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RESEARCH ARTICLE

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Geomorphic effects of natural flood management woody dams in upland streams

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Abstract

One popular Natural Flood Management (NFM) technique involves the construction of channel-spanning woody dams in low-order streams that maintain a clearance height above base flows. While extensive research has examined the geomorphic effects of natural wood accumulations, little has been documented of NFM woody dams, which are structurally distinct from natural accumulations and may produce different patterns of erosion and deposition. This consideration is crucial because changes in physical habitat characteristics have implications for flood management objectives as well as ecosystem structure and functioning. This study adopted a Before-After Control-Impact (BACI) design to assess the geomorphic effects of NFM woody dams in the upper River Cover catchment, United Kingdom. One baseline survey prior to and three monitoring surveys up to 2 years following dam construction were conducted. Structure-from-Motion (SfM) photogrammetry was employed to capture topographic change, supplemented by bathymetric surveys. Results highlight that where the dams remained secure in place, they promoted in-stream habitat diversity by creating underflow pools. Sediment storage was observed only where the dams had clearance heights <0.3 m from the stream bed. Additionally, the dams commonly led to bank erosion, likely enhanced by inherent bank instability in the study catchment as observed along the control reaches. However, volumes of sediments eroded and deposited were not statistically different between the control and woody dam reaches. Longer monitoring is required to determine whether these effects on channel morphology and habitat diversity will persist, amplify, or diminish over time, and to better understand the longevity of NFM woody dams.

KEYWORDS
BACI study, bank erosion, geomorphic change, in-stream wood, pool formation, sediment storage

1 | INTRODUCTION

Natural Flood Management (NFM) refers to flood risk reduction techniques that work with and promote natural processes, and it has been adopted worldwide recently (Lane, 2017). In-stream wood structures are frequently used for NFM in upland areas (e.g., Burgess-Gamble et al., 2018; Dodd, Newton, & Adams, 2016; Forbes, Ball, & McLay, 2015; Natural Water Retention Measures, 2013; Nisbet et al., 2015; Robinwood, 2015; The SOURCE, 2019; Woodland Trust, 2016; Yorkshire Dales National Park Authority, 2017; Yorkshire Dales Rivers Trust, 2018). Although these structures can take different forms (Lo, Smith, Klaar, & Woulds, 2021), the most common type (named "NFM woody dam" hereafter) involves logs arranged perpendicular to the flow, completely spanning the channel, fixed to the stream banks, and suspended above base flow such that they only interact with the stream water during flood events (The SOURCE, 2019; Yorkshire Dales Rivers Trust, 2018; Figure 1).

With a particular spatial arrangement of wood pieces, these dams are structurally distinct from natural in-stream wood accumulations. Natural in-stream wood structures are known to substantially alter fluvial geomorphology. Common geomorphic effects of in-stream wood include pool formation (Elosegi, Elorriaga, Flores, Martí, & Díez, 2016; O'Neal, Roni, Crawford, Ritchie, & Shelley, 2016; Rosenfeld & Huato, 2003), sediment storage (Dumke et al., 2010; Pinto et al., 2019; Sweka, Hartman, & Niles, 2010), increasing stream bed heterogeneity (Hasselquist et al., 2018; Kail & Hering, 2005; Pilotto, Harvey, Wharton, & Pusch, 2016), and influencing floodplain morphology (Addy & Wilkinson, 2019; Venarsky, Walters, Hall, Livers, & Wohl, 2018; Webb & Erskine, 2003). While such diverse effects are documented in many previous studies, they have not yet been associated with NFM woody dams in particular (Lo, Smith, Klaar, & Woulds, 2021). The hydraulic influence of in-stream wood structures is determined by their internal structure (Manners, Doyle, & Small, 2007), so there is reason to suggest that the installation of NFM woody dams will lead to distinct patterns of erosion and deposition. Sanhueza et al. (2019) and Spreitzer, Tunnicliffe, and Friedrich (2019) previously used Structure-from-Motion (SfM) to study the spatial distribution of wood accumulations but not their geomorphic effects. Meanwhile, Ravazzolo, Spreitzer, Friedrich, and Tunnicliffe (2020) applied SfM to quantify the geomorphic effects of in-stream wood, but within the context of laboratory flume experiments. As such, this study represents one of the first applications of high-resolution three-dimensional topographic models to study the local geomorphic effects of in-stream wood in the field.

The major aim of this study is to quantify the geomorphic effects of NFM woody dams in upland streams and identify mechanisms contributing to the geomorphic changes observed. Such considerations are important as changes in the characteristics of the physical habitat can subsequently drive further changes in ecosystem structure and functioning (Maddock, 2001).

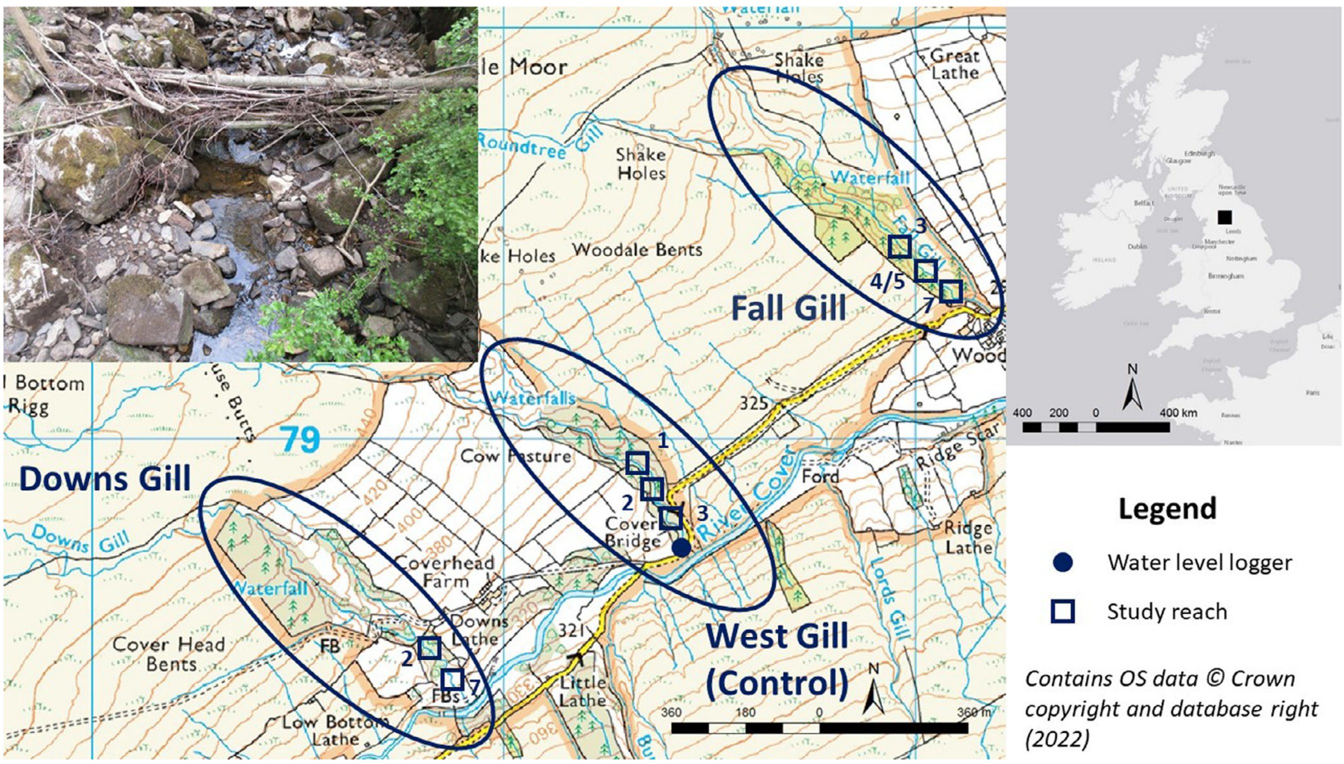

FIGURE 1 Map of the upper River Cover catchment, showing the three study tributaries and the main channel flowing towards northeast. Woody dams on each tributary are given numbers sequentially from upstream to downstream, and only monitored dams are shown. The location within UK is shown in the upper right-hand corner. An example of an NFM woody dam constructed in the study catchment shown in inset in the upper left-hand corner. Base map (OS MasterMap) obtained from UK Ordnance Survey [Color figure can be viewed at wileyonlinelibrary.com]

2 | METHODS

2.1 | Study site

The upper River Cover catchment (Figure 1) in the Yorkshire Dales National Park, United Kingdom (UK) was the location selected for a hydrological experiment that aimed to evaluate the effectiveness of woody dams as an NFM technique. The lithology is dominated by horizontally-bedded Carboniferous limestone, whereas the upper catchment (between 470 m and 580 m.a.s.l.) is formed of Carboniferous gritstone (British Geological Survey, 2020). During the Quaternary Period, glaciers eroded the bedrock and deposited till on the valley floors that were later incised by glacial meltwater, giving rise to deeply-incised V-shaped valleys (Yorkshire Dales National Park Authority, 2002). Today, agricultural land-use predominantly devoted to sheep and cattle grazing activities occupies around 20% of the study catchment. Silvicultural land-use mainly in the form of Sitka spruce (*Picea sitchensis*) plantations constitutes another 5% and natural peatlands in areas >500 m.a.s.l. make up the rest. The flows experienced by the River Cover at the study site are shown in Figure 2. There was a prolonged dry period in spring and summer of 2018. Higher flows returned in 2019, with the highest peak of the year caused by Storm Gareth in March. The highest peaks within the study period were recorded in February 2020, brought by Storms Ciara and Dennis.

2.2 | Research design

A Before-After Control-Impact (BACI) design was adopted herein. Baseline surveys took place in spring/summer (between May and July) 2018 to assess the geomorphic conditions of the study reaches before the installation of woody dams. Following dam construction (August and September 2018), three rounds of monitoring surveys were conducted in autumn (October and November) 2018, spring (May) 2019, and autumn (September) 2020 respectively. Five woody dam sites were selected for intensive monitoring, comprising two on Downs Gill and three on Fall Gill (Figure 1). The survey extent at each site encompassed the entire channel width and extended 10 m both upstream and downstream of the dam. Additionally, three 10 m control reaches without woody dams were surveyed on West Gill (Figure 1). The three tributaries were selected because they had similar channel widths and gradients, and all exhibited step-pool morphologies. This allowed differences between the control reach and the other study reaches to be more readily attributed to the NFM woody dams.

2.3 | Topographic survey and processing

Channel and floodplain topography above water was captured using established SfM photogrammetric methods (Carrivick, Smith, & Quincey, 2016). Since the discoloration of stream water by dissolved organic compounds precluded the use of through-water SfM techniques recommended by Woodget, Dietrich, and Wilson (2019), SfM surveys were supplemented by bathymetric surveys that involved recording points on the submerged stream bed using a total station (Leica TPS1000) and a 360° prism mounted on a pole. Points were measured in a grid format, with a targeted interval of 0.1 m between points (i.e., approximately 100 points per m^2). No interpolation was made to avoid introducing additional errors. Surveys were conducted during low flows to maximise the exposed area that could be captured by SfM.

The SfM workflow employed was adopted from the recommendations of James et al. (2019), Smith, Carrivick, and Quincey (2016), and Westoby, Brasington, Glasser, Hambrey, and Reynolds (2012). In compliance with the standards set out by James et al. (2019), details of all the digital cameras used to capture field images are summarised in Table 1 and Table S1. During each survey, a pole-mounted and remotely-triggered digital camera (Visser et al., 2019) was held approximately 5 m above the ground, and a photograph of the channel was captured approximately every 0.5 m while moving along the

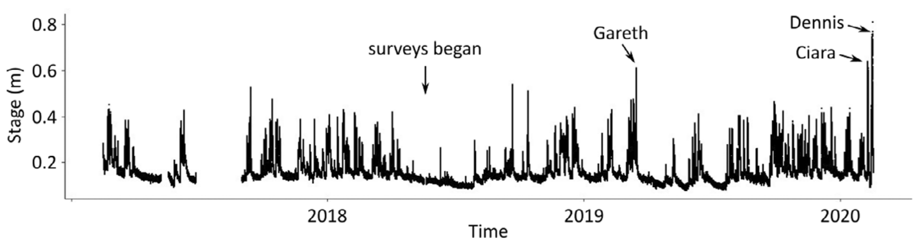

FIGURE 2 Stage hydrograph showing the flows experienced by the study site as recorded by the water level logger on West Gill (labelled in Figure 1). Gauging ended in February 2020

TABLE 1 Physical parameters of the digital cameras used

Make and model of camera used	Sensor size (inch)	Photograph size (pixels)	Effective focal length (mm)
Casio EXILIM Zoom EX-Z800	1/2.3	4,320 × 3,240	27
Canon IXUS 285 HS	1/2.3	5,184 × 3,888	25
Panasonic LUMIX DMC-TZ60	1/2.3	4,896 × 3,672	24

two banks. This yielded at least 60% overlap between any two consecutive photographs, as recommended by James and Robson (2012). Typically, 80 photographs were captured for each survey (Table S1). Easily-visible coloured tiles made of square (0.2 × 0.2 m) metal plates with a white circle in the centre were used as Ground Control Points (GCPs) for georeferencing the point clouds later. For each survey, at least six GCPs were placed on the banks, evenly distributed along the study reach. The positions of the GCPs were measured to the nearest millimetre reflectorlessly by the total station. Where the GCPs were not directly visible to the total station, they were measured using a prism mounted on a detail pole.

Photographs from each survey were imported into Agisoft Metashape photogrammetric software version 1.5.1.7618 to generate a sparse point cloud. Further quality control was implemented following the guidance provided by James (2017). The total station co-ordinates of the GCPs were used to georeference the sparse cloud into a local co-ordinate system, and the bundle adjustment was re-run. The georeferencing error was typically <0.03 m and in many cases sub-centimetre (Table 2). A dense point cloud was then generated using multi-view stereo techniques. The dense cloud was cleaned (water surfaces and terrestrial vegetation removed manually) and fused with the bathymetric survey data in CloudCompare version 2.10-alpha to yield a full three-dimensional (3D) representation of the geomorphology of the study reach. An orthophotograph with 1 mm pixel size was also generated, using the dense cloud.

To register repeat surveys into the same co-ordinate system, allowing geomorphic changes over time to be accurately quantified, permanent benchmarks were installed on the banks of each tributary. The locations of these benchmarks were recorded by the total station and used to co-register point clouds. Where necessary, easily recognisable points on stable bedrock supplemented the permanent benchmarks and were used for fine-tuning the alignments of point clouds. The registration error associated with such transformation was typically <0.03 m (Table S2).

2.4 | Quantitative analysis of topographic changes

Each georeferenced point cloud was converted into a digital elevation model (DEM) with a cell size of 0.1 m. This resolution was selected having taken into consideration the georeferencing errors listed in Tables S1 and S2 as well as the sampling intervals of the bathymetric surveys. ArcMap version 10.6 was used for differencing DEMs. Elevations in the older DEM were subtracted from the corresponding elevations in the newer DEM, yielding a DEM of difference (or DoD). It was necessary to ensure that these changes were real geomorphic changes instead of errors. In a DEM, the elevational variability within any cell could be summarised as the detrended standard deviation of elevations (σ_d, in m). During each differencing, there would then be two σ_d values for each cell (σ_{d1} in the older DEM and σ_{d2} in the newer DEM). The error of each cell was assumed to be represented by σ_d, on the basis that it was often more than an order of magnitude higher than the errors reported in Tables S1 and S2 (Smith & Vericat, 2015; Wheaton, Brasington, Darby, & Sear, 2010). The minimum level of detection (minLoD) for the cell was then calculated with the following equation using the critical *t*-value for 90% confidence intervals (i.e. 1.65; following Brasington, Langham, & Rumsby, 2003; Lane, Westaway, & Hicks, 2003; Wheaton, Brasington, Darby, & Sear, 2010):

$$\text{minLoD} = 1.65\sqrt{\sigma_{d1}{}^2 + \sigma_{d2}{}^2}$$

Cells with a magnitude of elevation change smaller than the minLoD were identified and removed from the DoD, so that only areas with 'real' geomorphic changes remained. The volumes of sediments eroded or deposited for all cells were calculated and aggregated to yield reach-scale sediment budgets. The disadvantage of implementing this filtering approach was that small changes (<0.01 m) could not be detected. Anderson (2019) advised against such filtering while considering net volume changes, but since the current study

TABLE 2 Georeferencing error (m) for individual Structure-from-Motion (SfM) surveys. The surveys at some sites were comprised of several parts, and the various parts were aligned (Table S2) and combined to produce a full three-dimensional model for the site

Site	Spring/summer 2018	Autumn 2018	Spring 2019	Autumn 2020
West Gill 1 (control)	0.0151	0.0059	0.0248	0.0165
West Gill 2 (control)	0.0167	0.0109	0.0212	0.0115
West Gill 3 (control)	0.0236	0.0114	0.0317	0.0110
Downs Gill (second dam)	0.0113	0.0174	0.0188	0.0048
Downs Gill (seventh dam)	0.0194	0.0196	0.0120	0.0222
Fall Gill (third dam)	0.0285	0.0257	0.0206	0.0172
Fall Gill (fourth and fifth dams)	0.0028 (part 1) 0.0088 (part 2a) 0.0283 (part 2b) 0.0120 (part 2c) 0.0143 (part 3)	0.0124 (part 1) 0.0206 (part 2a) 0.0048 (part 2b)	0.0108	0.0198
Fall Gill (seventh dam)	0.0228	0.0112 (part 1) 0.0051 (part 2) 0.0042 (part 3)	0.0129	0.0255

also involved quantifying volumes of erosion and deposition separately, the calculation of minLoD was preserved herein.

Sediment volumes eroded, volumes deposited, and net volume changes were ln-transformed to ensure normality. Two-way ANOVA tests were then performed on each of the three transformed parameters using DoD and reach type (i.e., control, upstream, and downstream of dam) as factors.

The analysis of DoDs was supplemented by visual comparisons of orthophotographs representing the same site at different points in time. After importing the orthophotographs into ArcMap 10.6, they were registered into a common co-ordinate system by identifying benchmarks and prominent stationary features as per the co-registration of point clouds. The registration errors were generally <0.01 m (Table S2). The aligned orthophotographs provided further confidence in the geomorphic changes identified by the DoDs, by allowing movements of clasts, lateral shifts in channel planform, and changes in the size of channel units or sedimentary facies to be interpreted. Three modes of deposition were identified and classified manually: accumulation upstream of dams (no upstream limit if the accumulation was continuous and in contact with the dam), bank growth (deposition along the banks and not submerged in water), and stream bed aggradation. Three modes of erosion were also identified: pool formation (relatively deep and stagnant areas), bank erosion, and stream bed scouring. These areas were identified on orthophotographs, and demarcation of the corresponding areas on the DoDs permitted the volume of each mode of erosion or deposition to be computed.

3 | RESULTS

The two-way ANOVA tests suggested that the temporal patterns of volumes deposited, volumes eroded, and net volume changes did not differ across the three reach types (Figure 3; Table S3). The main effect of 'reach type' was also insignificant.

Figure 4 illustrates the study reaches individually and provides insights into the lack of statistical significance reported above. Similar trends were observed across most study reaches (aggradation dominated in DoD 2 while degradation dominated in DoD 3). The reaches around the second dam on Downs Gill were exceptions in that degradation dominated in DoD 2 and aggradation in DoD 3. Overall, the geomorphic effects of the NFM woody dams are not immediately clear if we only consider reach-scale sediment budgets. For this reason, the sub-sections that follow will consider the geomorphic changes induced by the NFM woody dams at the sub-reach scale (e.g., changes in the spatial distribution of channel units within individual study reaches).

3.1 | Bank erosion

Bank erosion was widespread across the study catchment. For example, in the most upstream control reach (West Gill 1), erosion along the left bank (1.3 m^3) was first observed in DoD 1 and further observed in DoD 3 (Figures 4b and 5a,b: clear retreat of the bank from its original position marked in blue). The average channel width at this site increased by 0.05 m (2.5%) over the study period. The middle control reach (West Gill 2) also experienced pronounced bank erosion during the study period. In DoD 2, the right bank near the upstream end of the study reach and the left bank near the middle of the study reach both experienced some erosion (0.38 m^3 in each area). The right bank recovered in DoD 3 following deposition. In contrast, the left bank continued to retreat after more erosion (0.17 m^3; Figure 5c,d). The middle part of the study reach, therefore, became approximately 0.5 m wider at the end of the study period.

Bank erosion was also associated with the NFM woody dams. For instance, at the second dam on Downs Gill, flows were concentrated to the left side of the channel, resulting in the erosion of the left bank within the 3 m immediately downstream of the dam after October 2018 (1 month after dam installation; 0.20 m^3 eroded in DoD 2; 0.17 m^3 eroded in DoD 3; Figure 6b). At the seventh dam on Downs Gill, some localised bank erosion caused by water flowing around the dam was observed in May 2019. This was particularly evident in September 2020, where an accumulation of gravel-sized alluvium was observed on the left bank, at the original location of the dam (Figure 6g: red arrow). Similarly, localised erosion of the right bank was observed at the original location of the third dam on Fall Gill (Figure 7b), which was displaced in DoD 2. Meanwhile, the slightly-rotated fourth dam on Fall Gill diverted water into the left bank and led to the localised erosion observed in DoD 2 (Figure 7f). Finally, the seventh dam on Fall Gill was pushed a few metres downstream by high flows, and it caused erosion of the right bank through abrasion (Figure 7k,l).

3.2 | Sediment storage

The monitored dams on Fall Gill stored only negligible amounts of sediments. Some gravels accumulated in the area enclosed by the left bank and the displaced third dam on Fall Gill (Figure 7b: red circle), but the volume was small (0.14 m^3). Reach-wide aggradation along the tributary occurred in DoD 2 (Figure 7d), but the deposits were transported by high flows in DoD 3 (Figure 7e,i) even when most of the dams remained in place, suggesting that the dams on Fall Gill generally had low sediment retention ability.

In contrast, much greater and more persistent storage was observed at the two dams on Downs Gill, which had smaller clearance heights (0.30 and 0.24 m respectively) than the dams on Fall Gill (0.33–0.52 m; Figure 8). Immediately upstream of the second dam on Downs Gill, some gravels (0.02 m^3) started to accumulate near the right bank after October 2018, clogging the gap between the dam and the stream bed. Deposition along the right bank extended further upstream in DoD 3 (a total of 2.87 m^3 along the entire reach; Figures 4a and 6a). Since upstream sedimentation diverted flow to the left side of the channel, deposition was also predominant on the right side immediately downstream of the dam, resulting in the

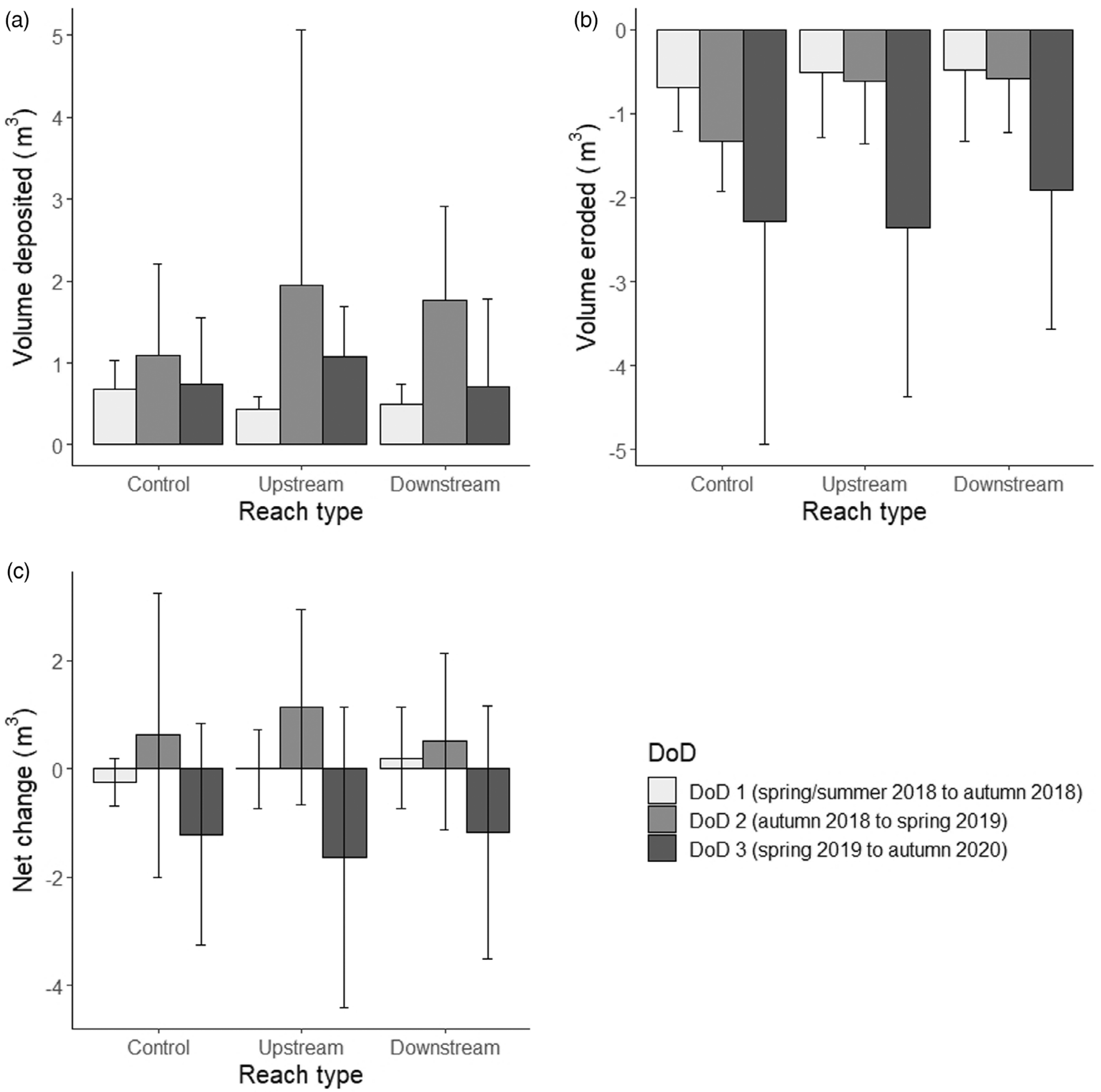

FIGURE 3 Sediment budgets in the three reach types over the study period; (a) volume deposited (m^3); (b) volume eroded (m^3); (c) net volume change (m^3). Error bars show ± one standard deviation

accumulation at the toe of the right bank (0.32 m^3 deposited; Figure 6b). Overall, the channel appeared to have shifted 0.2 m laterally towards the left.

By May 2019, accumulation of clasts (0.50 m^3) also clearly took place immediately upstream of the seventh dam on Downs Gill (Figure 6d,f: upstream blue rectangle). At some time before September 2020, the dam was displaced by the flow and became aligned to the right bank (Figure 6g). Some of the sediments previously stored (0.30 m^3) were released (Figure 6e) but were subsequently retained by a large boulder on the left bank (Figure 6f: downstream blue rectangle), originally around 2 m downstream of the dam. Moreover, some non-closely monitored dams in the study site (e.g., the first dam on Fall Gill; Figure 9) had low clearance heights, and they clearly led to the accumulation of sediments upstream. These observations contrasted the widespread degradation observed in the control tributary (particularly West Gill 3 in DoD 3; Figure 5e–g). No persistent sediment storage zones arose on the control tributary during the study period.

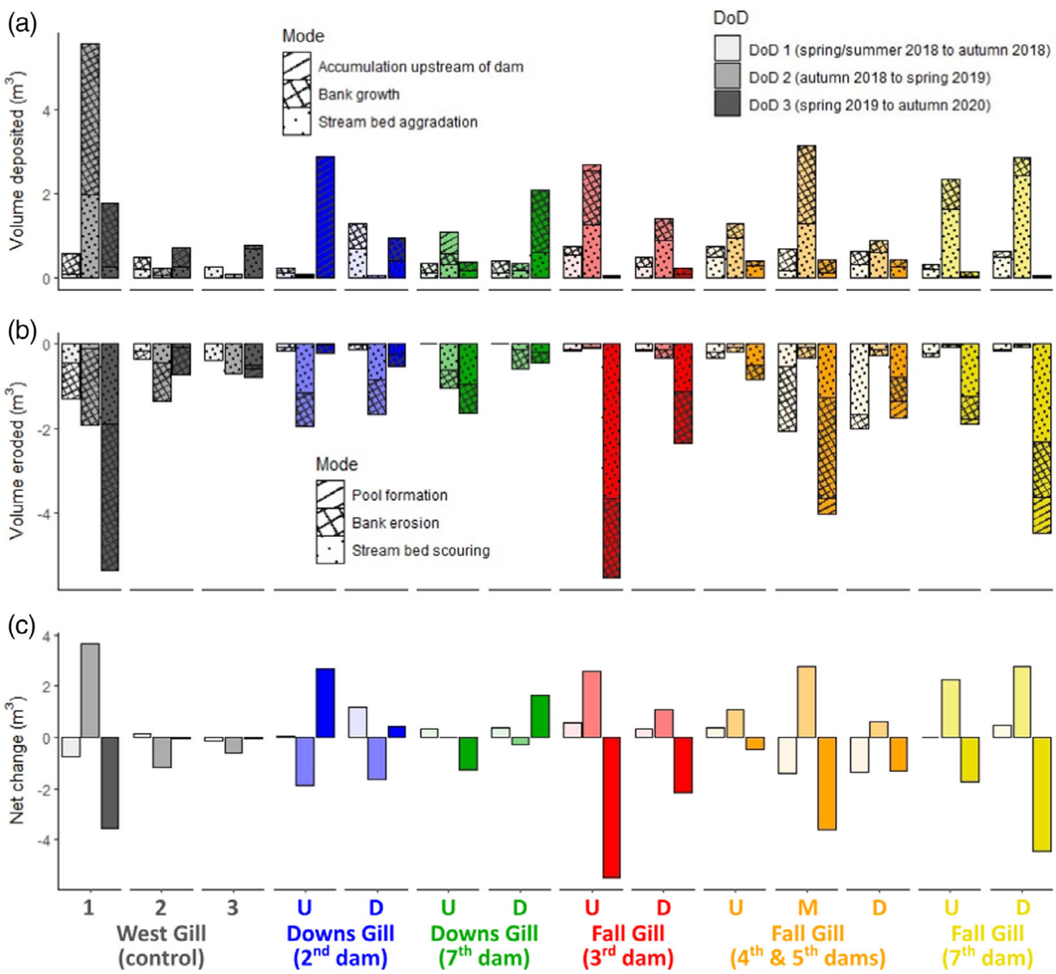

FIGURE 4 Topographic changes at the intensively-monitored reaches (U: upstream of dam, D: downstream of dam, M: between two dams); (a) volumes (m^3) of sediments deposited; (b) volumes (m^3) of sediments eroded; and (c) net volume changes (m^3) recorded by the DoDs; fill intensity described in the legend (upper right) applies to all colours [Color figure can be viewed at wileyonlinelibrary.com]

3.3 | Pool formation

Two major pools were formed near the fifth dam on Fall Gill between May 2019 and September 2020 – one underflow pool vertically beneath the dam (0.56 m^3; Figure 7h: blue rectangle) and another smaller pool 4 m downstream of the dam near the left bank (0.17 m^3; Figure 7h: blue ellipse).

At the seventh dam on Fall Gill, an underflow pool started to develop between October 2018 and May 2019, with a boulder originally immediately downstream of the dam near the right bank being displaced to the left side of the channel (Figure 7j: red arrow). By September 2020, after repeated high flows earlier in the year, the pool became well-developed (0.96 m^3), spanning almost the entire channel width (Figure 7k). The clasts displaced during pool formation appeared to be deposited around 3 m downstream of the dam, on the right side of the channel (Figure 7k: green box). This diverted flow to the left side of the channel, resulting in scouring of the stream bed (0.63 m^3 removed) near the left bank (Figure 7k: red box). Based on the orthophotographs, the pool associated with the seventh dam on Fall Gill appeared to be larger than the one associated with the fifth dam (length along the flow direction: 3.5 m vs. 2 m; Figure 7h,k).

A scour hole near the upstream end of West Gill 3 started to develop in DoD 3 (Figure 5f,g: red circle). However, it was smaller (0.21 m^3) than the underflow pools described. It was also shallow, and the stream bed is visible in Figure 5g.

3.4 | Dam instability

It is notable that two of the six dams monitored (i.e., the seventh dam on Downs Gill and the third dam on Fall Gill) had been completely displaced. Furthermore, the fourth dam on Fall Gill had been rotated clockwise by 30°, and the seventh dam had been pushed 0.4 m downstream. As described earlier, the latter two continued to exert geomorphic influence on the channel. However, the former two also served some geomorphic functions. Between May 2018 and May 2019, the outer bank of the bend downstream of the seventh dam on Downs Gill was gradually eroded, but the displaced dam protected it from further erosion in September 2020 (Figure 6d–f). The displaced third dam on Fall Gill allowed the left bank to develop towards the thalweg, resulting in a channel width 0.2 m narrower than the baseline condition (Figure 7b,c).

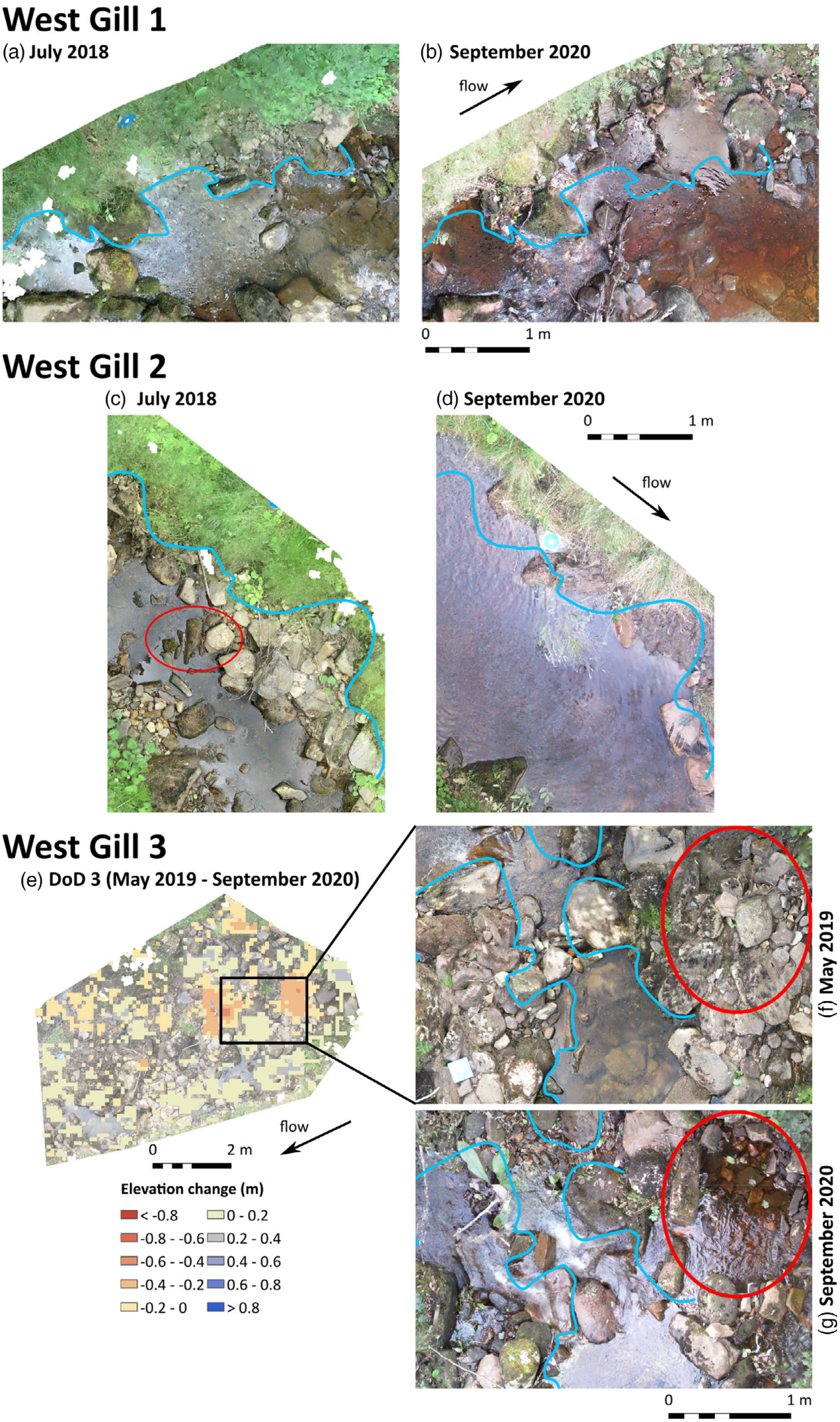

FIGURE 5 Major geomorphic changes along West Gill (the control tributary). Blue lines show bank positions recorded during the baseline survey in July 2018 [Color figure can be viewed at wileyonlinelibrary.com]

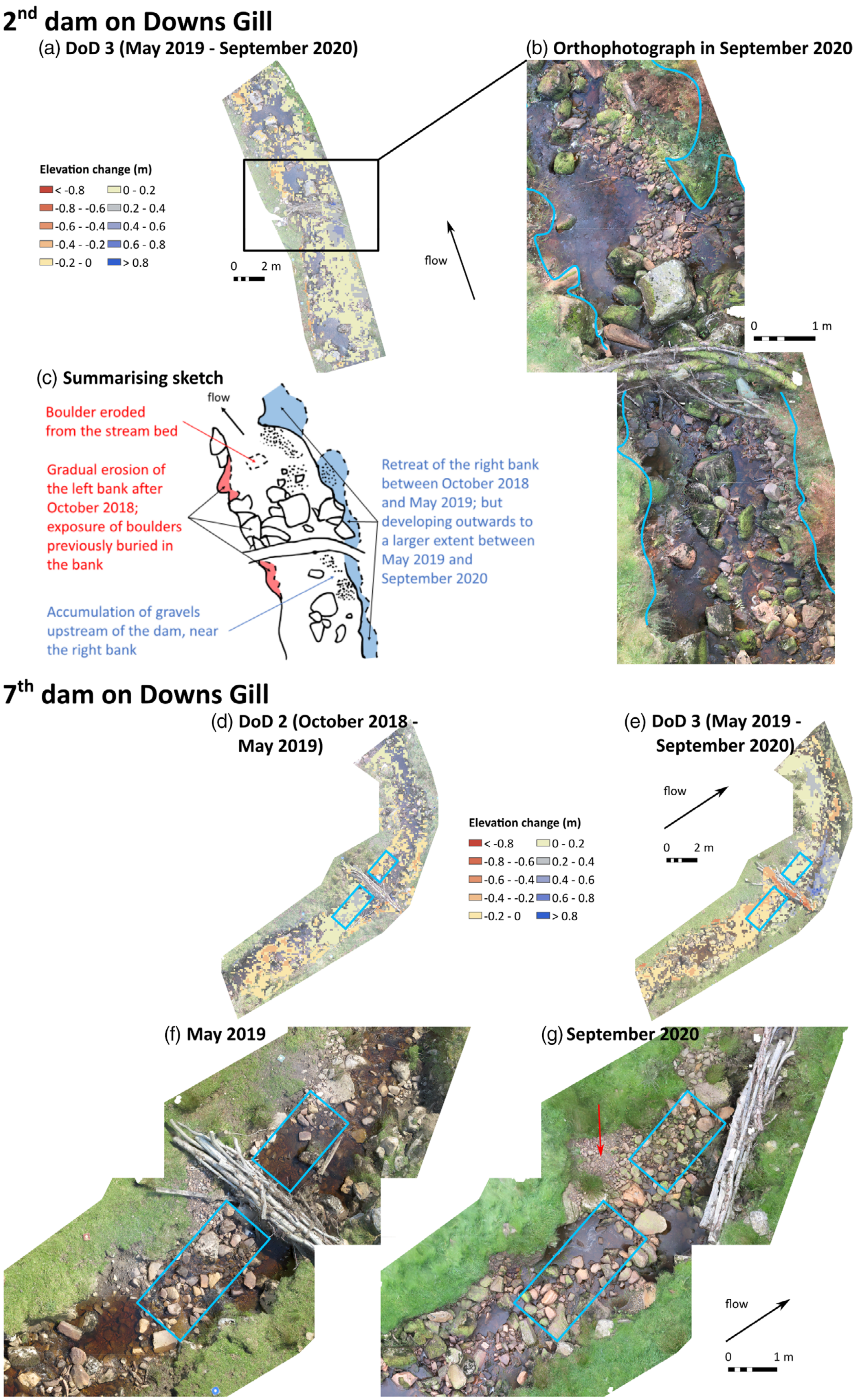

FIGURE 6 Major geomorphic changes at the monitored dams on Downs Gill. Blue lines in (b) show bank positions recorded during the baseline survey in July 2018 [Color figure can be viewed at wileyonlinelibrary.com]

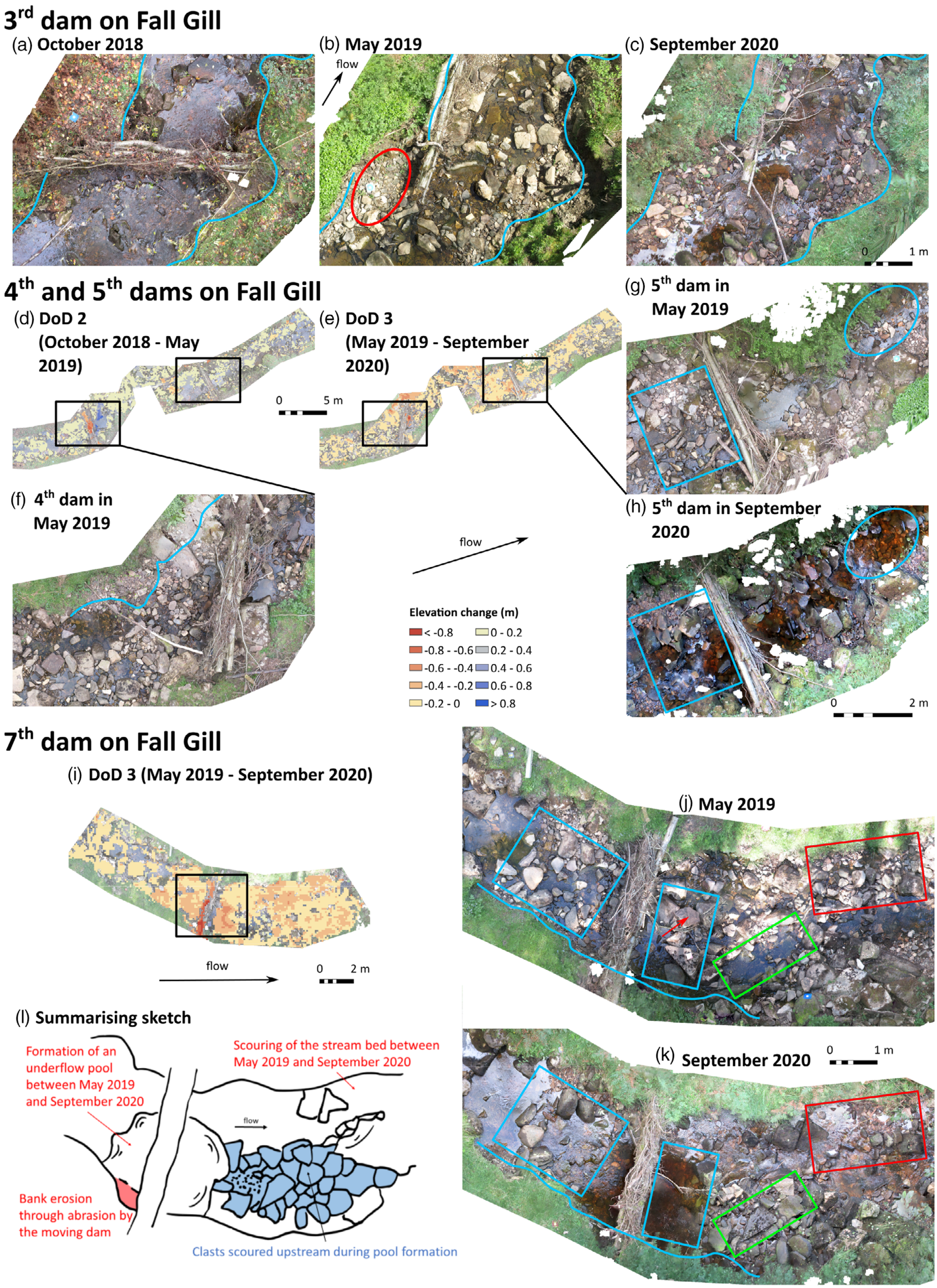

FIGURE 7 Major geomorphic changes at the monitored dams on Fall Gill. Blue lines show bank positions recorded during the baseline survey in July 2018 [Color figure can be viewed at wileyonlinelibrary.com]

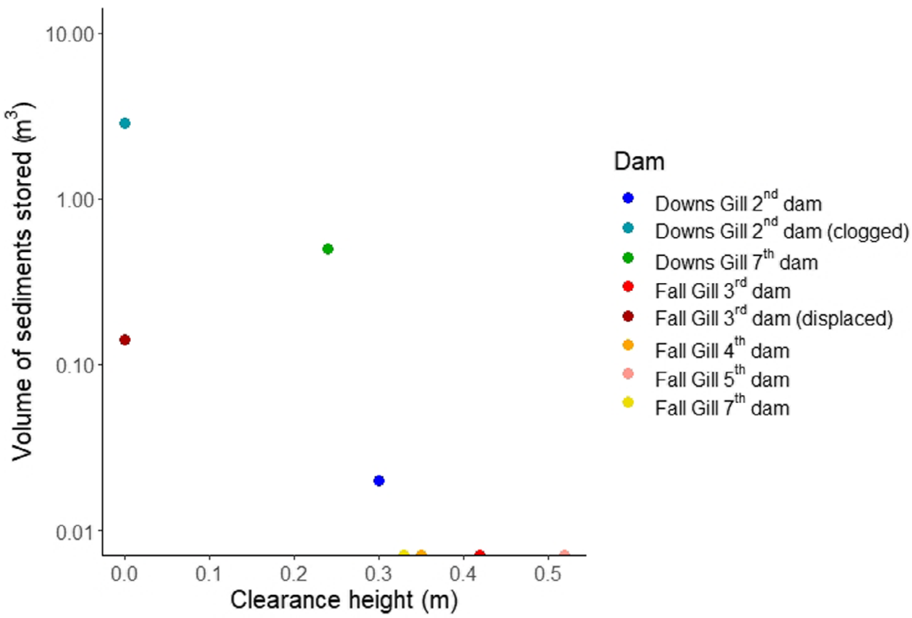

FIGURE 8 Maximum volume of sediments stored (m^3) as a function of dam clearance height (m) measured in October 2018. The second dam on Downs Gill and the third dam on Fall Gill are shown twice as their clearance heights had changed after being clogged and displaced respectively [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 9 Clasts piling up against the most upstream dam on Fall Gill; as captured by a hand-held camera on February 21, 2019 (upper) and a time-lapse camera on June 21, 2019 (lower); both facing downstream; red circles indicate a reference boulder that had remained stationary [Color figure can be viewed at wileyonlinelibrary.com]

4 | DISCUSSION

Areas of erosion and deposition identified by DoDs corresponded well with those visually-identified by overlaying orthophotographs. Results indicate that the NFM woody dams monitored led to small geomorphic changes within 2 years, including localised bank erosion, pool formation towards the end of the study period, and sediment storage only when the dams had small clearance heights and remained in place. Overall, greater dynamism was observed in the second half of the study period (Figure 3).

4.1 | Bank erosion

It is worth noting that bank erosion occurred at both control and woody dam reaches, but it was typically more localised around the woody dams. In most cases, this was likely caused by water being forced to flow around the two sides of the full-spanning structures (Nakamura & Swanson, 1993). According to Wallerstein, Alonso, Bennett, and Thorne (2001), this mode of bank erosion should be more pronounced for suspending structures than those in contact with the stream bed because the former would divert faster-flowing water in the upper part of the water column experiencing less friction offered by the stream bed into the two banks. In two cases, bank erosion was found to be more prominent at one side of the dam (the seventh dam on Downs Gill and the third dam on Fall Gill). This was likely due to differences in the erodibility of the two banks in addition to the effects of natural lateral channel migration, which was extensive on West Gill (the control tributary). One exception in the current study was the fourth dam on Fall Gill, which triggered a different mechanism of erosion. It was slightly rotated before May 2019 and detached from the left bank. It, therefore, functioned as a deflector (Gallisdorfer et al., 2014), actively diverting water into the left bank, resulting in the erosion of this bank. In contrast, bank erosion along the control tributary was more widespread (Figure 5a–d) instead of being confined to localised areas. The left bank of West Gill 1 was steep and was therefore particularly prone to erosion (Duan, 2005).

Localised bank erosion around woody dams did not result in significant influence on floodplain morphology. One of the non-closely-monitored dams on Downs Gill created a secondary channel, but it soon re-joined the main channel, so there was no significant change to the overall floodplain morphology. These observations were different from those of Sear, Millington, Kitts, and Jeffries (2010), who recorded the formation of an extensive floodplain channel network in association with in-stream wood. Vegetation such as grasses surrounding Downs Gill might have added roughness to the floodplain

(Straatsma & Baptist, 2008), so overbank flows would lose energy quickly, and it was unlikely that they were concentrated enough to carve well-defined channels on the floodplain. Flows underneath the NFM woody dams also implied that less water was diverted into the banks to carve floodplain channels (Livers & Wohl, 2021).

4.2 | Pool formation

Underflow pools were observed in association with dams on Fall Gill. This finding agrees with previous studies that have considered wood structures spanning the entire channel width while maintaining a gap with the stream bed at the same time (Robison & Beschta, 1990; Schalko, Lageder, Schmocker, Weitbrecht, & Boes, 2019; Wallerstein & Thorne, 2004). When water levels rose during high discharges, the NFM woody dams clearly interacted with the water and reduced the cross-sectional area of the water column. Suspended structures such as NFM woody dams would force water to flow underneath them, concentrating flows that are already fast-flowing, greatly enhancing their erosive power (Wallerstein, Alonso, Bennett, & Thorne, 2001). This explains why scouring of the stream bed occurs vertically underneath the structures. The underflow pool associated with the seventh dam on Fall Gill was larger than that associated with the fifth dam, likely because the former was maintained at a lower height (0.33 m vs. 0.52 m) above the stream bed, making it more effective than the fifth dam in constricting flows. Another common phenomenon observed within the reach downstream of the fifth dam on Fall Gill and that downstream of the seventh dam was the formation of a secondary pool at a location approximately 3 m downstream of the underflow pool. Wallerstein, Alonso, Bennett, and Thorne (2001) suggested that the secondary pool might be due to the plunging effect caused by water flowing over the zone of deposition composed of materials eroded during the formation of the underflow pool immediately upstream.

Both underflow pools were formed between May 2019 and September 2020 but not earlier during the study period. This was presumably related to the magnitude and frequency of flood events experienced by the sites after May 2019. Flood peaks became more densely packed towards the end of the study period (at least 12 peaks exceeding 0.4 m after May 2019 vs. only eight such peaks between May 2018 and May 2019; Figure 2), and the highest peak ever recorded was in February 2020. In contrast, flood events during the previous autumn and winter over late 2018 and early 2019 were clearly less frequent, resulting in less intense erosion of the stream bed. This echoes the findings of Jackson and Sturm (2002), who argued that the in-stream wood in the high-gradient streams of the Coast Ranges, Washington, USA failed to create pools because of the low discharge in those streams. The streams in the current study are dominated by coarse sediments including cobbles and boulders requiring a high critical shear stress for entrainment, making pool formation possible only under high discharge (Hilderbrand, Lemly, Dolloff, & Harpster, 1997; Wohl, 2015). Elosegi, Díez, Flores, and Molinero (2017) suggested that pools could be infilled by sediments during base flows. Since hydrological monitoring at the upper River Cover catchment ceased in February 2020 owing to the COVID-19 pandemic, there was no stage information after February 2020. Data from nearby gauges suggest that flows were low between March and June 2020 (National River Flow Archive, 2002). However, the return of higher flows after June may have helped maintain the pools.

There was no plunge pool formed downstream of the closely-monitored NFM woody dams. To form plunge pools, in-stream wood structures have to maintain contact with the stream, allowing water only to flow over their tops but not underneath them, so that the drop in elevation created will provide the water with sufficient kinetic energy to scour the stream bed immediately downstream (Bilby & Ward, 1989; Wohl & Scott, 2017). All of the intensively-monitored dams in the current study maintained a gap above the stream bed, so there was no sudden drop in stream bed elevation, resulting in the failure to form plunge pools. However, some of the other non-closely-monitored NFM woody dams in the study catchment were constructed closer to the stream bed (e.g., Figure 9), and the gaps were clogged by small clasts. In these cases, plunge pools were formed when water flowed on top of the sediment accumulations during high flows.

The two closely-monitored dams on Downs Gill did not lead to the formation of pools. As described earlier, the right side of the second dam on Downs Gill was clogged by sediments, so the flow was unable to scour the stream bed. Although a gap remained underneath the left side of the dam, an underflow pool was not formed. This is most likely accounted for by the pronounced bank erosion observed, which indicates that energy of the flow was preferentially expended to erode the left bank instead of scouring the stream bed. Once the bank was eroded, the resulting channel widening would lead to less flow being constricted underneath the dam, subsequently reducing its erosive power on the stream bed. The seventh dam on Downs Gill was clogged by sediments at one point during the study period, but it did not persist long enough for a plunge pool to develop downstream of it.

A small pool was formed in West Gill 3 towards the end of the study period. It was shallow because the boulder at its upstream end only provided a small drop in elevation (Mao, Comiti, & Lenzi, 2008).

4.3 | Sediment storage

NFM woody dams in the current study led to some sediment storage. Field observations suggest that the amount of material accumulated upstream of the NFM woody dams was controlled by the clearance height between the structure and the stream bed (Figure 8). For example, the seventh dam on Downs Gill was suspended above the streambed at the lowest height among all the intensively-monitored dams and appeared to have stored the highest amount of material by autumn 2018 (0.50 m^3). However, it did not store as much sediment (judged visually) as the non-monitored dams that were in contact with the stream bed (e.g., Figure 9), confirming previous observations that wood structures suspended above base flows are less effective in retaining clasts (Smith, Sidle, Porter, & Noel, 1993). This is particularly true for the upper River Cover catchment as the average grain size of the study streams (i.e., cobble) suggests that the primary mechanism of sediment transport is bedload transport, which can only be intercepted by structures in close contact with the stream bed. Similar to the findings of Scott, Montgomery, and Wohl (2014), only clasts that were too large to pass through the gap were retained. Another reason why the few closely-monitored dams on Fall Gill stored less sediment was probably due to a cascade effect stemming from sediment starving (Wohl & Beckman, 2014) caused by the most upstream dam on the tributary (Figure 9). It is worth noting that most previous studies have documented wood-formed sediment wedges made of sand-sized or even finer materials (Beschta, 1979; Martin, Pavlowsky, & Harden, 2016; Pilotto, Bertoncin, Harvey, Wharton, & Pusch, 2014; Wallace, Webster, & Meyer, 1995). However, when significant accumulations were formed in the current study, they were made of cobble-sized materials. This might be due to the limited supply of fine sediments from the surrounding catchment (Berg, Carlson, & Azuma, 1998). It was also likely that finer sediments were flushed away by underflows as the NFM woody dams were not in contact with the stream bed (Livers & Wohl, 2021).

4.4 | Implications for aquatic ecosystems

The geomorphic effects discussed so far have profound implications for aquatic species, some of which are of management interest. For example, bank erosion and the subsequent enhanced interaction with riparian environments may benefit fish that feed on terrestrial invertebrates (Garman, 1991). Shallow and slow-flowing areas near the banks are also important for the spawning of species such as nase and barbel (Pander & Geist, 2018). Pool formation induced by NFM woody dams, in the meantime, may be crucial for taxa that prefer deep-water habitats, including centrarchids (Shields, Knight, & Cooper, 1998), cyprinids (Butler & Fairchild, 2005), and salmonids (Woelfle-Erskine, Larsen, & Carlson, 2017). Finally, localised sediment accumulations immediately upstream of NFM woody dams may favour the colonisation of benthic macroinvertebrates that prefer finer substrates, particularly in streams that are otherwise dominated by bedrock and boulders (Lorenz & Wolter, 2019).

4.5 | Woody dam stability

The persistence of the geomorphic effects associated with the NFM woody dams was determined by their stability. Out of the six closely-monitored dams, two (the seventh dam on Downs Gill and the third dam on Fall Gill) had been completely displaced and one (the fourth dam on Fall Gill) had been slightly rotated before the end of the study period. Prolonged scouring is required before well-defined pools can form (Osei, Harvey, & Gurnell, 2015), but once these dams were moved, they could no longer persistently concentrate flows onto the stream bed underneath them. The two dams that got completely displaced became aligned to the bank. They protected the bank from erosion but only resulted in slight channel narrowing. Therefore, they appeared to have little influence on the scouring of the stream bed as they no longer caused much reduction in the cross-sectional area of the water column. Persistence of the dams was also found to determine the distribution of localised sediment accumulations. The seventh dam on Downs Gill was displaced sometime after June 2019, and most of the sediments originally stored upstream of it were clearly released by September 2020. This echoes the observations of Cadol and Wohl (2011), who found that mobilised wood pieces in their study site could not retain much material.

4.6 | Summary and suggestions for future research

The NFM woody dams in the upper River Cover catchment resulted in pool formation in some study reaches and accumulation of finer sediments in others. Previous research has suggested that the diversity of channel units (Hilderbrand, Lemly, Dolloff, & Harpster, 1997; Stewart, Bhattarai, Mullen, Metcalf, & Reátegui-Zirena, 2012) and sediment facies (Doeg, Marchant, Douglas, & Lake, 1989; Mathers, Rice, & Wood, 2017) can contribute to increases in local biodiversity. Further studies are necessary to investigate if this increased in-stream habitat diversity has indeed led to the presence of more diverse ecosystems.

To more reliably discern the secondary effects of NFM woody dams, more replication is needed in the future. First, this involves spatial replication. The current study focused on one study catchment with coarse stream bed sediments, and the tributaries had very similar physical characteristics as they were chosen deliberately to minimise confounding variables. Future research should expand to other climatic and geological environments to examine whether current findings regarding the geomorphic effects of NFM woody dams still apply. Moreover, there are multiple ways of constructing in-stream wood structures for NFM. Even in the current study, variation exists between the woody dams that arguably belong to the same "type". They have different clearance heights, different distances from adjacent dams and hence presence or absence of cascade effects arising from sediment starving by dams upstream. Further studies should therefore cover a continuum of dam types, so that systematic differences and quantitative relationships (e.g., relationship between the volume of sediments stored and the clearance height or the distance from the next dam upstream) can be better established.

The current study involved four fieldwork campaigns over 2 years. Longer monitoring may be required to determine if the geomorphic changes observed will develop further over time (Downs & Kondolf, 2002). Moreover, to quantify timescales of geomorphic changes and to identify processes leading to these changes, in addition to monitoring using time-lapse cameras, future field surveys should be conducted more frequently and in response to flood events.

5 | CONCLUSION

The NFM woody dams in the upper River Cover catchment resulted in sediment storage only where they had small clearance. They also led to underflow pool formation if the gap was not clogged. Localised bank erosion was also commonly observed in association with the dams. Reach-scale sediment budgets were not statistically different between the control and woody dam reaches. However, the ecological implications of these minimal geomorphic changes should not be overlooked because hotspots of biological processing can be concentrated in very localised areas. Some of the NFM woody dams monitored in the upland environment studied had short lifespans. They were displaced by high flows, and most geomorphic functions (e.g., sediment storage and pool formation) appeared to be lost following displacement. On the other hand, some of the dams that remained stationary were clogged by sediments. If practitioners would like the NFM woody dams to have prolonged effects, they will have to inspect and repair the dams regularly. Longer monitoring beyond 2 years is required to determine whether these geomorphic effects will persist, amplify, or diminish over time.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the supplementary material of this article. Further data are available from the corresponding author upon reasonable request.

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