International Journal of River Basin Management

ISSN: 1571-5124 (Print) 1814-2060 (Online) Journal homepage: www.tandfonline.com/journals/trbm20

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To cite this article: David Furnues, Judith R. Cudden & Matthew McParland (03 Jun 2025): Modelling the efficacy of woody debris dams in slowing and reducing peak discharge, International Journal of River Basin Management, DOI: 10.1080/15715124.2025.2505596

To link to this article: https://doi.org/10.1080/15715124.2025.2505596

Published online: 03 Jun 2025.

INTERNATIONAL JOURNAL OF RIVER BASIN MANAGEMENT
https://doi.org/10.1080/15715124.2025.2505596

Modelling the efficacy of woody debris dams in slowing and reducing peak discharge

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ABSTRACT

As part of Natural Flood Management, networks of engineered woody debris dams are deployed in upper catchments. There is currently a great deal of interest shown in hydro-environmental modelling (hydro-environmental, referring here to the dynamic parameters, i.e. water levels and velocities, and environmental in the context of the catchment characteristics) to overcome upscaling from plot to catchment. However, there is no standard hydraulic unit to simulate woody debris dams in the modelling domain. This study develops and validates a hydraulic modelling unit that accounts for the physical properties of the woody debris dams and tests this unit with real-world empirical data. Pier-loss bridge units were used to simulate a network of woody debris dams. Woody debris dam blockage area and gap sizes were investigated, and seasonal changes and designs of woody debris dams were simulated by altering the pier-loss bridge legs and soffits. The modelling software package, Jacobs Flood Modeller v6.1 (FM) enabled field data to be imported as boundary conditions so the model could represent the real-world. Two storm events were simulated with data obtained from on-site automated monitoring equipment. Results show pier-loss bridge units within FM, 1D simulations, effectively represented varied woody debris dam designs in attenuating peak discharge.

ARTICLE HISTORY
Received 2 August 2024
Accepted 9 May 2025

ASSOCIATE EDITOR
Michael Nones

KEYWORDS
Natural Flood Management; woody debris dams; flood modeller; 1D simulations; hydraulic structure representation

Introduction

Engineered woody debris dams, known as Runoff Attenuation Features (RAFs) in Natural Flood Management (NFM), are small-scale flood intervention structures designed to mitigate downstream flood risk. These structures, which emulate naturally occurring wood in streams, reduce velocity by increasing roughness and impound backwater in the channel, enhancing temporary floodplain storage so mitigating downstream flooding. However, there is limited scientific research which quantifies their efficacy as an NFM approach at the catchment scale (Wingfield *et al.* 2019). To parametrise individual catchment variations, computer modelling has become the favoured technique. However, uncertainty remains in modelling woody debris dams due to difficulties in realistically representing their hydrological and hydraulic complexities (Dixon 2015).

With no standardised approach in representing woody debris dams, results can vary between studies as illustrated by recent literature. The most common techniques for modelling woody debris dams, include geometry modifications, roughness changes, and hydraulic structural representations such as weirs (Addy and Wilkinson 2019). Senior *et al.* (2022) used HEC-RAS 2D, combining geometry adjustments and roughness changes to represent woody debris dams. Their results showed that combining walls, pits, and roughness, reduced peak flow by 16.6% during a 1-year return rate event, though effectiveness fell below 5% during high discharge. Similarly, Villamizar *et al.* (2024) used the Soil and Water Assessment Tool (SWAT) coupled with a water routing model to represent woody debris dams as permeable sluice gates, accounting for porosity and bank overtopping. Despite robust modelling capabilities, this approach faced challenges in capturing structural overtopping and effectively representing floodplain connectivity. Pearson (2020) employed CAESAR-Lisflood morphodynamic modelling and HEC-RAS 2D hydraulic modelling to represent woody debris dams as simplified weirs with a culvert placed at the bottom to represent the gap under the structure. While observing enhanced floodplain connectivity and geomorphological changes, simulated structures lacked realistic porosity. A key limitation across these studies is the absence of a standardised modelling approach for representing woody debris dams, making direct comparison difficult.

This study uses the hydraulic structure representation approach to represent woody debris dams based on the concept that their hydraulic effects are comparative to weirs or culverts (Addy and Wilkinson

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2019). However, there remains no specific tool for modelling woody debris dams (Ngai *et al.* 2017, Leakey *et al.* 2020). The aim of this study is to address the research gap to develop a unit to represent woody debris dams in the modelling domain (Ngai *et al.* 2017). Flood Modeller v6.1.(FM) was chosen as it has been benchmarked against other modelling programmes and is an approved Environment Agency Flood Modelling package. The objectives are to: (i) develop and validate an empirically derived unit, and (ii) use the developed modelling approach to assess the effectiveness of woody debris dams in attenuating the flow in two peak storm events.

Materials and methods

Study site

This study was located at Wilderhope Brook, Shropshire, UK, a first order upland tributary of the River Corve located from 522554.59E and 5820344.6N (source) to 523290.59E and 5817990.09N (sink). In 2017, 105 engineered woody debris dams were installed (Figure 1). This study focuses on a 0.2 km channel reach containing 5 engineered woody debris dams located in Wilderhope Brook lower reach to the east of the B4368 bridge (355147E, 290683N).

Fieldwork monitoring

Two storm events during the summer (10–12 June 2019) and winter months (15–17 February 2020) were identified using automated field equipment, including a Hach FL900 automated flow logger supporting an AV 9000 Area Velocity Sensor. The sensor (working depth of 0 to 3 m), installed next to the B4368 bridge between 02/04/2019 and 31/03/2021, measured flow depth, localised velocity, discharge and temperature every 15 min, while the automated flow logger recorded readings. Storm events were verified by cross-referencing Met Office data with readings from a Lambrecht 4 cm^3 tipping bucket rain gauge (precision 0.2 mm) supporting a Hobo pendant event logger installed at Stanway Farm, northwest of Wilderhope Brook catchment (352113E, 289342N). Regular field photography documented seasonal changes in woody debris dams, establishing a baseline for representing these structures within hydraulic models.

Topographical survey

The Bluesky Mapshop online portal enabled acquisition of a Digital Surface Model (DSM) dataset (Resolution: 0.25 m, Accuracy xy: ± 1 m RMSE, Accuracy z: ± 1.5 m RMSE) for Wilderhope Brook catchment. This dataset was acquired using LIDAR with an Optech Galaxy and LW640 Thermal Camera mounted on a

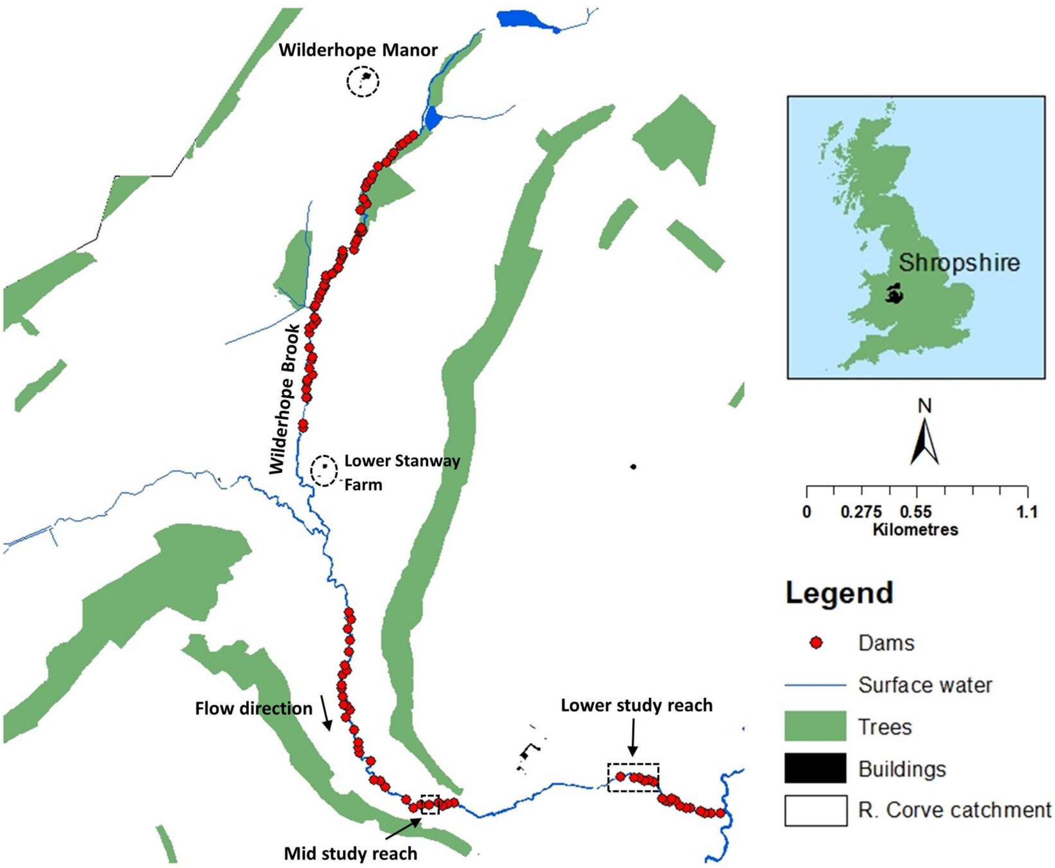

Figure 1. Map displaying 105 woody debris dam locations from source to sink at Wilderhope Brook. The lower study reach (length: 0.2 km) is labelled. Source from Furnues (2023).

surveying aircraft (BlueSky 2021). A DSM represents the elevation of surface terrain including above-ground features such as buildings and vegetation. Manual editing in ArcGis Pro 2.9.0. removed above-ground features, constructing a Digital Terrain Model (DTM) that represented bare ground. Photography provided the means of visually inspecting the precision before importing into the hydraulic model.

Hydraulic modelling

The DTM generated from the DSM dataset served as the foundational data for developing the 1D hydraulic model in Flood Modeller v6.1. (FM). FM was the chosen software package as it has been benchmarked against other recognised software packages, including ESTRY, HEC-RAS, InfoWorks ICM and MIKE FLOOD (Environment Agency 2021a). 1D models primarily focus on in-channel flows (Collell *et al.* 2019). Woody debris dams were represented using pier-loss bridge units, designed to restrict flow while allowing throughflow during varying discharges. Environment Agency (2021b) guidelines, classify structures with a downstream width-to-height ratio below 5 as bridges, supporting the use of pier-loss bridge units.

Calibration

To calibrate field data to FM a single woody debris dam was selected in the mid reach positioned 800 m upstream of the B4368 bridge (Figure 2). This woody debris dam was selected, as OTT Orpheus Mini pressure levels were installed 3.8 m upstream of the woody debris dam face and 3.9 m downstream, with recordings taken every 15 min. By selecting a woody debris dam with pressure levels, readings could be taken that could be cross-referenced to examine model precision.

Woody debris dam representation

To model the woody debris dam, the hydraulic structure representation approach using a pier-loss bridge unit was chosen (Figure 3). This unit was geo-positioned on the DTM in conjunction with a spill unit to simulate structural overtopping (Figure 4). Cross sections representing bed morphology were extracted

Figure 2. Photograph documenting mid reach woody debris dam used for model calibration with adjacent floodplain storage. Adapted from Furnues (2023).

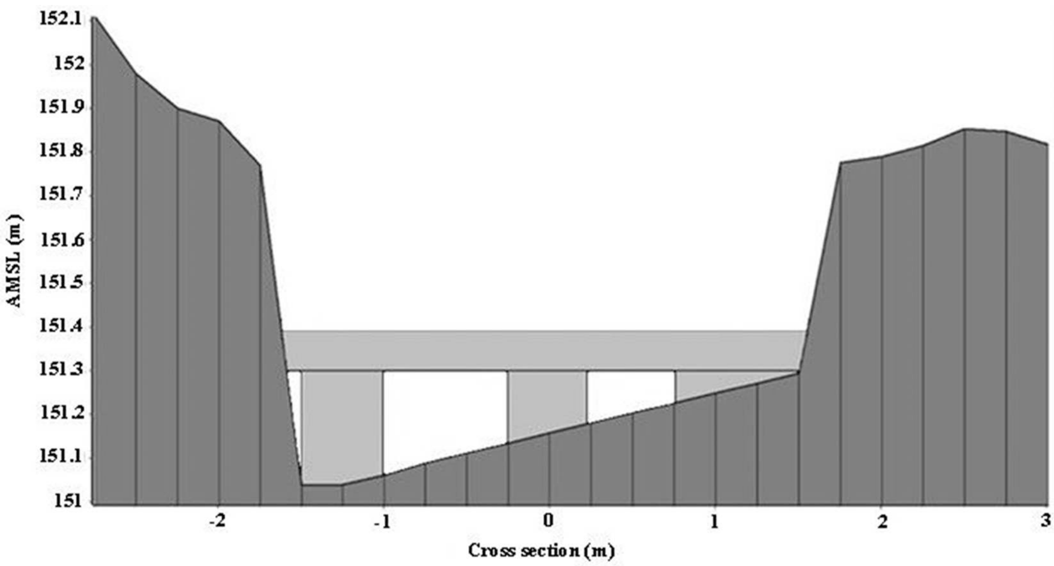

Figure 3. Diagram displaying pier-loss bridge unit representation of the mid reach woody debris dam (Figure 2). Adapted from Furnues (2023).

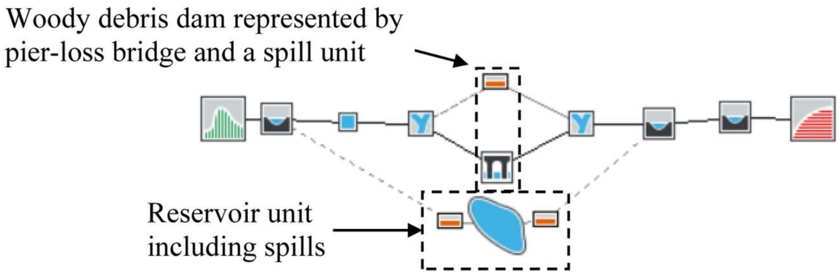

Figure 4. Schematic displaying woody debris dam model units. Pier-loss bridge is set in parallel to the spill unit. Adapted from Furnues (2023).

from the DTM and positioned at fixed intervals of 12.5 m along the centreline longitudinal profile. A Manning's n roughness coefficient of 0.022 s/m$^{\frac{1}{3}}$, classified as 'Earth channel – clean', was applied based on the coarse silty loamy bed composition, while a value of 0.03 s/m$^{\frac{1}{3}}$ was assigned to the floodplain, typical of grassy conditions (Chow 1959). Field photography was used to determine the blockage area of the woody debris dams, to replicate this in the pier-loss bridge units by altering diameters and soffit sizes. Blockage area of woody debris dams changed in respect to their unique designs and seasonal changes, with less blockage during the summer compared to the winter, due to loss of detritus which builds-up in the autumn. Comparison between storm events allowed analysis of seasonal change in the effectiveness of woody debris dams in attenuating peak discharge. At the upper end of the network, to simulate the chosen storm event, discharges were imported into the flow-time boundary (QTBDY) unit at hourly intervals for 24 h.

To account for bank overflow a reservoir unit, supported by spill units connected to cross sections, was inserted on the floodplain south of the network. The model reflects the catchment's characteristics using pre-defined reservoir geometry z-values from the DTM. While expanded floodplain storage could offer additional insights, this study focuses on the realistic conditions of the site.

Structural attenuation was quantified and compared to the pressure levels by measuring the afflux. Afflux is defined as the increased upstream flow depth from a perturbation that creates a step in the flow regime (Lamb *et al.* 2006). Afflux is calculated by subtracting downstream flow depth from upstream flow depth.

Modelling the network of woody debris dams

Using the same procedure as used to calibrate field data to FM, a network of 5 woody debris dams were modelled located downstream of the B4368 bridge in the lower reach. However, for this model Revitalised Flood Hydrograph (ReFH) conditions were installed to the north of the network to emulate surface-runoff. To achieve this, localised catchment descriptors and rainfall Depth-Duration-Frequency supporting derivation of runoff rates and quantity was obtained from the UK Centre of Ecology and Hydrology (2022), Flood Estimation Handbook (FEH) Web Service. Upon acquisition of the FEH, this was imported into FM as a ReFH.

Results

Model validation

Results display a very strong statistical significance between the pressure level and the woody debris dam representation within FM. During the summer storm event, a Pearson's correlation coefficient (P_c) of 0.977 was calculated upstream and 0.972 downstream of the woody debris dam (Equation (1)). During the winter storm event the statistical significance decreased to 0.88 upstream and 0.937 downstream. A chi-squared (C_s) statistical assessment (Equation (2)) also supports that the structural representation produced in FM significantly represented the woody debris dam located at Wilderhope Brook. However, though there was a statistical significance, the modelled woody debris dam displayed less attenuation compared to pressure levels. This finding supports the work by Pinto *et al.* (2019) in that 1D simulations tend to underpredict upstream stage and overpredict downstream stage which can be most noted at the 12 h. mark for both summer and winter storm events (Figure 5).

$$P_c = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_2 - \bar{y})^2}} \quad (1)$$

Equation (1) calculated the Pearson correlation coefficient (P_c), values of the x-variable in a sample (x_i), mean of the values of the x-variable ($\bar{x}$), values of the y-variable in a sample (y_i) and mean of the values of the y-variable ($\bar{y}$) are required.

$$C_s = \sum \frac{(z_i - \hat{z}_i)^2}{\hat{z}_i} \quad (2)$$

Equation (2) determines the Chi-squared (C_s), expected vertical values ($\hat{z}_i$) and observed vertical values (Z_i) are required.

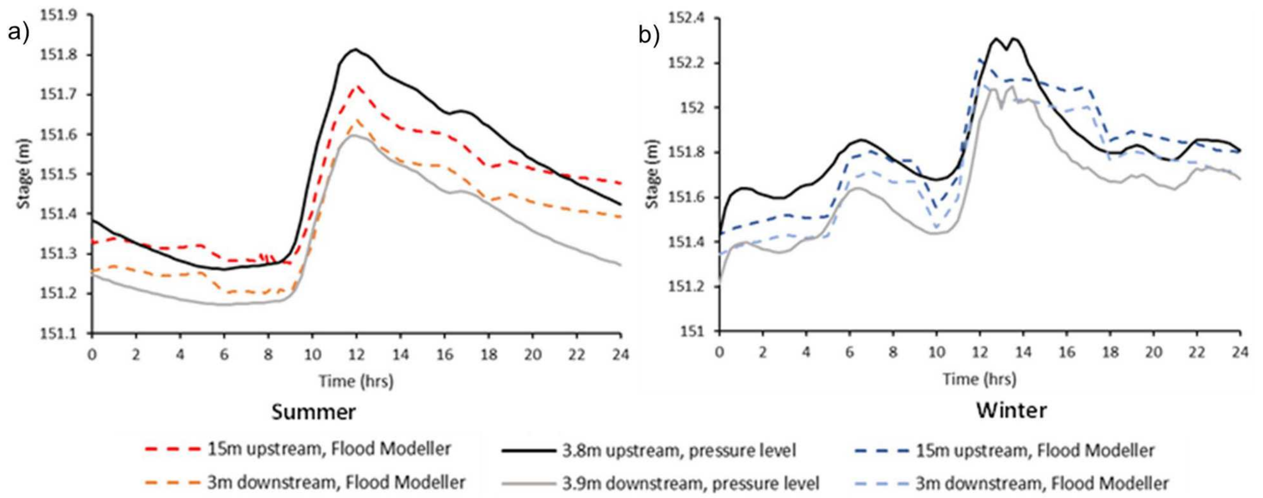

Figure 5. Two time-series graphs making comparison between (a) summer storm event: FM results vs pressure level field readings and (b) winter storm event: FM results vs pressure level field readings. Adapted from Furnues (2023).

Networks of woody debris dams

During the summer storm event, a 5-minute travel time was recorded across the 0.2 km section. The presence of woody debris dams did not change the lag time. In the obstructed channel, peak discharge reduced from 1.292 to 1.291 m^3/s, a reduction of 0.001 m^3/s. During the winter storm event with a larger discharge, travel time over the 0.2 km section increased from 5 to 10 min. creating a 5 min. lag time in the obstructed channel compared to unobstructed channel. Peak discharge decreased from 3.532 to 3.515 m^3/s a reduction of 0.017 m^3/s from the unobstructed to the obstructed channels. The larger the discharge, the larger the amount attenuated by the woody debris dams though within this simulation this was predominantly caused by the woody debris dams increasing bank overtopping onto the adjacent floodplain.

During the summer storm event, 11.86% of total discharge overtopped onto the floodplain in the obstructed channel, while in the unobstructed channel this decreased to 6.74%. This indicates that the obstructed channel created ≈ 1.75x more bank overtopping. During the winter storm event, the obstructed channel created bank overtopping of 58.06% compared to the unobstructed channel at 50.89%.

Discussion

The findings of this study emphasise the innovative role of the pier-loss bridge unit in modelling woody debris dams, directly addressing gaps identified in previous research. For example, Pinto *et al.* (2019) and Leakey *et al.* (2020) examined the effects of woody debris dams, using different modelling approaches due to the lack of a standardised method for representing these structures. Pinto *et al.* (2019) simulated woody debris dams in a 1D hydraulic model constructed in Flood Modeller by introducing blockages at cross sections and adjusting Manning's n values to account for hydraulic roughness, combining field observations with hydrodynamic modelling. Leakey *et al.* (2020) employed a 1D Godunov-Type Scheme to model flow behaviour influenced by woody debris dams, focusing on their hydraulic impacts and flow patterns. Both studies highlight the need for a bespoke tool to improve the simulation of woody debris dams.

In contrast to prior studies, the pier-loss bridge unit provides a novel and adaptable tool by incorporating adjustable leg and soffit sizes to modify the orifice coefficient. This advancement enables the realistic representation of dam blockage behaviour under varying conditions, such as pre-surcharging states and seasonal detritus changes. By addressing the need for more detailed and empirically validated hydraulic modelling methods, as emphasised by Addy and Wilkinson (2019), its potential impact lies in reducing inconsistencies between studies and improving predictive accuracy.

During high discharge, woody debris dams effectively attenuated flow. In modelling, their performance depended on factors such as catchment storage capacity, drainage characteristics and the ability to recover between high discharge events through infiltration and residence time. Metcalfe *et al.* (2018) note that flood modellers inevitably make assumptions regarding storage capacity and surface run-off. Woody debris dams are unlikely to attenuate peak flow in catchments with limited storage.

Results indicate attenuation significantly increases when floodplain attenuation is accounted for, as a small percentage increase is attenuated in-channel compared to on the floodplain. The floodplain acted as a flood storage area where water, could be removed from the flow regime and over time could infiltrate and evaporate. Simulations showed that in unconfined channels, woody debris dams enhanced lateral flow onto the floodplain, supporting the premise that they increase channel-floodplain connectivity which corroborates previous literature (Thomas and Nisbet 2012, Keys *et al.* 2018).

In the unconfined channel, woody debris dams effectively raise flow depth to enable temporary floodplain storage. Once flow reaches the bankfull stage, water overtops the banks and re-enters the channel downstream. Riparian buffer zones can increase lag time by promoting sinuous over-land flow, enhancing infiltration and evaporation. To optimise attenuation, woody debris dam design and placement should consider flow pathways. These structures can intercept surface flow and regulate water movement, as demonstrated at the Pickering field site (Peak Chief Executive 2016).

Down the longitudinal profile, woody debris dams were found to change their functionality. In the upper reach, where the channel is confined by steep valley slopes and a deep channel, they should be tall for maximum in-channel attenuation. In the lower reach, woody debris dams should be built to the bankfull stage as once bank overtopping occurs, in-channel attenuation decreases while floodplain connectivity increases. Although woody debris dams spanning the floodplain, such as at the Pickering field site, would enhance out-of-channel storage (Peak Chief Executive 2016), this was not feasible at Wilderhope due to farm access routes and agricultural land, where such structures could obstruct farming activities.

Conclusion

This study uses field data imported into FM to analyse the efficacy of woody debris dams in slowing and reducing peak discharge. Unlike research reliant on manual collection of datasets or ReFH acquired datasets, these results have the advantage of being collected continuously over two years by automated equipment in the field. Results show that the tested pier-loss bridge unit was successful in replicating woody debris dams in the field, displaying a very strong statistical significance particularly during the summer storm event. Pier-loss bridge unit design can replicate blockage area by altering leg width and soffit size, changing the orifice coefficient to provide greater resemblance to the woody debris dam design, which makes the unit more realistic.

As this study site, with a catchment size of ≈5.6 km^2 is relatively small, the impact of the woody debris dams is correspondently small. Further research would be to undertake similar measuring and modelling for a larger site, where the effects would have greater impact.

Acknowledgements

Thanks go to Dr Richard Crowder of Jacobs, for his support. My especial thanks to Dr Andrew Crayford, Cardiff University and Professor Roger Falconer for their help and guidance. Thank you to the reviewers for their feedback.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This paper was conducted as part of The Department for Environment, Food and Rural Affairs (DEFRA) and The Engineering and Physical Sciences Research Council (EPSRC) funded PhD.

Notes on contributors

Dr David Furnues was awarded his PhD in 2024 at Cardiff University, UK, specialising in modelling woody debris dam form to function to location for Natural Flood Management purposes.

Dr Judith R. Cudden, Associate Director at Jacobs, completed her PhD in 2002, at the University of Glasgow, researching braided river dynamics using a new numerical modelling approach.

Dr Matthew McParland also works at Jacobs, having gained his PhD at the University of Liverpool (2020), where he specialised in modelling the hydraulic and sediment dynamics of leaky barriers in relation to NFM.

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