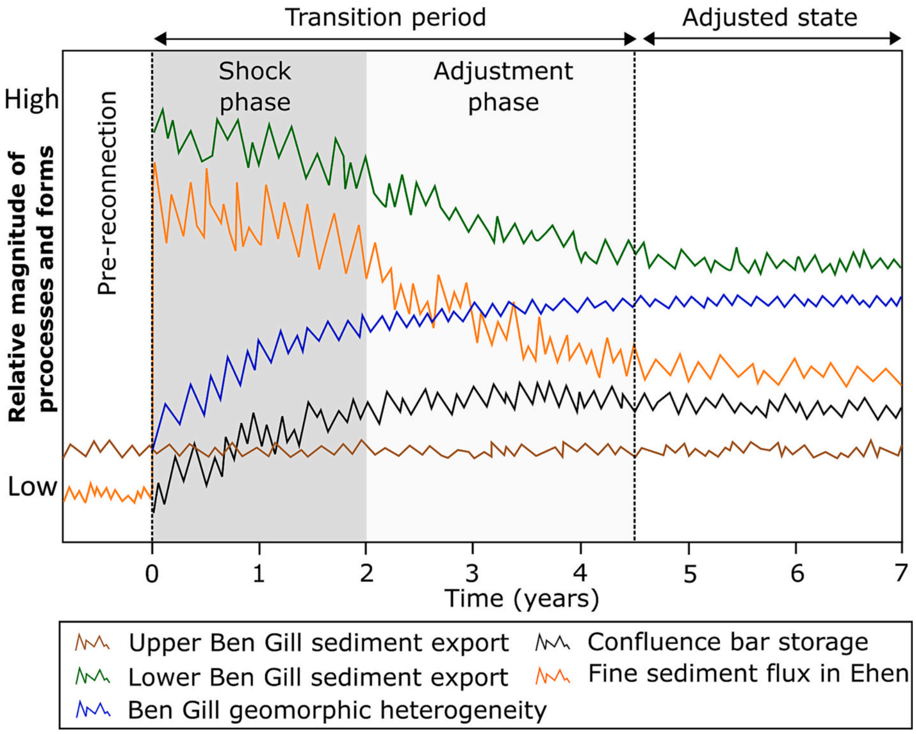

Fig. 10. Conceptual representation of the relative magnitudes of processes and forms and their trajectories in Ben Gill, at the confluence and in the uppermost River Ehen over the study period. The point on the X-axis labelled 0 is October 2014, when Ben Gill was reconnected to the Ehen. All changes and trajectories displayed are derived from the evidence presented in Section 4. Lines highlight the general trends whilst stressing the occurrence of short term fluctuations caused by event-based and seasonal variability.

5.2. Post-reconnection changes

5.2.1. Transition period

The reconnection re-coupled the Ehen to its major source of sediment after 43 yr of disconnection (Marteau et al., 2020a, b). The transition period (period between the initial and adjusted regime states) began immediately after Ben Gill and its catchment were reconnected to the Ehen. It lasted approximately 4.5 yr and consisted of two distinct phases - a highly dynamic shock phase and an adjustment phase (Fig. 10).

5.2.2. Shock phase (October 2014 - approximately October 2016)

Ben Gill: Geomorphic adjustments began with an initial shock phase dominated by erosion and incision in the newly engineered Ben Gill channel where it crossed the alluvial fan. By coincidence, a period of exceptionally high rainfall occurred the day after Ben Gill was reconnected to the Ehen (Marteau et al., 2020a). This rainfall resulted in a 100-yr flow event that, coupled with abundant sediment coming from the steep upper part of the catchment and the loose sediment used to line the new channel, exhibited debris flow characteristics. Thus, over the first few weeks and months, as a result of this and subsequent flows, the new channel underwent rapid changes. The channel gradient was over steepened at the fan toe (closest to the Ehen), where typically the channel profile would be expected to shallow-out. This oversteepening was associated with significant incision and the development of two main knick-points as the channel adjusted towards a more natural profile. These knick-points migrated upstream before fading out in 2016. Thalweg sinuosity increased, resulting in some lateral erosion and channel widening.

River Ehen: Significant erosion in Ben Gill caused high volumes of coarse and fine sediment to enter the upper Ehen in the first days following the reconnection. A confluence bar developed rapidly from the deposition of coarse gravels and cobbles exported from Ben Gill. This bar acted as a buffer, storing much of the coarse sediment which the Ehen could not transport downstream under normal flow conditions. Peak SSC values at Bleach Green increased sharply from pre-reconnection values (Marteau et al., 2017). Peak SSC values were at their highest during this shock phase, frequently exceeding 100 mg l^{-1} in association with high levels of erosion in Ben Gill. Time-lapse imagery showed turbid, sediment-laden water entering the Ehen during periods of flow. A small, lateral coarse gravel bar began to develop in a riffle section about 100 m downstream of the confluence.

Adjustment phase (Approximately November 2016 to late 2018/ early 2019).

Ben Gill: The second part of the transition period saw changes that were less dramatic than in the shock phase. By this stage, the major incision associated with the knick point migration during the shock phase had faded out, so incision during the adjustment phase was lower in magnitude, and more localised in comparison to the shock phase. Erosion rates gradually decreased through the adjustment phase and the predominant erosion type switched from bed incision to lateral erosion. Channel widening dominated in areas where the banks were composed of material (rubble, soil, clay) that was used in the 1970s to infill the original (natural) channel. These anthropogenic sediments were typically less cohesive than the coarse alluvial fan sediments and were therefore preferentially eroded. Bend migration and associated undercutting resulted in bank collapses and widening of up to 3 m during the adjustment phase. The channel thalweg frequently migrated and increased in sinuosity, forming new meanders. Marked changes in sinuosity continued during 2017–2018 as reduced incision increased the potential for lateral flow path variability. Minor incision formed small knick-points and low floodplain terraces whilst lateral bars developed within wider channel sections. Bank collapses led to turf failures and bank toe colluvium, upon which grasses and meadow plants began to colonise. Geomorphic heterogeneity in Ben Gill increased with the rapid development of new water-worked features that included incipient lateral bars, proto-terraces, bottle necks, slot channels, steps, step-pools and debris lobes. Gurnell et al. (2006) observed similar rapid bed profile adjustments and the establishment of riffles within the first two years of a newly constructed channel reach on the River Cole in England.

River Ehen: During the adjustment phase, coarse material continued to be transported from Ben Gill and deposited in the Ehen at the confluence bar, increasing bar size and elevation. This raised the base level of Ben Gill resulting in channel filling (deposition) within the lower reaches where incision had previously occurred (Fig. 6A). Some coarse sediment was transported downstream from the gravel bar, forming a carpet of mobile gravels on the Ehen riverbed, and increasing the size of the lateral bar that had developed since the reconnection. Decreasing erosion in Ben Gill led to a gradual reduction in volumes of fine sediment entering the Ehen, resulting in a decrease in the frequency of peak SSC values exceeding 100 mg l^{-1}.

5.2.3. Adjusted state (Mid-2019 onwards)

Ben Gill: By approximately mid-2019 Ben Gill appeared to have reached a new adjusted regime state. It is best considered as a state of dynamic equilibrium, as expected for such a high energy channel. Erosion and deposition continue but at an order of magnitude lower than during the shock phase, as the channel has now adjusted towards a more natural state. Minor episodic incision and channel filling occur, possibly associated with changes to the base height of Ben Gill (height of the confluence gravel bar). Lateral erosion from thalweg migration continues, though bank collapses are less frequent, typically only occurring during high magnitude flow events. Many banks have stabilised to some degree and are vegetated with grasses, meadow plants and gorse, though unstable, erodible bank material remains. Thalweg sinuosity is much greater, equating to a 25 m increase in length since October 2014. Thalweg sinuosity continues to slowly increase but with reduced variability compared to the adjustment phase. The channel comprises well developed geomorphic features including step-steps, step-pools, cascades, abandoned high terraces, low terraces, lateral bars and minor riffles (Fig. 7). Many areas of major bank collapse have recovered, with bank toe colluvium deposits colonised with grasses and meadow plants that help to stabilise the banks and protect them from further erosion.

River Ehen: A reduction of sediment entering the Ehen from Ben Gill along with occasional high river flows have led to slight erosion of the confluence bar. Channel stabilisation in Ben Gill has resulted in a further decrease in peak SSC values within the upper Ehen, with low magnitude flows in Ben Gill having only a negligible impact on SSC in the Ehen. Though peak SSC values typically remain higher than pre-reconnection ones, they rarely exceed 100 mg l^{-1}. The uppermost Ehen ($<$ 130 m downstream of the confluence) appears to have adjusted to the reconnection. This includes a 45 m long lateral bar which has formed along the right bank in the middle part of the study reach. Farther downstream in the reach, the Ehen morphology continues to adjust as coarse sediment derived from Ben Gill is periodically conveyed downstream. Observations include the development of smaller lateral bars and associated narrowing and deepening of the channel.

Despite the reduction in both coarse and fine sediment entering the Ehen, Ben Gill remains a high energy, dynamic system with plentiful sediment sources (material delivered from the upper catchment and material forming the alluvial fan).

5.2.4. Conceptualising changes

Our conceptual model is useful for summarising changes in the newly re-coupled Ben Gill - Ehen system. Nevertheless, such models are most useful in instances where the ideas they represent are transferable to other systems or circumstances. It is unclear whether other river rehabilitation projects progress through a similar series of changes, as few comparable studies have been published. It is therefore best to see our conceptual figure as providing some hypotheses that need to be tested. We predict that most systems adjust to their new regimes state via a series of phases, but that characteristics and durations of these phases will differ as a function of catchment hydrology, geology (sediment supply), channel characteristics (e.g., gradient and confinement), flood frequency and the type of intervention involved (as outlined, e.g., by Reinfelds et al., 2004). It is likely, for example, that the extreme nature of the shock phase evident in the Ehen system arose because of the somewhat peculiar circumstance of a new, engineered channel cutting across an alluvial fan and the fact that flows in this section of channel are intermittent.

In contrast to the model of Petts and Gurnell (2005), which depicts downward trajectories of heterogeneity and dynamism following dam construction, our model shows an increase in the magnitude of geomorphic processes from pre-reconnection to the post-reconnection adjusted state. Both models, however, indicate a transition period comprising different phases as the fluvial system adjusts from one state to another. Our model may help represent responses to other types of restoration. For instance, the fine sediment flux and geomorphic heterogeneity trends represented in the model capture changes reported by Sear et al. (1998) following channel restoration on the River Cole. Elements of our model such as geomorphic heterogeneity and sediment export might also capture changes resulting from artificial gravel augmentation initiatives, although the long-term effects will depend on whether augmentation continues over time (Chardon et al., 2018).

5.3. Project goals, objectives and lessons

The overall goal of the reconnection was to improve conditions in the River Ehen for the freshwater mussel *Margaritifera margaritifera*, an endangered and important species (Quinlan et al., 2015; Killeen and Moorkens, 2013). The recoupling of the Ehen to this small, headwater sub-catchment has resulted in the periodic delivery of sediment to a river that had been starved for 43 yr. The new channel not only reconnected the Ehen to long-since disconnected sediment source areas, but resulted in their production (e.g., via erosion of the fan). Thus, the specific objective of restoring the mass and energy budget of the catchment so that Ben Gill could passively supply sediment to the Ehen has been achieved.

Quantitative data on geomorphic conditions and sediment dynamics (presented in Marteau et al., 2020b) as well as field observations suggest that habitat is now more heterogeneous in the Ehen, and natural habitat-forming processes (bedload movement) are once again evident. For example, geomorphic features including a confluence bar, an extensive lateral bar and smaller gravel bars have formed in the section immediately downstream from the confluence, as a result of coarse sediment from Ben Gill being reworked. The lateral bar has concentrated flows (wetted width reduced by up to 40 %), creating new deeper, higher velocity areas; these areas provide improved conditions for mussels as well as upstream passage for salmonid fish (the mussel host) during dry periods. Moreover, field observations indicate that juvenile fish use newly formed backwater areas associated with some of the lateral bars. The bed morphology in the Ehen has become more heterogeneous, as a result of scour in pools and aggradation in riffles (Marteau et al., 2020b). The original armoured riverbed is beginning to break up in places, while sediment is now looser and more dynamic than before the reconnection (Marteau et al., 2020b).

These changes potentially improve hydraulic and sedimentary conditions for both the freshwater mussel and its host salmonid species (Killeen and Moorkens, 2022). However, the slow recruitment and growth of freshwater mussels (Hastie et al., 2000) means that it is too early to properly assess whether the changes in habitat are allowing recovery of the Ehen's mussel population, but it is hoped that ongoing ecological monitoring will make it possible to properly evaluate this. This monitoring will, in turn, allow us to relate the pace of ecological recovery in the Ehen to the pace of the physical changes described in this paper.

A number of important lessons can be learnt from the reconnection project. The first relates to post-project monitoring, with the common <1–3 yr post-restoration monitoring time-scale (England et al., 2021) seemingly unlikely to capture the entire transition period or include all the adjustment phases. The timing and frequency of monitoring needs to reflect the possibility that post-project changes may not be continuous, but rather that there may be rapid initial responses (depending on the occurrence of floods), followed by more gradual changes before the anticipated new regime state is reached. Data that allow for recognition of such phases is necessary to avoid attempting to assess project success prematurely. A second lesson is that understanding the lengths of these phases, and their characteristics, may provide important insights into the functioning of the system, which in turn may be important for adaptive management and intervention (Levine, 2004). For example, in Ben Gill and the Ehen, the first part of the transition stage was characterised by an unexpectedly dynamic shock phase. The characteristics of this shock phase stem from the fact that Ben Gill consists of two distinct components - a perennial upper catchment that flows through a steep gorge, and an ephemeral lower section that flows across an alluvial fan (Fig. 2). The shock phase not only reflected the immediate response of the new man-made channel to its first high flows, but also the renewed delivery of sediment and water from the upper catchment. The over steepened profile gradient design of the lower channel and presence of large quantities of noncohesive fine sediment (largely anthropogenic infill) surrounding the channel, amplified the magnitude of change during the shock phase resulting in major bed incision and high volumes of fine sediment being delivered to the Ehen, raising concerns over negative environmental impacts. At the time this caused some discussion of whether some form of intervention was necessary, but the decision was made not to intervene. This avoided potentially becoming trapped within a series of responses to short-lived problems. Our project shows that managers need to be careful not to conflate the desire to operate within an adaptive management paradigm with responses that might be needed to deal with short-lived issues that do not alter overall trajectories of change. A comprehensive understanding of the system can help avoid such issues, or it may allow them to be anticipated in advance; e.g., geophysical investigations of Ben Gill would have revealed the presence and extent of lenses of fine sediment, and flagged the likelihood of occasional, short-lived fine sediment issues (Blackburn et al., 2021). Lorenz (2021) describes some of the pitfalls when understanding of the system is incomplete.

6. Final remarks

The reconnection of Ben Gill channel to its main-stem river is rare example of system-scale rehabilitation. The project benefitted from a programme of frequent and extensive monitoring that allowed us to show how the various components of the system responded to the recoupling of a regulated main-stem channel with its small headwater sub-catchment. The rehabilitation project focussed on re-instating fluvial processes rather than the artificial creation of habitat. This brought uncertainly over the precise details of how the system might respond (although in general we anticipated greater dynamism and heterogeneity post-reconnection), and in particular it brought uncertainty over how long the transition to a new regime state might take. The monitoring indicated that even small or ephemeral watercourses and their catchments can significantly impact main-stem river morphology and sediment dynamics, and helped show the pace and trajectories of change in response to the reconnection. On the one hand, process-based rehabilitation projects that are conceived at the system scale bring advantages over local, form-based ones because they allow natural, fluvial processes to take over and dictate the pace and nature of instream habitat change. On the other hand, the complex and/or poorly understood interactions between system components create uncertainties in river response. Our conceptual model of responses in the Ehen, though itself simplified to show the general nature of changes, was based on quantitative evidence from each of the key components of the system that we monitored. We encourage other studies to test the generality of the changes represented by our model and, in-so-doing, evaluate its utility in understanding system responses to other interventions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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