

The use of woody dams in Natural Flood Management – temporal implications on in-channel hydrology, sediment dynamics and ecology

Temporal changes associated with in-channel woody dams

Matthew D Taylor^{1,2}, Lucy Clarke³, Anne Harrison¹, Laura Weldon¹, Estefania Golob¹, Hannah J Robson¹

¹ Conservation Evidence Department, Wildfowl & Wetlands Trust, Gloucestershire, United Kingdom

² School of Natural and Social Sciences, University of Gloucestershire, Cheltenham, GL50 4AZ, UK

³ School of Animal, Rural and Environmental Sciences, Nottingham Trent University, Brackenhurst Campus, NG25 0QF, UK

Corresponding Author: Matthew Taylor (matt@westcumbriarivertrust.org)

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Abstract

The use of Natural Flood Management (NFM) interventions, and in particular woody dams, have become increasingly widespread over the last ca. 15 years. These interventions help to reduce flood risk downstream, diversifying geomorphology and hydraulics, and may influence aquatic biota. This study examines how the age of woody dams affects the hydrology, geomorphology and ecology in the Stroud Frome and Twyver catchments in Gloucestershire, UK. Our study examined three sites with similar environmental characteristics: (1) no woody dams (control); (2) woody dams recently installed; and (3) older woody dams installed more than five years previously. Five flow events of varying magnitude were monitored with variables related to hydrology, geomorphology and ecology collected to enable a broad comparison between the sites. There was clear evidence that woody dams mitigated the impact of high magnitude flow events by reducing water velocity and increasing water storage compared with the control site, as well as reducing the amount of sediment transported downstream. Following installation, the woody dams altered hydrological conditions rapidly and maintained a good level of efficiency as they aged. The addition of woody dams also improved riparian vegetation structure and provided positive impacts on habitat availability, showing an increase for in-stream macroinvertebrates and habitat complexity. This research provides evidence to stakeholders that woody dams can be implemented with minimal future maintenance and deliver multiple benefits to a high level of efficiency over at least a 5-year time period. The management implications of siltation around woody dam structures are also discussed.

Key Words: Working with Natural Processes, Flood Mitigation, Multiple Benefits, Macroinvertebrate, Hydrology, River Restoration, Geomorphology

1. Introduction

Global flood risk affects approximately 1.81 billion people (Rentschler *et al.*, 2022) and climate change will increase the number of people at risk from flooding (Tellman *et al.*, 2021). Between 1960-2010 in the UK, flood discharge increased by almost 11% per decade, with northern England and southern Scotland the worst affected (Blöschl *et al.*, 2019). Under future climate change scenarios this prediction is expected to increase up to four-fold, with higher winter river flows and rainfall expected over the rest of the 21st century (Murphy *et al.*, 2007; Defra, 2012; Watts *et al.*, 2015). In 2009, it was estimated that 2.4 million properties in the UK were located in flood prone areas and that flooding costs the UK £1.3 billion annually (Environment Agency, 2009). This figure could rise by 1500% by 2080 if high-emission scenarios continue to occur (Seneviratne *et al.*, 2021). Therefore, environmental regulators and river managers need to prepare for an increase in flooding, to mitigate their impacts and protect high value areas.

Natural flood management (NFM) works with natural processes to reduce flood risk and improve the ecological status of a river (Burgess-Gamble *et al.*, 2018), these focus on enhancement, restoration and alteration of natural features. A range of NFM interventions exist (outlined in full in Pearson *et al.*, 2025), here we focus on woody dams. Woody dams (alternatively known as woody barriers, coarse woody debris, large woody debris, large wood, wood accumulations, wood jams/barriers or leaky barriers/dams) are purposely placed pieces of wood that form an obstruction in the water course. During normal or low flow conditions, water passes underneath the obstruction but when water flow increases, the barrier slows the flow and acts as a temporary water storage area (Cabaneros *et al.*, 2018; Grabowski *et al.*, 2019). A key barrier to the uptake of NFM by land managers and practitioners is the uncertainty around longevity, in terms of both hydrological/geomorphological effects and ecological benefits, and implications on management and maintenance regimes (Wells *et al.*, 2020). Studies that can provide evidence on the longevity of woody structures benefiting hydrology, geomorphology and ecology are therefore a priority.

Woody dams have displayed positive hydrological impacts during flood events with a small return period especially during events up to 1 year in frequency (Mulligan *et al.*, 2023; Van Leewuwen *et al.*, 2024), reducing discharge during peak flow and attenuating water. The installation of woody dams can lead to streams becoming less flashy further downstream and successfully delaying flood peaks (Mulligan *et al.*, 2021; Bradshaw, 2023). SHETRAN modelling in the Coalburn catchment displayed a 31.7% reduction in peak flow during a 1 in 7.5-year event (Barnes *et al.*, 2023), with TOPMODEL and HEC-RAS modelling supporting woody dams causing a delay to flood peak downstream, up to 90 minutes during a 1 in 5-year event (Ferguson, 2020). Hydrological uncertainty increases for events with a large return period with modelling suggesting impacts on flood risk is limited (Gilbert, 2021; Barnes *et al.*, 2023), especially when accounting for the wider catchment area (McKenna, 2021.)

In-stream woody dams can be a driver of geomorphic change leading to the formation of pools, bar formation and bank erosion (Wen Lo *et al.*, 2020). Woody dams have been shown to accumulate sediment (Gilbert, 2021), which predominantly occurs in the upstream barrier area (Deane *et al.*, 2021). Downstream of woody dam areas, scour pools have been observed along with an increase in gravel deposits (Powell *et al.*, 2021; Muhawenimana *et al.*, 2023). Geomorphological changes can depend on the type of woody dam installed, with erosional

processes noted to be more severe in naturally designed dams compared to those that have a more artificial appearance (Powell *et al.*, 2021).

In addition to hydrological and geomorphological changes, woody dams bring multiple ecological benefits through improved water quality (Janes *et al.*, 2016; Craigen, 2020), and increased storage of in-channel sediments (Osei *et al.*, 2015) which in turn enhances the river ecology through the creation of new habitats (Thompson *et al.*, 2018). Macroinvertebrate communities have been shown to respond positively to the introduction of woody dams, displaying an increase in diversity and abundance on the River Dane, Cheshire, as well as improved biodiversity in further downstream areas 10 months post installation (Deane *et al.*, 2021). Woody dams promote habitat composition and complexity through changes to organic matter, flow regimes and sediment cycles, especially where dams are more complex structures (Cashman *et al.*, 2018; Pinto *et al.*, 2019). Vegetation structure has been noted to improve around woody structures, especially emergent/marginal vegetation which appear to build up around woody dams (Harvey *et al.*, 2017; Pinto *et al.*, 2019).

In this study we aim to examine the hydrological, geomorphological and ecological changes associated with woody dams to add further evidence of their multiple benefits. Specifically, we predicted that (1) the installation of woody dams will reduce the in-channel velocity especially during high flow events, (2) the impact of woody dams on the hydrology and geomorphology will increase as these structures age, and (3) the introduction of woody dams will improve the channel habitat and ecological diversity. To achieve this, we set out to monitor the effect of different flow events on the hydrology and geomorphology, the impact of woody dam age and the effects of multiple structures on habitat/ecological diversity.

2. Methods

2.1 Study Area and Site Selection

The source and headwaters of the Stroud Frome and Twyver catchments in Gloucestershire, UK (Figure 1A) are predominantly rural, flowing through grassland and steep valleyed woodland. Both catchments have urban areas downstream, with the Frome flowing into Stroud (population 120,903: ONS, 2020) and the Twyver into Gloucester (population 129,709: ONS, 2020) respectively. Both of these urban areas were severely impacted by the 2007 summer floods (Environment Agency, 2007). The steep sided headwaters of the upper parts of both the Frome and Twyver mean they transport water rapidly during rainfall events and increase the risk of flooding downstream. NFM interventions (woody dams, bunds, cross drains, tree planting and fencing off livestock) have been implemented in both catchments to help reduce flood risk (Gloucester City Council, 2022; Stroud District Council, 2022). There exists a range of woody dam iterations but in the Stroud Frome and Twyver catchments, the woody dams are predominantly felled trees or large naturalistic log jams that have been placed into the river channels.

Fieldwork was carried out between February 2020 and December 2021. Three river reaches were selected for study with similar land use, aspect, geology, slope, elevation, channel dimensions and sub-catchment area (Figure 1, H, I & J). Although the reaches shared similar catchment characteristics, they differ in the number and age of woody dams. The channel

width, bankfull width and bank height were measured to assess channel size and ensure similarity. These were (Figure 1):

- Reach C1: no woody dams (control) – Three Groves sub-catchment in the Stroud Frome catchment (latitude, longitude: 51.725118 , -2.1290492).
- Reach L1; five woody dams installed in the year prior to the study (2019) – Prinknash Abbey sub-catchment in the Twyver catchment (latitude, longitude: 51.823627 , -2.1811288).
- Reach L2: four established woody dams installed 5 years prior to the study (2015) – Workman's Wood sub-catchment in the Stroud Frome catchment (latitude, longitude: 51.795406 , -2.1471433).

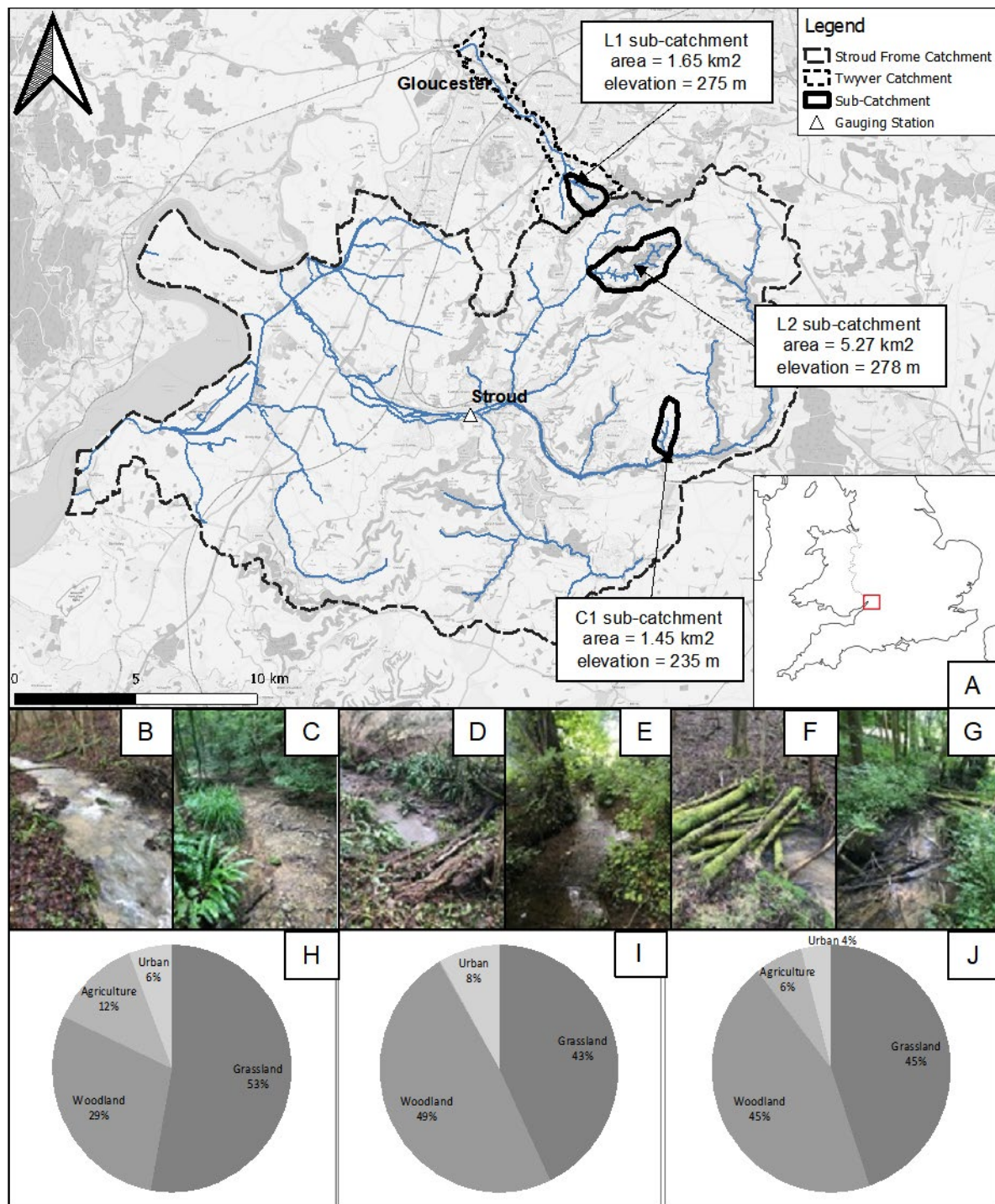


Figure 1: (A) Site location map of the Stroud and Twyver catchments together with the three sub-catchment monitoring reaches, their areas and maximum elevation. Inset map indicates location of the study area within the UK. Site photographs are seen in; (B/C) Reach C1 - control with no woody dams, (D/E) Reach L1 woody dams installed 2019, (F/G) Reach L2, woody dams installed in 2015. Images B, D, F were taken in winter, and C, E and G in summer. H, I and J show the proportion of land use within each sub-catchment surrounding the three monitoring reaches indicated above for (H) Reach C1, (I) Reach L1, (J) Reach L2.

To evaluate site characteristics further, the channel habitat diversity for each reach was assessed using the Modular River Physical (MoRPh) survey between June-July 2020; a habitat scale assessment of a section of river channel that records 14 numerical indicators on

the bank top floodplain, the bank face and channel margin, and the channel bed features (The Modular River Survey, 2019) that provides a rating of habitat diversity. A MultiMoRPh10 method was used, which collects information across ten adjacent 10 m sections (determined by the width of the channel under investigation) to give a detailed profile of that reach of river (The Modular River Survey, 2019), covering the 100 m area under investigation at each site. The leaky barrier reaches had a higher value for riparian structural complexity, extent of bed siltation and a greater number of pools and riffles recorded which indicates greater diversity, but otherwise the MoRPh values were very similar across the sites (Table 1). All reaches also recorded the lowest value for human influence, the highest energy flow type as unbroken standing wave and for natural bed material the coarsest as cobble and average as silt.

Table 1: Channel habitat diversity characteristics recorded using the MultiMoRPh10 survey events at the three study reaches: C1 (control – no woody dams), L1 (five woody dams installed in the previous year) and L2 (four woody dams installed more than five years previously)

Reach	No. flow types	No. bed material types	Extent of bed siltation	Channel physical habitat complexity*	Riparian vegetation complexity+	Total no. pools	Total no. riffles
C1	2.7	3.4	1.7	4.5	4.6	6	6
L1	2.3	2.6	4.3	4.0	5.5	8	11
L2	2.4	2.9	3.6	4.6	5.9	8	11

*Channel physical habitat complexity ranges from 1 (minimal complexity) to 10 (extremely high complexity) and is calculated as a weighted average of the number of natural channel bed material types, water surface flow types, natural bed features and ways in which vegetation is interacting with wetted channel.

+Riparian vegetation complexity ranges from 1 (minimal complexity) to 10 (extremely high complexity) and represents the number of riparian vegetation morphotypes found on the bank tops and bank faces within the survey site.

2.2 Monitoring Sampling Strategy

Each reach was approximately 100 m in length, with slight variation due to spacing of woody dams. Five monitoring locations were selected at each site. At C1 (the control reach with no NFM) there were five equidistant sample points 20 m apart. At the two reaches with NFM installed (L1 and L2) the five monitoring locations were determined by the position of the woody dams. The first point was located upstream 10 m before the sequence of woody dams, the second at the first dam, the third at the middle dam, the fourth at the final dam and the fifth 10 m downstream of the final woody dam. At the three monitoring locations associated with woody dams, measurements were collected 0.5 m upstream and 0.5 m downstream of the intervention. Therefore, there were eight sample points over the five locations at both L1 and L2 (refer to Section 2.1 for full detail of woody dams on each reach).

2.3 Frequency of Sampling

The key variables (outlined in section 2.4) were measured during five flow events of different magnitudes. Average flow conditions and recurrence intervals were determined using long-term flow records from the nearby Ebley Mill Gauging Station (National Flow River Archive station reference 54027, Figure 1A). The five flow events were labelled by increasing flow magnitude (Table 2).

Table 2: Information for different flow events

Flow Event	Date	Conditions	Gauging Station Average Flow	Peak Flow	Flow at start of Data Collection	Monitoring Time (hours) After Peak Flow
F1	August 2020	Dry antecedent conditions	1.15 m/sec	1.36 m/sec	1.32 m/sec	N/A
F2	July 2020	Dry antecedent conditions	1.20 m/sec	1.24 m/sec	1.24 m/sec	N/A
F3	February 2020	Minimal rainfall the week prior to collection	4.62 m/sec	4.67 m/sec	4.62 m/sec	N/A
F4	March 2020	Monitoring completed after Storm Jorje which had intense rainfall on already saturated ground	10.6 m/sec (1 in 4-year event)	12.14 m/sec	10.42 m/sec	24
F5	February 2020	Monitoring completed after Storm Ciara and Dennis which had heavy rainfall, with Gloucestershire receiving over 200% of the monthly average rainfall for February (Met Office, 2020) during these events	13.09 m/sec (1 in 9-year event)	14.35 m/sec	13.35 m/sec	20

2.4 Field Sampling Methods

Active water width, water depth and silt depth were measured to assess for hydrological and sediment differences between the three sites. Water depth and silt depth were measured at five points across the active water width (0, 0.25, 0.5, 0.75, 1) to generate a mean value. All measurements were recorded using a tape measure and meter stick.

Flow velocity was measured below the surface at approximately 0.6 water depth for 60 seconds (Meals and Dressing, 2008). The average active water width for the three sites was between 1.2 and 1.4m, meaning there should be 5-8 velocity measurements (Herschy, 1999). However due to the higher flow conditions the required number of sampling points across the channel had to be reduced for safety. Therefore, to ensure an accurate representation of water flow within the channel, velocity was recorded at three points (0.25, 0.5 and 0.75) across the

active water width using a Model 801 EM Flowmeter (Valeport, Totnes, UK) to calculate the mean.

Turbidity was measured infield using a photometer (Palintest 7100, Palintest, Gateshead, UK). A technical error meant that during F3, turbidity was not recorded. To standardise the collection of water samples for turbidity, the centre of the channel was identified from the active water width.

Approximately 200 g of fine bed sediment material was collected at three points across the channel width (0.25, 0.5 and 0.75). Samples were oven dried at 100 °C for 24 h then sieved using a Wentworth system (Endecotts, UK) (Angradi, 1999), together with an analysette 3E vibratory sediment shaker (Fritsch, Brackley, UK). Finally, to determine particle size a Mastersizer 2000 (Malvern Panalytical, Malvern, UK) was used. All grain sizes >16 mm were excluded. This was to facilitate clearer visualisation of the data. Bed sediment material was collected and measured twice, once in winter and repeated in summer 2020.

To assess macroinvertebrate diversity and abundance a 3-minute kick sample with a 1-minute stone turn was conducted downstream of woody dam interventions. The Anglers Riverfly Monitoring Initiative (ARMI) method of assessment was used. This is a standardised non-destructive monitoring technique that was developed to detect severe perturbations in river water quality based on the presence of pollution sensitive invertebrate taxon (The Riverfly Partnership, 2022). Eight taxa are identified and enumerated which together contribute to a simple metric or ARMI score. A high ARMI score generally indicates higher river water quality with lower pollutants. Macroinvertebrate samples were collected monthly, however due to COVID-19 lockdowns in the UK and bi-annual samples that were preserved in methanol for species level identification there are some missing months (there were no data collected in April, May and September 2020, and April 2021, and additionally no data for: C1 in July 2020 / February 2021 / May 2021, L1 in June 2020, and L2 in March and June 2020; equivalent to 25% of the period).

2.5 Statistical Analysis

Statistical analysis was performed in RStudio using R Statistical Software (v4.4.3: R Core Team, 2025). A Shapiro-Wilk (function: `shapiro.test`) test for normality was used to determine the distribution of each variable. The datasets for velocity ($p = 0.000$), water depth ($p = 0.000$), water width ($p = 0.000$), turbidity ($p = 0.000$) and silt depth ($p = 0.000$) all displayed significant difference. ARMI ($p = 0.215$) was the only variable to display a normal distribution. For variables that were not normally distributed a Kruskal-Wallis (function: `kruskal.test`) was performed and for variables of normal distribution an ANOVA (function: `aov`) was selected. If a result was significant, then a post-hoc test was performed. For an ANOVA, this was a Tukey HSD (function: `TukeyHSD`) and for a Kruskal-Wallis a Dunn (function: `dunnTest`). ANOVA and Kruskal-Wallis tests were selected as each test had at least two or more groups (Ross and Wilson, 2017; Weaver *et al.*, 2023).

3. Results

3.1 The effect of different flow events

3.1.1 The impact of woody dams during different flow events

During low and moderate flow events (F1 (August 2020), F2 (July 2020) and F3 (February 2020)), no significant difference occurred between the three sites in terms of channel velocity (Figure 2A; F1, $p = 0.527$; F2, $p = 0.249$; F3, $p = 0.076$). However, during the high flow events (F4 (March 2020) and F5 (February 2020)) a significant difference was observed between the three sites (F4, $p = 0.009$; F5, $p = 0.038$). During F4, L1 was 58% and L2 was 59% lower than C1, with C1 being significantly different from L1 (C1-L1, $p = 0.018$; C1-L2, $p = 0.122$; L1-L2, $p = 0.765$). During F5 the velocity was lower by 51% at L1 and 38% at L2 compared with C1, with a significant difference occurring between C1 and L1 (C1-L1, $p = 0.031$; C1-L2, $p = 0.212$; L1-L2, $p = 0.281$). At C1, there was a 410% increase between its lowest flow (F2) event and its highest (F5). Whereas at the two woody dam sites flow velocity increased by 74% at L1 and 190% at L2. The rise in velocity from F2 to F5 was observed to be significantly different at C1 and L2, but not L1 (Dunn: C1, $p = 0.000$; L1, $p = 0.142$; L2, $p = 0.000$). Apart from F5, active water depth was significantly different between each site during each flow event (Figure 2B: F1, $p = 0.000$; F2, $p = 0.001$; F3, $p = 0.000$; F4, $p = 0.000$; F5, $p = 0.355$). Sites with woody dams continuously had a higher average water depth across each flow event. There was a significant difference observed between the flow events at each site, with water depth increasing as the flow events increased in magnitude (C1, $p = 0.000$; L1, $p = 0.000$; L2, $p = 0.000$). Lower turbidity values were associated with the two woody dam sites which was most evident during F5 (Figure 2C). The three sites were continuously significantly different during all flow events (F1, $p = 0.001$; F2, $p = 0.005$; F4, $p = 0.002$; F5, $p = 0.000$).

Figure 2: A) channel velocity B) water depth and C) turbidity during the five flow events at the three study sites C1, L1 and L2. Boxplots show the spread of data indicated by quartile ranges.

3.1.2 Changes to in-stream/micro hydrology around woody dams during different flow events

During low flow events (F1 and F2), there was no significant difference between upstream and downstream areas for water velocity (Figure 3A: F1, $p = 0.327$; F2, $p = 0.453$), active water width (Figure 3B: F1, $p = 0.423$; F2, $p = 0.631$) and water depth (Figure 3C: F1, $p = 0.631$; F2, $p = 0.482$). In the three higher flow events, a significant difference was observed during F3 and F4 for velocity (F3, $p = 0.024$; F4, $p = 0.001$; F5, $p = 0.058$) and on all three events for water depth (F3, $p = 0.000$; F4, $p = 0.000$; F5, $p = 0.021$). This was caused by upstream areas displaying lower velocity readings and higher water depths compared with downstream areas. Upstream to downstream, the velocity increased by 120% during F4 and 110% during F5. Although active water width was larger in upstream compared with downstream areas during F4 and F5, this was not observed as a significant difference (F4, $p = 0.423$; F5, $p = 0.470$).

There was a significant difference between all flow events in the downstream areas of woody dams for velocity (Downstream, $p = 0.000$). Downstream areas increased in velocity by up to 259% (F2-F5, $p = 0.002$) compared to 66% in upstream areas from their lowest to highest values. There was no significant difference between flow events for velocity in the upstream area (Upstream, $p = 0.165$), or for either area in terms of water width (Upstream, $p = 0.176$; Downstream, $p = 0.700$). A significant difference was observed in both upstream and downstream areas for water depth (Upstream, $p = 0.000$; Downstream, $p = 0.000$). Between low flow events (F2) and high flow events (F5), the upstream active water depth around the woody dams increased by 533% (F2-F5, $p = 0.000$) and in the downstream area the increase was 400% (F2-F5, $p = 0.000$).

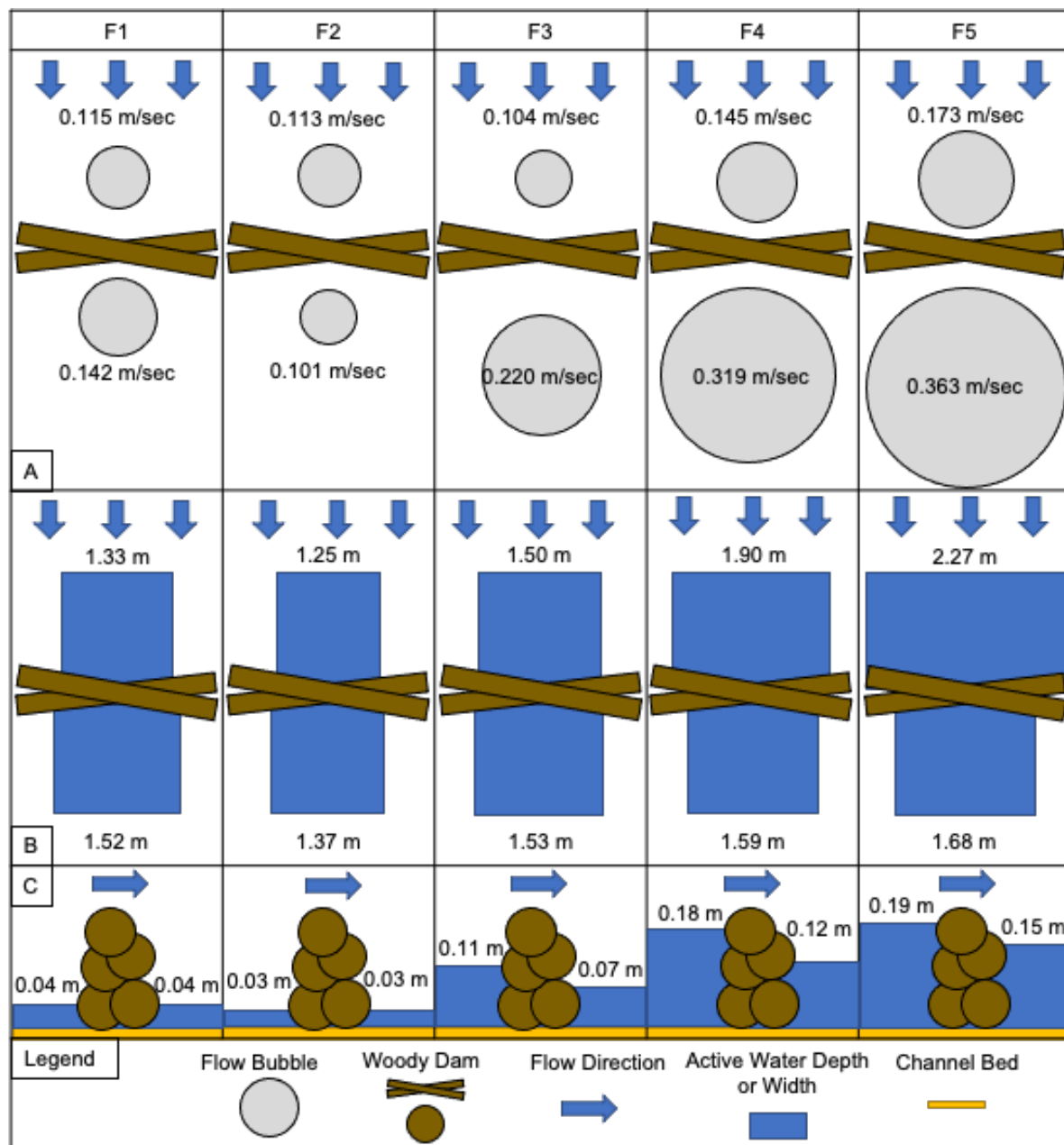


Figure 3: Hydrological variables for upstream and downstream intervention analysis, average of L1 and L2 for each flow event, for A) mean flow velocity B) active water width and C) active water depth. Variables are proportional to raw data with mean formulated by combining all monitoring points from both woody dam sites. Woody dam, flow direction and channel bed not proportional.

3.2 The impact of woody dam age

Lower channel velocity was observed at both woody dam sites when compared with the control site C1. Between C1 and L1, there was a 37% reduction in velocity and between C1 and L2 a 40% reduction (Figure 4A). Despite this reduction, there was no significant difference observed between the three sites ($p = 0.066$). Mean active water depth was higher at sites with woody dams, with a smaller range than C1 (Figure 4B). Sites with woody dams regardless of their age maintained similar channel velocity and active water depth. There was a significant

difference between the sites for active water depth ($p = 0.000$), with C1 observed to be significantly different to both woody dam sites (C1-L1, $p = 0.000$; C1-L2, $p = 0.000$; L1-L2, $p = 0.985$).

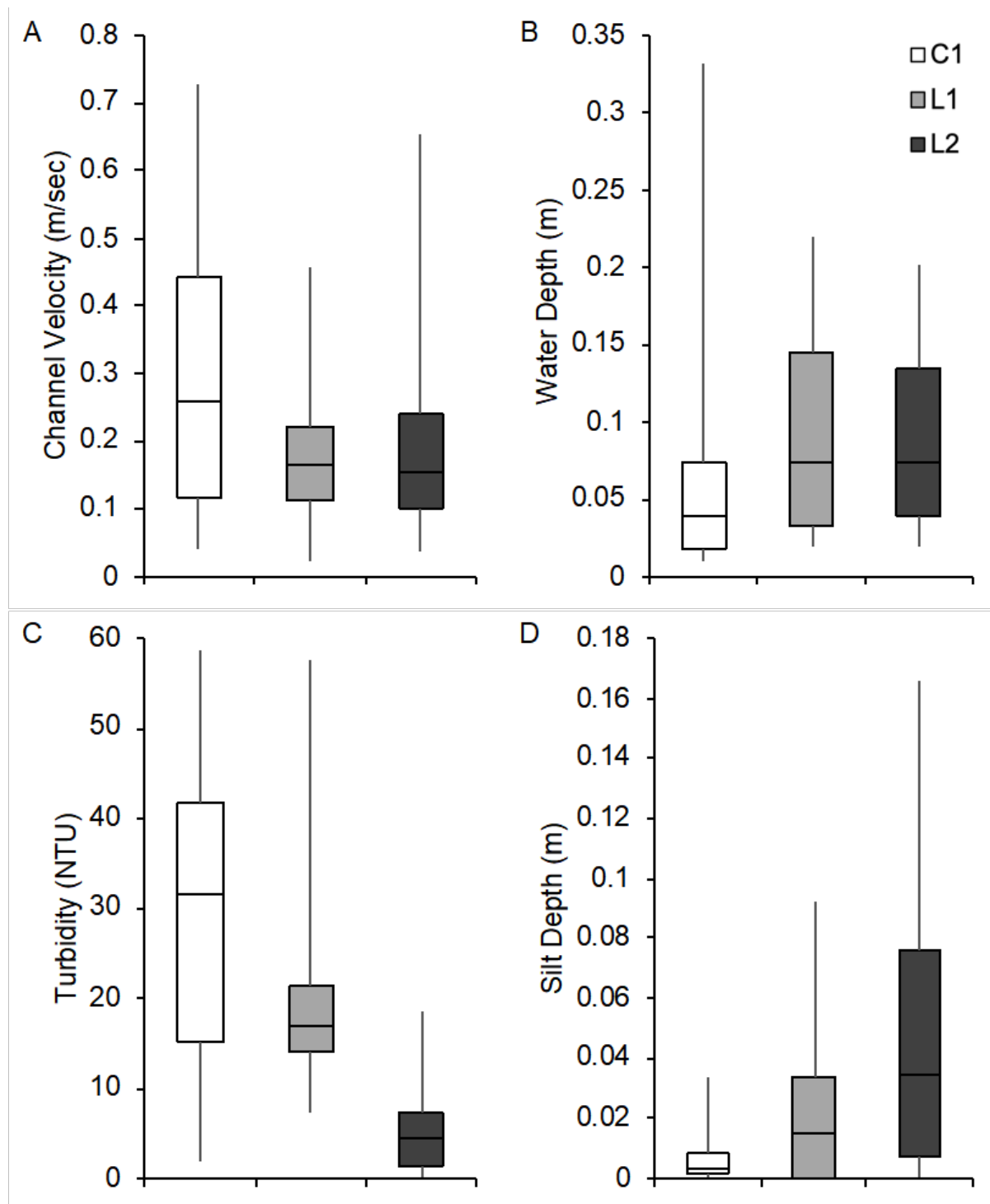


Figure 4: Variables for A) channel velocity B) active water depth C) turbidity and D) silt depth for the three sites. Boxplots represent the quartile ranges of the data and were formulated by taking the average from each monitoring point for every flow event recorded.

Turbidity was lower at sites with woody dams compared to C1, providing the lowest readings at L2 (Figure 4C). There was a significant difference between sites for turbidity ($p = 0.000$). Post hoc tests revealed there was a significant difference between C1 and L2, as well as L1 and L2 (C1-L1, $p = 0.258$; C1-L2, $p = 0.000$; L1-L2, $p = 0.000$).

There was an increase in silt depth at the woody dam sites, with the deepest silt deposits measured at the older woody dams L2 (Figure 4D). In addition, the oldest site had the largest range in silt depth and all three sites were significantly different to each other (C1-L1, $p = 0.001$; C1-L2, $p = 0.000$; L1-L2, $p = 0.000$). There was also an overall change in the bed sediment material at the sites with woody dams that included more fine-grained fractions, especially at the older site, L2 (Figure 5).

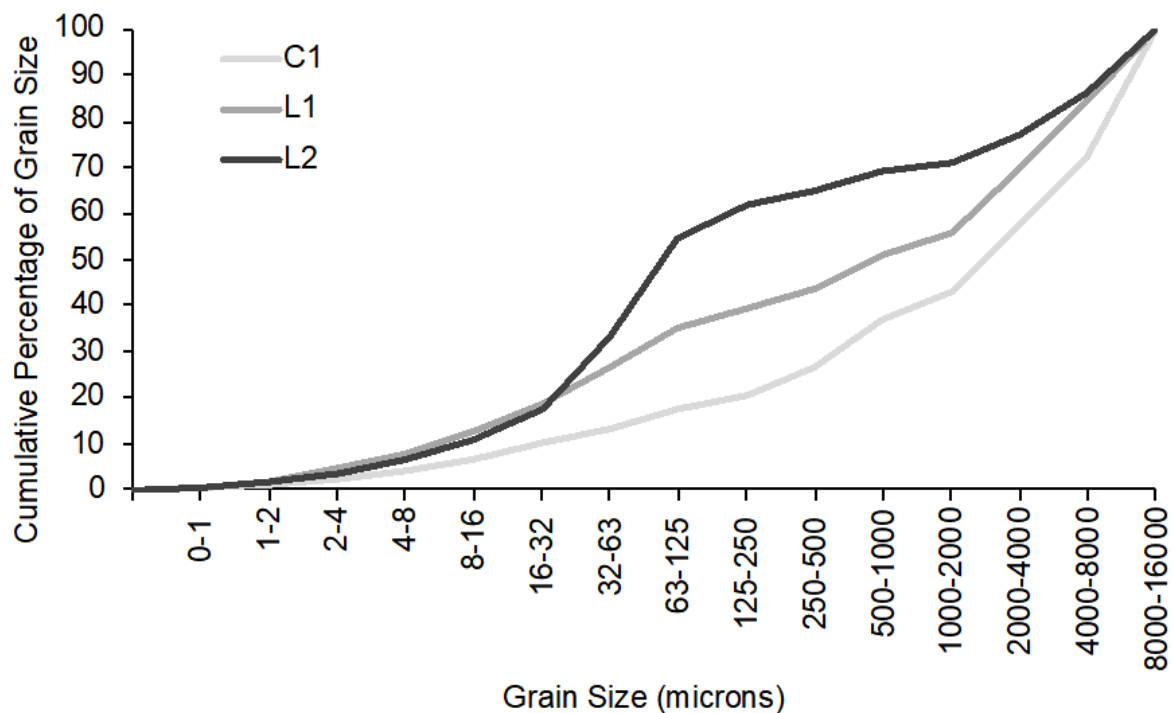


Figure 5: Cumulative percentage of grain size for bed sediment material at the three sites.

3.3 Effects of multiple structures on habitat/ecological diversity

There was a wider range of channel velocity at the woody dams sites compared with C1 (Figure 6). Sites with woody dams had more areas of high and low velocity that created a mosaic of different hydrological flow patterns, whereas C1 showed little variation between the monitoring points. At the sites with woody dams, the areas of low velocity tended to be in the areas immediately upstream of each woody dams feature, whilst higher velocity areas were more often associated with downstream areas.

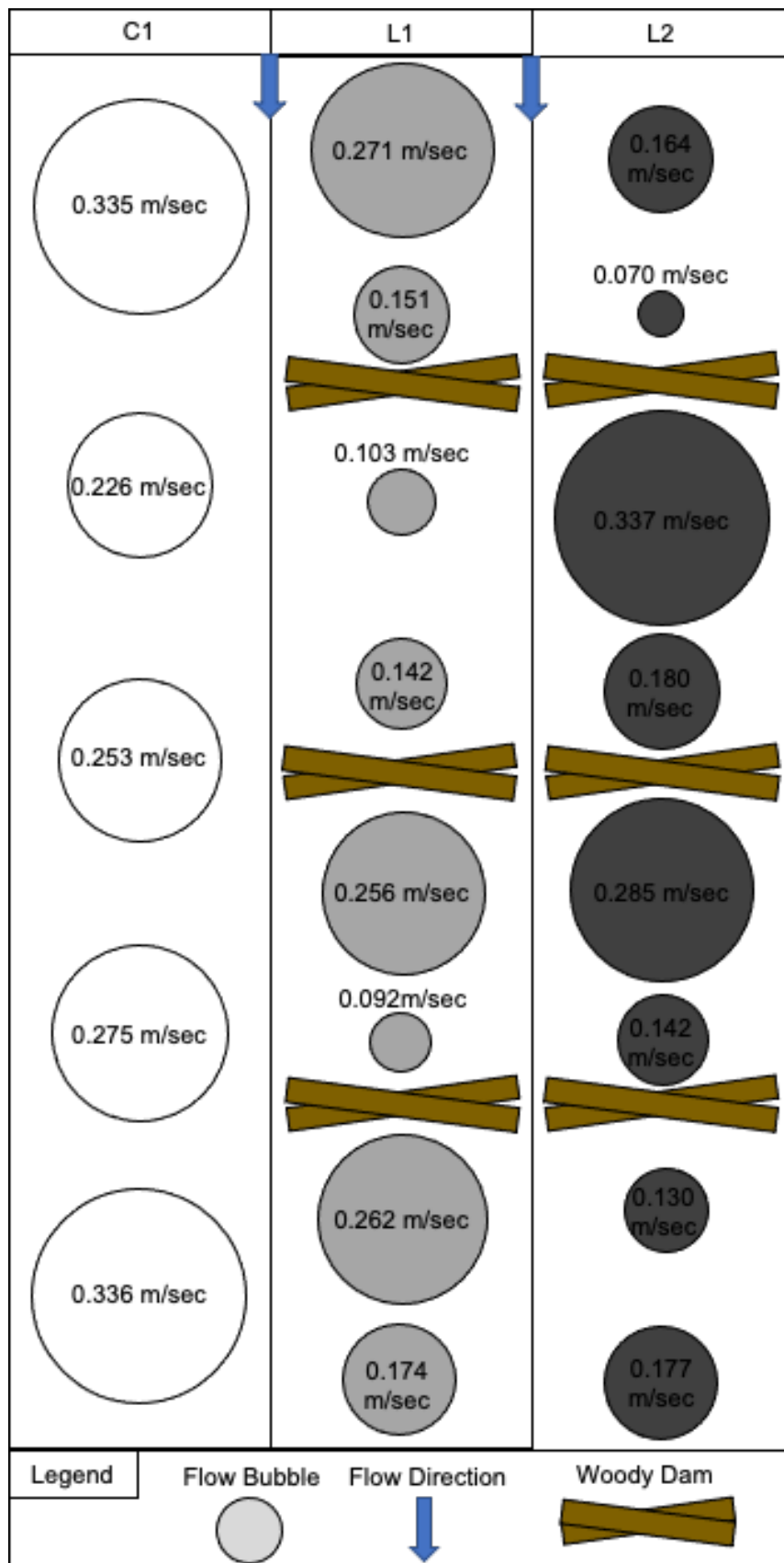


Figure 6: Velocity (m/sec) of all monitoring points for the three sites. Variables are proportional to raw data with the mean calculated by combining the data from each flow event for each monitoring point.

Sites with woody dams retained a wider mix of bed sediment material. At the control site (C1) all monitoring points contained a similar high sand/pebble with a low silt content that rarely rose above 20% (Figure 7). However, at sites with woody dams there was higher silt content in the areas upstream of each woody dam feature (Figure 7). The site with oldest woody dams (L2) also had the highest silt content in bed material. In addition, the data shows there exists a greater variation in sediment grain size at sites with woody dams L1 and L2 (Figure 7).

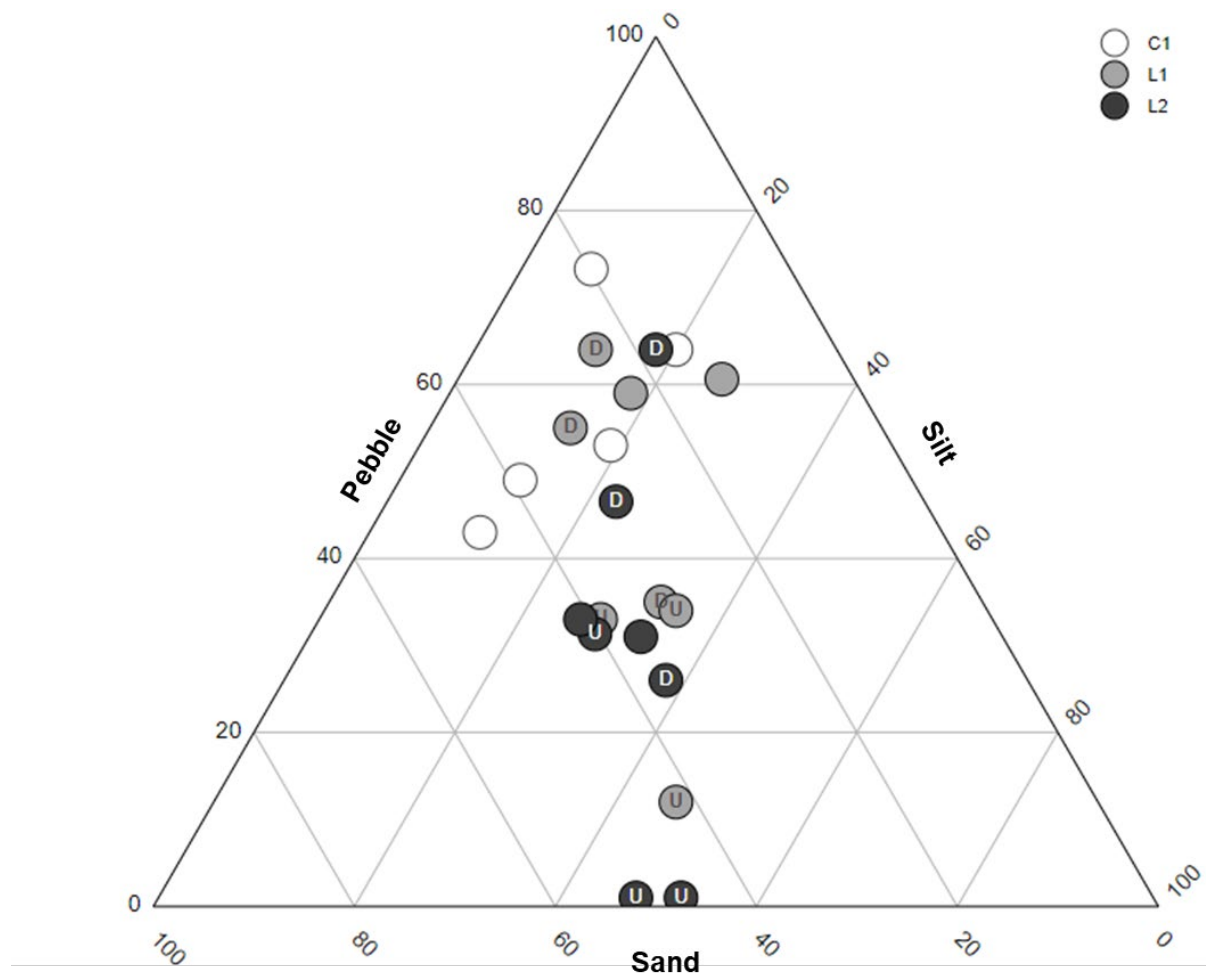


Figure 7: Bed sediment material distribution across all monitoring points at the three sites. Monitoring points are labelled U (directly upstream of woody dam) and D (directly downstream of a woody dam). Ranges were set as silt 0-63 microns for silt, 63-2000 microns for sand and 2000-16000 microns for pebble.

The highest ARMI scores (a reflection of macroinvertebrate abundance and diversity) were associated with the site with older woody dams (L2, Figure 8). C1 showed the lowest average ARMI score with a median value of 6, and the highest median of 11 was L2. *Gammarus pulex*, *Baetidae* and *Trichoptera* were common at all three sites, with L2 also supporting high abundances of *Plecoptera*, *Ephemeroidea* and *Heptageniidae*. The three sites were observed to be significantly different from each other ($p = 0.000$), with L2 being significantly different to C1 and L1 (C1-L1, $p = 0.116$; C1-L2, $p = 0.000$; L1-L2, $p = 0.001$).

Figure 8: ARMI (Anglers' Riverfly Monitoring Initiative; a metric used to track severe changes to water quality using macroinvertebrates) scores for the three sites. Boxplots calculated by taking the score for each month from a single Riverfly kick sample downstream of the woody dam area.

4. Discussion

4.1 The effect of different flow events

Previous research has indicated that woody dams only impact high flow events (Metcalf *et al.*, 2017; Burgess-Gamble *et al.*, 2018; Leahey *et al.*, 2020; Hankin *et al.*, 2020). This study supports this finding. During low flow events (F1 and F2), streams with and without woody dams had comparable low flow velocities and water depths (Figure 2). During low flow events, water flows underneath the woody dams and there was no difference in velocity upstream and downstream of woody dam areas (Figure 3A). This finding was also observed at the Bowmont woody dam project in the Scottish Borders, where velocity was unaffected in low flow conditions (Addy and Wilkinson, 2017) and in another study of woody dams in the Stroud Frome catchment (Smith and Uttley, 2016).

During high flow events (F4 and F5), woody dam sites had lower channel velocities compared with the control site. During F4 and F5, velocity was up to 59% lower at the woody dam sites compared with C1 (Figure 2A). Other studies have recorded a reduction in flow. At Pickering, North Yorkshire a reduction in flood peak discharge of 15-20% was measured (Nisbet *et al.*, 2017), and modelled data in woodland catchments were proposed to reduce flood peak magnitude by 21% (Kitts, 2010). The data from this study is much higher because it presents a snapshot of the flow events, and unlike the literature above it is unknown when our flood peak occurred as discharge was not calculated. However, it does highlight the effectiveness of woody dams at reducing flow velocity and increasing water storage during high magnitude flow events.

Flow velocity was slower in the upstream areas around woody dams during high flow events which was associated with increased water depth resulting in large pool formations (Figure

3A). This is similar to beaver dams, which have been shown to promote pool formation and provide additional water storage capacity (Puttock *et al.*, 2021; Brazier *et al.*, 2021). A backlog of water will reduce channel velocity (Linstead and Gurnell, 1999). As the pressure builds up the shear stress value will reduce as water is released, creating a temporary area of increased high velocity in the downstream areas (Gurnell, 2013; Grabowski *et al.*, 2019). Although the observed velocities were higher downstream of dams, the active water depth was much lower. This finding was also observed at woody dams in the Lymington catchment in Hampshire where a backlog of water forced flow beneath the barrier thus creating a transitional hydraulic jump (Dixon, 2013). Although there is a temporary increase in velocity in downstream barrier areas, when woody dams are placed in sequence the flow rapidly de-accelerates once it encounters subsequent barriers and then the adjacent pool area (Linstead and Gurnell, 1999).

Active water depth was highest at woody dam sites during high magnitude flow events (Figure 2B). Sites with woody dams are designed to store water during high flow (Burgess-Gamble *et al.*, 2018), and an observed increase in active water depth confirms this at L1 and L2. Both active water depth and width increased upstream of individual woody dams compared to the downstream areas (Figure 3B and 3C) resulting from a backlog of water which pools and fully utilises the channel dimensions thus maximising the amount of water being stored (Linstead and Gurnell, 1999). Water depth is lower downstream of woody dam areas compared to the control site, C1. The greater active water depth and width upstream of woody dams can act to increase the hydrological connectivity to the floodplain when breached further creating extra storage areas during high flow events (Grabowski *et al.*, 2019). Breaching bankfull heights can also supply the soil in these areas with extra nutrients, improving the fertility of the floodplain (Grabowski *et al.*, 2019). This knock-on effect was identified within the MoRPh survey, where the woody dam sites had a higher score in terms of riparian vegetation complexity compared with C1.

Turbidity rises in high flow events as particles become activated and create a turbid environment (Lawler, 2005; USGS, 2020). Woody dams will reduce channel velocity upstream of the structure, thereby reducing the potential energy to transported sediment and leading to lower turbidity, which was observed during the highest flow event at the sites with woody dams in this study. This effect has previously been noted at hard-engineered dams, suggesting that woody dams act in a similar manner (Szatten *et al.*, 2018). High flow events are a major cause of sediment transportation (Lawler, 2005), which can choke channels further downstream and increase flood risk (Slater *et al.*, 2015; Nones, 2019). The increased silt and lower turbidity associated with woody dams at L1 and L2 demonstrates reduced sediment transportation, which has also been observed at the Devon beaver project (Puttock *et al.*, 2021; Brazier *et al.*, 2021) and across other nearby sites in the Stroud Frome catchment (Smith and Uttley, 2016). Although turbidity was highest at C1 compared with woody dam sites during F1, F2 and F5 this was not the case during F4. This was an unusual finding. One potential explanation for this result was that F5 occurred two weeks prior to F4 and was the first major storm event of winter. If a large amount of sediment were available for transportation during F5 it would have resulted in a reduced amount of sediment during F4. This would support modelling outputs which display less fine sediment availability for transportation during subsequent flow events (Mao, 2018).

4.2 The impact woody dam age

There is an instant effect on velocity and water depth when woody dams are placed into a system during high flow conditions (Burgess-Gamble *et al.*, 2018); this is demonstrated at L1 and L2 (Figure 4A and 4B) suggesting that these woody dams maintain their function over at least a five-year period. The difference in average reach velocity found in this study (37% from C1 to L1; 40% from C1 to L2, Figure 4A) is similar to an investigation of naturally occurring woody dams in the New Forest, UK in which a drop of 55% was recorded when comparing reaches with woody dams to control sites (Linstead and Gurnell, 1999).

Our data shows that the longer a woody dam site has been *in situ*, the lower the turbidity measured when compared to the nearby control site (Figure 4C). Turbidity will be lower at sites with woody dams as they create areas of deposition by reducing velocity, resulting in a less turbid environment (Jeffries *et al.*, 2003; Dixon, 2013). This study suggests that woody dams continue to reduce the transportation of sediment downstream areas over at least a five-year time period.

Increased silt depth was most prevalent at woody dam sites, with the oldest site containing the deepest silt (Figure 4D). This was associated with a less coarse mix of bed sediment material at the woody dam sites (Figure 5). Woody dams promote the storage of sediment within upstream areas of the structure, resulting in the development of silt layers and a siltier bed sediment material mix (Linstead and Gurnell, 1999; Burgess-Gamble *et al.*, 2018). Excess sediment remains an issue in downstream areas of all of the study sites, so successfully storing sediment upstream may alleviate this contributing factor to flood risk in downstream areas (Walter and Merritts, 2008; Slater *et al.*, 2015; Nones, 2019). However, siltation of impounding structures is one of the largest management issues associated with the installation of woody dams, weirs and small or large dams (Csiki and Rhoads, 2010). Continued sedimentation ultimately reduces the effectiveness of a woody dam through reduction in the channel storage capacity which reduces the flood mitigation potential of the interventions. Although L2 did have much higher silt depths than L1, in high flow events both sites behaved similarly indicating their effectiveness in retaining silt had not been reduced. This is still an important aspect to continue monitoring though. Silt build up associated with woody dams creates a dilemma. On the one hand, this sediment is being trapped in low-risk areas and protects vulnerable settlements downstream. However, eventually there becomes a point that silt builds up and woody dams no longer provide the flood mitigation solution they have been implemented for. It is therefore important to address this management issue. This might require the removal of sediment on a periodic basis or building more woody dams to replace those that have become ineffective. Further investigations into woody dams and sediment dynamics should be investigated. As there was a limited time period for this study, we were not able to investigate the potential of sediment fluxes, pulses and blow out events in further detail. More information on this would help in the understanding of sediment movement downstream and water storage potential.

4.3 Effects of multiple structures on habitat/ecological diversity

Both woody dam sites demonstrated changing flow characteristics creating a mosaic of different flow patterns (Figure 6) and pool-riffle systems (Table 1), an important factor for river ecology. Results from the MoRPh survey indicated that pool-riffle systems were a much more common feature in streams with woody dams compared to a control site (Table 1). Riffles

provide a prime habitat for macroinvertebrates life by increasing oxygen concentration and water turbulence (Statzner *et al.*, 1998; Merritt *et al.*, 2008). The pools provide deeper habitat during periods of low flow and an area of protection during high flows (Brown and Brussock, 1991; Thompson, 2018). A broader range of velocity in these areas may attract more macroinvertebrates species that prefer a pool or riffle environment (Logan and Brooker, 1983; Brown and Brussock, 1991; Herbst *et al.*, 2018).

Sediment grain size is an important factor that influences instream macroinvertebrate populations (Duan *et al.*, 2009), and woody dam sites provide a wider variety of habitats (Figure 7). In reaches with woody dams, the coarse bed sediment material that remains are a preferred habitat for macroinvertebrate taxa such as *Ephemeroptera* (e.g. *Serratella ignita* or *Ecdyonurus dispar*), *Plecoptera* (e.g. *Perlodes mortonii* or *Isoperla grammatica*) and *Trichoptera* (e.g. *Rhyacophila dorsalis* or *Plectrocnemia conspersa*) (Harrison *et al.*, 2007). Areas of coarse material also provide ideal habitat for fish species such as *Cottus gobio* (European Bullhead), which are common in these small headwater streams (Wildlife Trust, 2023). The woody dam reaches additionally provide areas of fine bed sediment material, preferred by species such as *Lampetra planeri* (Brook Lamprey) which rely on silty stream beds during their larval stage (Woodland Trust, 2023).

The highest macroinvertebrate ARMI scores were found at the woody dam sites and the oldest site had the highest scores (Figure 8). This is likely due to a combination of physical and environmental factors directly influenced by woody dams, such as the introduction of wood to the system which will provide more nutrients and habitat diversity (Wohl *et al.*, 2019). Bed sediment grain size and a mosaic of different velocities displayed in this study at the woody dam sites show an improvement in habitat diversity. Woody dams have also had a positive impact on macroinvertebrate communities at Black Brook in Cheshire, UK which analysed the effects 10 months after introduction (Deane *et al.*, 2021). The results from this study (Figure 8) introduce the possibility that woody dams continue to provide positive impacts to macroinvertebrate communities for at least five years.

5. Conclusion

This study found that woody dams do have a significant impact on ecology as well as hydrology and geomorphology during high flows. Woody dams mitigated the effects of high magnitude flow events, reduced water velocity and increased water storage compared with a control site. The data suggests that streams with woody dams transport less sediment to vulnerable downstream areas even 5+ years after installation. The highest magnitude event captured in this study was a 1 in 9-year flow which did not overwhelm the woody dams. It may be useful to capture a greater range of flow magnitudes to monitor more precisely the effects of woody dams during very high magnitude events.

Woody dams of at least five years in age maintain a good level of efficiency compared with newly installed woody dams, increasing confidence in their effectiveness over a long time period. Following the installation of woody dams hydrological variables alter rapidly and this effect remained five-years post installation. This means that sites can gain flood mitigation benefits immediately from a relatively quick and low-cost solution. Measurements of bed sediment material grain size and silt depths suggest that woody dams retain sediment in the

reach and increase the levels of siltation of the channel. Further monitoring would be useful to ascertain whether woody dams lose efficiency as silt depths increase.

Riparian vegetation complexity also scored best in the MoRPh survey at sites with woody dams. It will be important to monitor the wider biodiversity benefits that an increase in macroinvertebrates may have on other species, such as bats, birds and fish that feed on them. As well as monitoring species, it would be useful to monitor the physical habitat changes that occur around NFM features both in-channel and on the bank top. This will increase our understanding of the types of interventions that boost biodiversity, which will be useful knowledge for practitioners implementing NFM features.

This study demonstrates that woody dams are a multi-beneficial flood mitigation measure with positive impacts still evident at least five years post installation. The management implications from our study provides key knowledge for stakeholders implementing the UK governments strategy as part of the 25 Year Environment Plan, as well as other countries that are including WWNP in their flood mitigation and river restoration toolkit.

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Data availability statement

Data available on request