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Modelling Spatial and Temporal Controls on Leaky Wooden Dam Effectiveness for Catchment-Scale Flood Mitigation in an Upland Catchment

J. M. Wolstenholme^{1,2}  | C. J. Skinner^{2,3}  | D. J. Milan⁴  | R. E. Thomas²  | D. R. Parsons¹ ¹Loughborough University, Loughborough, UK | ²Energy and Environment Institute, University of Hull, Hull, UK | ³Department of Geography, York St John University, York, UK | ⁴School of Environmental and Life Sciences, University of Hull, Hull, UK**Correspondence:** J. M. Wolstenholme (j.m.wolstenholme@lboro.ac.uk)**Received:** 21 October 2025 | **Revised:** 20 May 2026 | **Accepted:** 23 June 2026

ABSTRACT

Natural Flood Management (NFM) is increasingly adopted as a sustainable strategy for mitigating flood risk. Among these measures, the installation of leaky wooden dams (LWDs) at catchment scale is a widely used intervention aimed at slowing flow and desynchronising runoff peaks between sub-catchments, thereby reducing flood magnitude. Despite their popularity, the long-term effectiveness of LWDs and particularly their influence on sediment transport and catchment-scale hydro-geomorphic connectivity remains poorly understood. To address this knowledge gap, we used a modified version of the CAESAR-Lisflood landscape evolution model to simulate the hydrological and geomorphic impacts of LWDs within a proxy of a catchment in North Yorkshire, UK. We ran a suite of 20-year numerical experiments driven by a spatially variable, convection-permitting rainfall timeseries to explore how the spatial configuration, stream order placement, and density of LWDs affect flood peak attenuation. All LWDs simulated were representative of channel-spanning structures within the catchment, with a uniform starting gap size of 0.2 m and height of 1 m. Results show that LWDs installed on first-order streams were most effective, reducing flood peaks by up to 44% and increasing both water and sediment retention. LWDs placed on higher-order streams had a limited overall impact, though they could reduce individual peaks by up to 35% in some instances, whilst in other cases, flood peaks were amplified by as much as 77%. Importantly, the introduction of LWDs increased geomorphic variability across the catchment. This included both enhanced erosion and deposition along channel segments, with first-order LWD placements generating the greatest geomorphic response. Furthermore, interactions between LWD in different stream orders and sub-catchments led to unexpected and non-linear effects, altering sediment transport regimes and morphodynamic feedbacks throughout the network and changing the efficacy of flood peak attenuation over time. These findings highlight the critical importance of spatial placement and stream network interactions in determining the long-term hydrological and geomorphic efficacy of LWDs, with notable implications for the design and installation of future catchment-scale natural flood management strategies.

1 | Introduction

Flood risk is increasingly being managed at the catchment-scale with the understanding that catchment function has been influenced by a range of anthropogenic interventions (Sayers et al. 2013; Hewett et al. 2020; Ely et al. 2025). Many of these catchment changes, along with climate change, have increased flood

risk (Stevens et al. 2016; Bates et al. 2023). However, there is growing recognition that the response to increased flood risk should not be to simply reverse individual aspects of catchment land use or management, but to holistically address the issue using a mosaic of approaches (Hewett et al. 2020). Indeed, approaches based on natural flood management (NFM) have gained significant traction as a flood mitigation strategy in preference to traditional

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hard engineering approaches. For example: upper catchment afforestation programmes and alterations to land management practices (Carrick et al. 2018; Bond et al. 2022; Monger et al. 2022); the installation of online and offline attenuation features (Nisbet et al. 2011; Lockwood et al. 2022; Roberts et al. 2023); and a combination of installations that build a cumulative effect (Dadson et al. 2017; Black et al. 2021).

A now common and widespread natural flood management intervention is leaky wooden dams (LWDs), which are segments of large wood installed within channels with the aim to decrease catchment longitudinal hydro-connectivity whilst increasing lateral hydro-connectivity, thus providing temporary flood storage areas in the upper catchment and “slowing the flow” (Burgess-Gamble et al. 2017; Wren et al. 2022; Roberts et al. 2023). However, how LWD features influence flood hazard over time and over varying space scales, particularly for flood events of varying magnitudes, is poorly understood. Such assessment of the influence of LWDs is critical because it is well known that natural wood in rivers and LWD installations can directly influence local channel morphology over time (Lo et al. 2022; Wolstenholme et al. 2025b) and thus have the propensity to alter the hydrological regime through temporally variable multiple feedback loops (Lo et al. 2021).

Catchment-scale numerical simulations provide a valuable means of investigating the complex interactions between hydrology, geomorphology, and NFM interventions. However, representing LWDs at this scale with a grid resolution fine enough to capture small, channel-spanning structures (≤ 10 m wide) is computationally demanding. As such, modelling NFM at catchment scale requires a compromise between temporal and spatial resolution while still accounting for sediment transport, which is an important driver of flood hazard that can outweigh hydrological effects alone (Dixon et al. 2016; Hankin et al. 2020; Slater et al. 2015). Previous studies have used a range of approaches to represent LWDs in catchments exceeding 10 km^2 , including network-based hydraulic models (Hankin et al. 2020), 2D hydrological models (Dixon et al. 2016; Ferguson and Fenner 2020; Pearson 2020), 2D hydrodynamic models (Pearson 2020; Hankin et al. 2021), and coupled modelling frameworks (Hankin et al. 2019; Barnsley 2022). These methods typically rely on assumptions about LWD function, often omitting long-term changes in efficacy and ignoring geomorphic adjustments driven by sediment transport. Indeed, there is currently no widely used 2D modelling approach that fully incorporates sediment transport for large numbers of LWDs across catchments greater than 10 km^2 . For example, Hankin et al. (2019) inferred geomorphic change indirectly by modelling hydraulic shear stress and applying estimated grain sizes and threshold Shields stresses (0.06 and 0.018) for erosion and deposition, without explicitly simulating sediment movement. This lack of process-based sediment modelling limits understanding of how sediment transport shapes LWD performance over large spatial extents and long timescales. More broadly, there remains a limited empirical and modelling evidence base for representing LWD behaviour, meaning that these uncertainties may exceed those related to rainfall variability or hydrological connectivity. The present study advances the work of Dixon et al. (2016) and Hankin et al. (2020) by: (1) explicitly incorporating sediment transport within a catchment-scale modelling framework; and (2) extending the analysis from event-scale to

a continuous 20-year period to capture the temporal evolution of LWD effectiveness in terms of peak discharge, sediment and water retention, and impact on LWD-localised roughness. Using a suite of simulations including an extreme endmember scenario representing the maximum feasible density of LWDs in each sub-catchment, we explore:

1. The influence of LWD numbers, densities and spatial distributions on peak discharges, sediment efflux and geomorphic change at nodal points in an experimental catchment; and
2. How LWDs alter the hydrological response of the broader catchment through time

These questions were addressed using the CAESAR-Lisflood (CL) landscape evolution model (LEM) and NFM toolbox introduced by Wolstenholme et al. (2025a). The simulations were driven by convective rainfall scenarios from the UKCP18 (UK climate projections 2018) suite (Lowe et al. 2019). The location of the LWDs was varied throughout a synthetic experimental catchment based on a prototype—Dalby Forest, North Yorkshire, UK—by systematically placing LWDs on six different stream order scenarios and combinations.

2 | Model Framework and Setup

In the absence of appropriate field-based validation and calibration data, an exploratory, heuristic approach was used to investigate catchment geomorphic response to systematically altering the locations and distributions of LWDs. This approach permits reliable results if the underlying assumptions regarding the model parameters are correct (Bankes 1993) and facilitates a consistent comparison between simulations when adjusting LWD and input rainfall variables. Exploratory modelling enables the overall catchment response to be compared between scenarios, focusing particularly on the order of magnitude and direction of the response, whether hydrological or sedimentological. A similar approach was adopted by Dixon et al. (2016) to discern the impact of different river restoration techniques on hydrology.

A 32.2 km^2 catchment based on the Thornton-le-Dale and Dalby Forest area (North Yorkshire, UK) was used as the prototype for the simulations. Owing to its high potential for “slowing the flow”, this catchment was identified by the Environment Agency as “...suitable for reducing flood risk using Natural Flood Management or land use management and land use change within the Environmental Land Management pilot schemes” (Environment Agency 2022). The study catchment has a maximum stream order (Strahler 1952) of three with 41.7 km (69%) of first order streams, 7.5 km (13%) of second order streams, and 11 km (18%) of third order streams, totalling 60.2 km . To reduce runtimes, the digital terrain model (DTM) from OS Terrain 5 data (Ordnance Survey 2020) was first resampled to a resolution of 10 m , resulting in over 250,000 cells, and then split into upstream and downstream sections, retaining catchment morphometry and producing two similarly sized, hydrologically correct areas (Figure 1). The output from the upstream section was

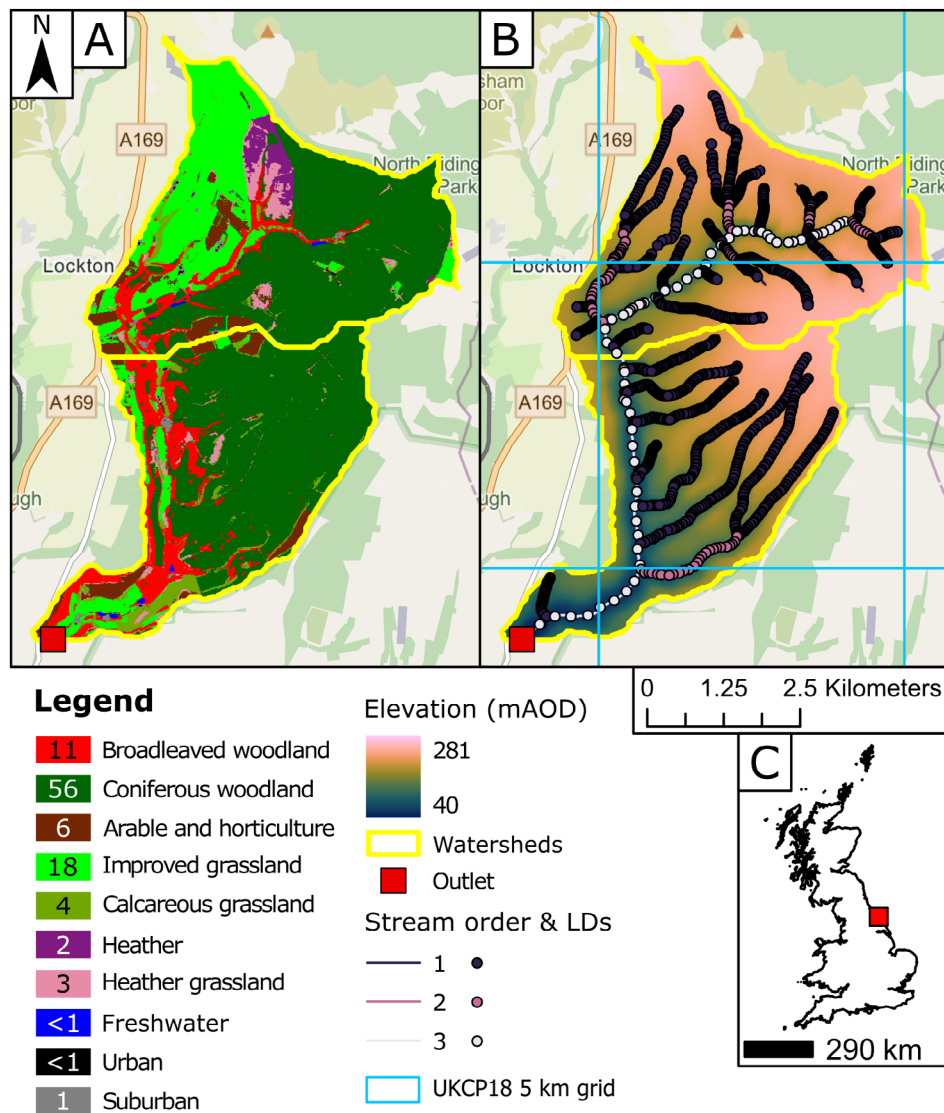


FIGURE 1 | Upper and lower catchments used for modelling with (A) Catchment land cover map. Percentages of each land use are shown over each legend key (Marston et al. 2022); (B) elevation from OS Terrain 5 resampled to 10m resolution with LWDs installed on first, second and third order streams (Ordnance Survey 2020), with the UKCP18 rainfall grid overlaid; (C) UK context. Base map is OpenStreetMap contributors, Microsoft, Facebook Inc. and its affiliates, Esri Community Maps contributors, Map layer by ESRI.

used as a direct input to the downstream, including any sediment transported alongside spatially-distributed rainfall. Any sinks were filled using the D4 depression-filling algorithm implemented in RichDEM before splitting the catchment (Barnes 2016). The grain size distribution (GSD) used by (Wolstenholme et al. 2025a) based on direct field observations (Wolstenholme et al. 2025b), was applied globally across the domain. To permit the initial distribution of sediment and generation of a channelised system, the catchment was “spun up” using rainfall from UKCP18 (1981–2000 epoch, described in Section 2.2). The period 1981–2000 was chosen to reduce the likelihood of model equifinality and was not used again after the spin-up period.

An evaporation rate of $0.0013 \text{ m day}^{-1}$ was used, determined by averaging spatially distributed daily potential evapotranspiration (2000–2017) for well-watered grass provided by Robinson et al. (2020). CL is highly sensitive to the evaporation rate, as

it removes a set volume of water from wet cells (Coulthard and Skinner 2016), therefore, this value was kept constant throughout all experiments. The chosen evaporation rate was of the same order of magnitude as previous uses of the model in similar climates (Skinner et al. 2018; Pearson 2020).

In CAESAR-Lisflood (CL), an unerodable bedrock layer is often specified to limit excessive scour, particularly in steep catchments (Hancock et al. 2011). This approach addresses a common issue in morphological models, where channel incision can be unrealistically high (Baar et al. 2019). In this study, the focus is on the behavioural influence of LWD placement rather than replicating the exact landscape, and soil thickness measurements were unavailable. Following Walsh et al. (2020), an unerodable bedrock surface was set to 1 m below the initial elevation of each cell to constrain unrealistic erosion. Aerial imagery inspection revealed no clear evidence of bedrock reaches and, given that the simulated catchment serves as a conceptual baseline for

exploring LWD effects, bedrock exposure was left to evolve naturally during the model spin-up period if shear stresses permitted. The capability of CL to simulate up to nine distinct grain sizes further reduces the risk of unrealistic scour and sediment export, while its lateral erosion function mitigates excessive channel incision by lowering adjacent bank cells (Coulthard et al. 2013). Finally, since this is an exploratory analysis, the emphasis is on relative differences between scenarios rather than absolute geomorphic values.

2.1 | Leaky Wooden Dam (LWD) Implementation

LWDs in CL are represented by a maximum localised roughness value, which was an approach first implemented as part of a novel NFM module developed by Wolstenholme et al. (2025a). The LWDs simulated in this study are representative of channel-spanning structures observed within the catchment (Wolstenholme et al. 2025b), typically consisting of large wood sections installed perpendicular to flow with a small gap beneath to maintain baseflow connectivity. Within this module, LWDs can be installed across the model domain by defining their location in a raster layer that has an identical resolution and extent as the DEM. Within the NFM module, there are three main user-defined LWD parameters:

1. LWD height, h_{top} , the distance from the initial surface of the DEM in a pixel containing an LWD to the top of the LWD. This defines a fixed elevation for the top of the dam.
2. Gap size, h_{gap} , the distance from the initial surface of the DEM in a pixel containing an LWD to the bottom of the LWD. This defines a fixed elevation for the bottom of the dam—if the current water level is below this value, the LWD is not active.
3. Roughness, n_{max} , the maximum roughness value for a pixel containing an LWD that is used to estimate the roughness within the flow equations, n_{local} , emulating the restriction to flow.

For each timestep n_{local} is calculated based on the current water level and its relationship to h_{top} and h_{gap} . If the water level is greater than h_{gap} , the proportion of the water column that is in contact with the LWD is calculated and this proportion is used to calculate n_{local} . This implementation allows for a dynamic LWD roughness that can be used to assess the efficacy of different LWD installations. Furthermore, all parameters can be applied using either a spatial method where each parameter is defined individually for each LWD, or using the global method, where up to five groups of LWDs are defined. Finally, the NFM module can install and remove LWDs at user-defined timesteps to not impede baseflow during the model spin-up period (see Wolstenholme et al. (2025a) for further details).

LWDs used herein were generated in a geographic information system (GIS). Contours were generated from the spun DEM at a defined interval (2m) which ultimately governed the vertical spacing of the LWDs, chosen to represent the likely highest density of LWDs possible in the system. The intersection between contours and the river network marked the location of the LWDs. To remove LWDs that were located near each other

at the same elevation (i.e., they occupied the same space on the DEM), a buffer was generated with a radius half the cell plan-form resolution of the DEM (5 m), and only one of the LWDs was retained. The LWD points were then converted to a raster layer with the same spatial reference and extent as the DEM before manual inspection to ensure correct LWD placement.

2.2 | Rainfall Representation

CL can natively use spatially variable rainfall by assigning discrete rainfall cells using a raster-based index, aligned to the DEM (Coulthard and Skinner 2016; Skinner et al. 2020). Spatial and temporal resolution of rainfall data is important for LEMs, especially when simulating sediment transport. Finer-resolution data (sub-daily timestep, 5 km²) increases localised rainfall intensity but causes only marginal increases to discharge while generating substantial increases to sediment efflux, with these changes becoming less significant when the timestep reduces to less than 1 h (Coulthard and Skinner 2016; Pidoto et al. 2022). The ability to consider rainfall spatial heterogeneity is also important as this can accelerate landscape evolution. When simulating spatially variable rainfall at high resolution, Peleg et al. (2021) observed a substantial (up to 50%) increase in erosion and deposition rates. Furthermore, the impact of different rainfall products (e.g., single gauge, gauge network and radar) transfers linearly to hydraulic processes, but non-linearly to sediment efflux (Skinner et al. 2020).

To reduce uncertainty caused by using different rainfall products outlined by Skinner et al. (2020), as well as to maximise rainfall spatial and temporal resolutions, herein the UKCP18 convection permitting model “Local” product was used to drive CL. This was chosen due to the fine spatiotemporal resolution (2.2 km², re-gridded herein to 5 km²) that is used operationally for short-term forecasts, and because it is better at simulating hourly rainfall than coarser products, particularly for rainfall extremes (Fosser et al. 2020; Chen et al. 2021). The ability to represent convective events provides increased accuracy for summertime rainfall intensity and duration, short duration rainfall extremes, and severe convective wind gusts (Met Office 2019). Using fine resolution, spatially variable rainfall is key to understanding whether and how LWD can mitigate against convective rainfall that can produce extreme floods (Smith et al. 2005). All UKCP18 datasets are provided as 360-day years across three successive time epochs (1981–2000, 2021–2040 and 2061–2080) for RCP8.5. The HadREM3-RA11M model generated 12 ensemble members for the UKCP18 local product which are derived from parameters from the 12 ensemble members of the RCM HadREM3-GA705 (Kendon et al. 2019). Since the aim of this study is to assess the efficacy of LWDs over a single epoch of time (2021–2040), only one ensemble member (01) was used.

2.3 | Experimental Design

A single simulation was performed without LWDs to establish a baseline scenario for comparison to LWD-present simulations. LWD spanned a single pixel (the channel) in the model while parameters were kept constant throughout all experiments where $h_{top} = 1 \text{ m}$, $h_{gap} = 0.2 \text{ m}$, and $n_{max} = 0.2$. These values are based

TABLE 1 | Total number of leaky wooden dams used in each experimental scenario.

Scenario	Stream order			Total number of LWDs	Maximum water storage capacity (m ³)	Median LWD capacity (m ³)
	1st	2nd	3rd			
S1	✓			1246	183,790	115
S2		✓		93	22,521	198
S3			✓	68	60,904	881
S12	✓	✓		1339	206,312	120
S23		✓	✓	161	83,426	284
S123	✓	✓	✓	1407	267,217	125

on field observations of structures in the Dalby Forest catchment where LWD are channel-spanning, up to 1 m in height above the riverbed and partially submerged with a gap size of <0.5 m. For further details the reader is directed to Wolstenholme et al. (2025b).

LWDs were placed either only on first, second, or third order streams, or a combination of these orders (see Table 1), resulting in S_o , where o represents the stream order(s) where LWDs were installed. The number of LWDs was not normalised across scenarios, but instead varied according to channel slope and stream length (Table 1), as determined by the criteria identified in Section 2.1, to represent the maximum feasible installation density. Consequently, LWD density and stream order were inherently coupled. Although substantially more LWD were installed on low order streams, the median of the LWD storage capacity (calculated as the maximum volume of water a 1 m high LWD could store based on the initial elevation model) is approximately seven times lower than higher order streams. This reflects the reduced storage potential in steeper headwater channels, and therefore results should be interpreted as reflecting combined effects of density and spatial configuration rather than fully independent controls.

Finally, to ensure that the catchment had opportunity to establish baseflow and to reduce the likelihood of the LWDs impeding initial hydrological connectivity (Wolstenholme et al. 2025a), LWDs were installed after 360 days (one model year).

3 | Results

3.1 | Catchment Sediment and Water Efflux

The presence of LWDs in the catchment system and their location drastically impacted cumulative water and sediment efflux compared to the baseline simulation with no LWD. Figure 2A,B show the difference in cumulative catchment efflux compared to this baseline scenario for discharge and sediment yield ($\Delta\Sigma Q$ and $\Delta\Sigma Q_s$ respectively), separated by stream order. Installing LWD impacted the proportion of water retained in the catchment, reducing outflow by up to −20% during the first 2 years of LWD installation as shown in Figure 2A. Installations of LWD in Stream Order 1 (S1) only, S12 and S123 resulted in a peak reduction of ΣQ of −4%, −7% and −16% respectively, and thus an increase in water storage (7500–15,000 m³) by the end of the simulation. The proportion stored varies throughout the simulation period with the majority of reduction occurring in years

1–2 for S123, years 3–4 for S12 and S123, as well as from year 10 onwards. The degree of retention and loss varies throughout the timeseries in response to individual storm events. In contrast, installation in S2, S3 and S23 all increased ΣQ and decreased water storage in the catchment by up to 10,000 m³ (S23), yet S23 and S3 had initial reductions within the first year of LWD installation of −20% and −16% respectively. All scenarios diverge in their water storage at around 10 years, following a series of flow peaks (see Figure 3) and maintain their trajectory away from the baseline scenario.

Sediment efflux (Q_s) was also highly variable between stream order combinations (Figure 2B). There was a substantive change in $\Delta\Sigma Q_s$ during year 3 for S23, with an increase of 230% (3500 m³) more sediment being removed from the catchment than the baseline scenario, a response disproportionate to the relatively modest change in water efflux at the same time. In contrast, S1 consistently reduced sediment efflux throughout the simulation period, remaining at or close to zero despite producing the greatest sustained reduction in water efflux of all single stream order scenarios, suggesting that first-order LWDs are trapping sediment within the catchment rather than simply routing it through. Nearly all other stream order combinations resulted in increased $\Delta\Sigma Q_s$ over the simulation period, though this recovered toward baseline rates by the end of the modelling period. Q_s as measured from the catchment outlet does not fully characterise internal sediment redistribution. The spatial patterns of localised erosion and deposition around individual LWD structures described in Section 3.4 provide a more direct indication of how LWD placement drives geomorphic change within the catchment.

3.2 | Suppression of Discharge Peaks

A total of 53 flood peaks were identified during the 20-year simulated timeseries (Figure 3). Herein, a peak is defined as a flow event greater than the 99th percentile (in this case 5 m³s^{−1}) that has an increased discharge of at least 4 m³s^{−1} compared to surrounding flow events within 24 h. The average discharge peak (Q_p) for the simulation was 15.15 m³s^{−1} with an average overall discharge of 1.18 m³s^{−1}. Each experiment underwent identical peak identification analysis, and peaks were matched to the no LWD scenario, allowing the change in peak discharge (ΔQ_p) to be quantified, as well as the number of peaks that were detected within a simulation. The installation of LWDs resulted

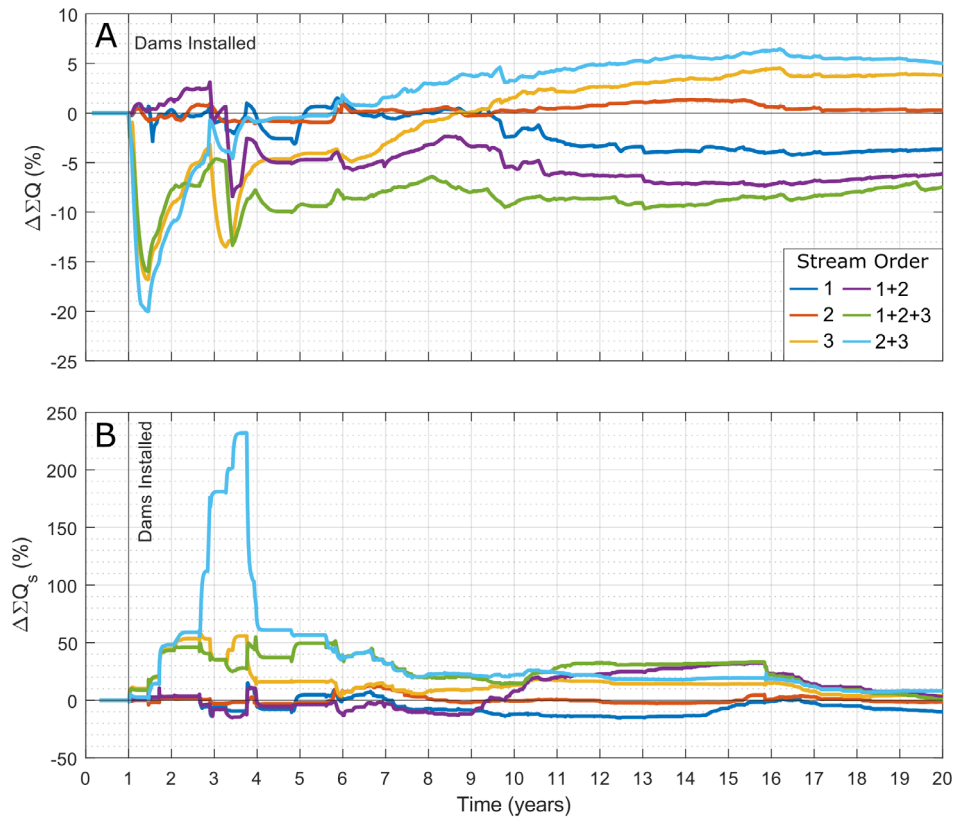


FIGURE 2 | (A) Normalised cumulative water discharge ($\Delta\Sigma Q$) compared to the no LWD scenario, and (B) normalised cumulative total sediment efflux ($\Delta\Sigma Q_s$) compared to the no LWD scenario.

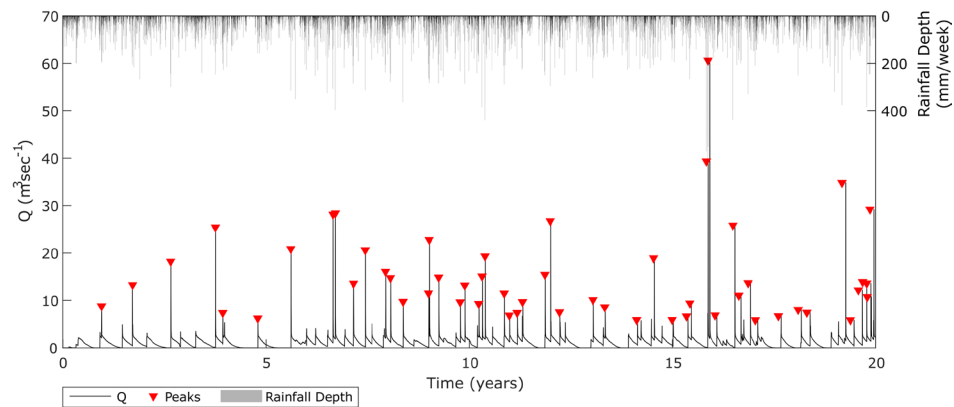


FIGURE 3 | Catchment discharge for the 2021–2040 no LWD scenario. Discharge peaks (Q_p) were automatically identified using the *findpeaks* function in MATLAB. The increase of the discharge (Q) signal was used to identify the peaks (i.e., the maximum of the peak compared to surrounding data). Automatically identified peaks are highlighted in red. Rainfall depth is aggregated to weekly total for visualisation.

in a reduction of the total number of identified Q_p . Simulations with LWD across S123, S1, S12, S2, S3 and S23 all reduced the number of Q_p by 11 (21%), 9 (17%), 8 (15%), 3 (6%), 3 (6%), and 2 (4%), respectively.

However, the suppression of identified peaks was found to vary throughout time, depending on the stream order scenario (Figure 4). All scenarios either had the same number of peaks or up to two more for the first 5 years of simulation time. S1 had fewer peaks following the five-year period and continued a reducing trajectory of Q_p for the remainder of the simulation. S12 and S123 both followed a similar pattern, but peaks were not

suppressed until approximately model year 10. In contrast, S2, S23 and S3 generally had more peaks during the first 17 years of the simulations, before a small reduction in peaks by the end of the simulation.

3.3 | Influence on Peak Discharge

Where flow peaks were not suppressed beyond automatic identification, most LWD stream order combinations reduced Q_p . Up to 37 peaks were reduced by up to 40% (S1 & S12; Figure 5). When LWDs were installed on first order streams (S1, S12 and

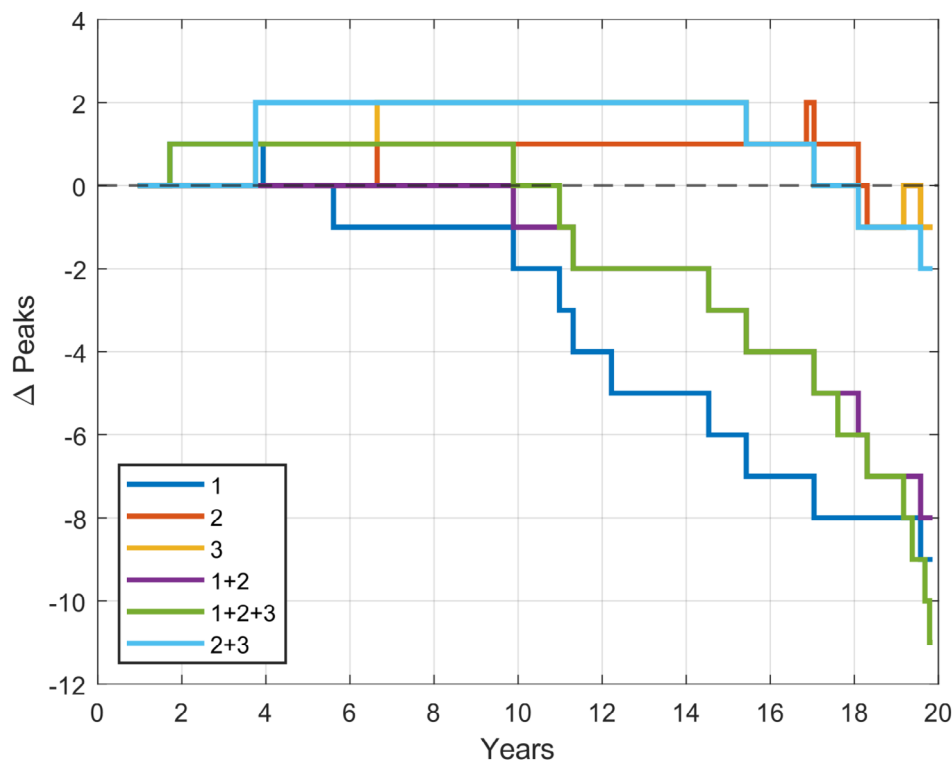


FIGURE 4 | Change (Δ) in the number of peaks identified throughout time compared to the baseline scenario with no LWD for LWDs installed on streams of order 1, 2, 3 or a combination of orders (1 + 2, 1 + 2 + 3 and 2 + 3).

S123), 32–37 peaks were reduced (60%–70%), with fewer than 15% exacerbated. Mean ($\bar{X}$) ΔQ_p for these stream orders was –10.6% to –8.5%. S2 reduced 60% of flood peaks, with a maximum Q_p reduction of up to 20%, however these LWDs also increased peak discharge by up to 60% for 16 storms (30%) resulting in $\bar{X} = -1.2\%$. S23 and S3 increased $\bar{X}$ by 3.2% and 2.1%, respectively, with the former increasing peak discharge for 24 storms.

To further assess the impact on peak discharge, individual peaks from experimental scenarios were directly compared to the baseline—Figure 6 grouped by stream order combination (Figure 6). Generally, S1, S12 and S123 were more effective at reducing Q_p (mean = –10%; Figure 6A). S1 and S12 had a similar effectiveness but S123 was less effective at reducing Q_p (maximum reduction 33% vs. 44%), yet more effective than S2, S3 and S23. Figure 6B shows that for smaller discharges ($Q_p < 20 \text{ m}^3\text{s}^{-1}$), the peak was more often reduced than increased but peak amplification of up to 77% was also observed, notably for S2 and S23. At larger discharges, the likelihood of flood peak exacerbation was much lower, with a maximum flow increase of 16%. There were few high magnitude flow events present in the simulation, with only three over $30 \text{ m}^3\text{s}^{-1}$. These events were all reduced by the presence of LWDs, most effectively by S12 and S123, resulting in ΔQ_p of up to –21%.

The effectiveness of peak reduction also varied throughout time. Figure 7 shows the change in peak discharge averaged over each model simulation year, separated by stream order scenario. S1, S12 and S123 reduced annual peaks by up to 29% on average, with only 2 years (different for each scenario) found to amplify average peak discharge by up to 17%. In contrast, S2, S3 and S23

fluctuate between a reduction (up to 20%) and an amplification (up to 30%) throughout time.

3.4 | Geomorphic Variability

To evaluate geomorphic variability localised to individual LWD structures, the location of each LWD was used to extract elevation change in the immediate vicinity of each structure. Using the LWD point locations, the catchment was separated into upstream and downstream components relative to each individual structure, and the median, minimum, and maximum elevation change was extracted for each. These values were then aggregated across all LWD locations, grouped by stream order, within each scenario to produce the cumulative density function (CDF) in Figure 8.

Localised elevation change ($\pm D_{50}$, 12.8 mm) varied depending on the location of LWD installation. When installed on first-order streams (S1, S12 and S123), LWDs increased downstream deposition by up to 20%, most notably when LWDs were restricted to first-order streams alone (S1). Localised erosion also decreased downstream for first-order installations by up to 10%. Installation on second-order streams alone (S2) generally increased downstream deposition (up to 7%) but also increased the proportion of erosion exceeding 0.6 m by up to 5%. For third-order installations alone (S3), differences between upstream and downstream were minimal, though erosion between 0.25 and 0.5 m was marginally greater downstream; the range of elevation change was notably wider for S3 than for other scenarios, reflected by the wider shaded region, indicating high sensitivity of geomorphic response to LWD placement location at third-order

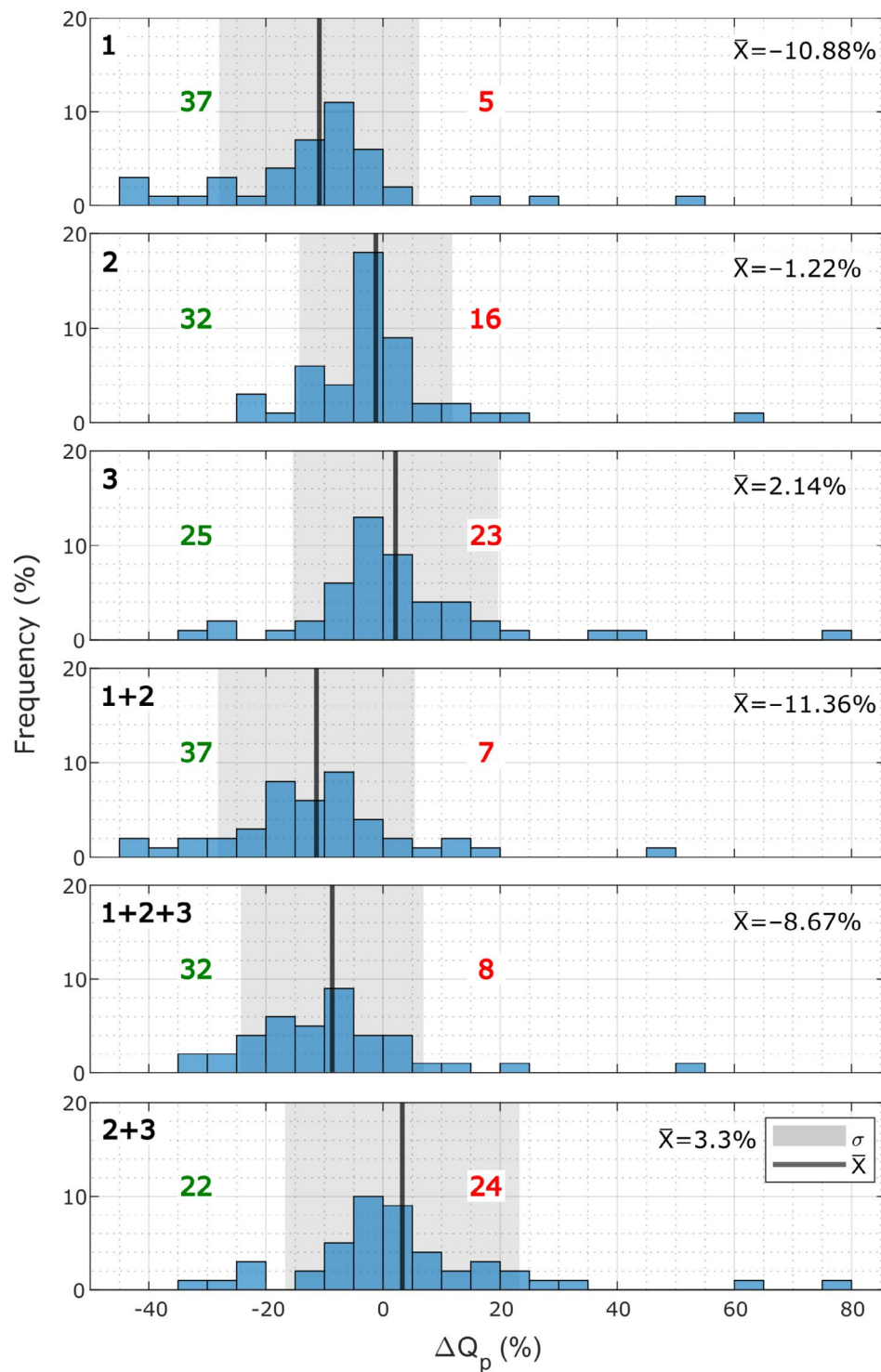


FIGURE 5 | Histograms of change to peak discharge (ΔQ_p) as a result of installing LWDs on different stream orders denoted in the top left of each plot. Mean ($\bar{X}$, bold black line), standard deviation (σ , grey shaded region), and the number of peaks reduced (green) and increased (red) are also shown.

streams. Combining first- and second-order installations (S12) increased downstream deposition relative to second-order installations alone (S2), suggesting an additive effect of LWD placement across stream orders; second-order installations were, however, associated with greater erosion than first-order installations. Where LWDs were installed on second- and third-order streams (S23), downstream erosion was greater than in S2 alone, and the range of elevation change across placements was

the widest of all scenarios, further indicating high sensitivity of geomorphic response to LWD location at higher stream orders. Overall, geomorphic response was greatest and most consistent for first-order installations, with both effectiveness and predictability decreasing at higher stream orders.

To contextualise the statistical patterns described above, Figure 9 shows representative examples of localised elevation

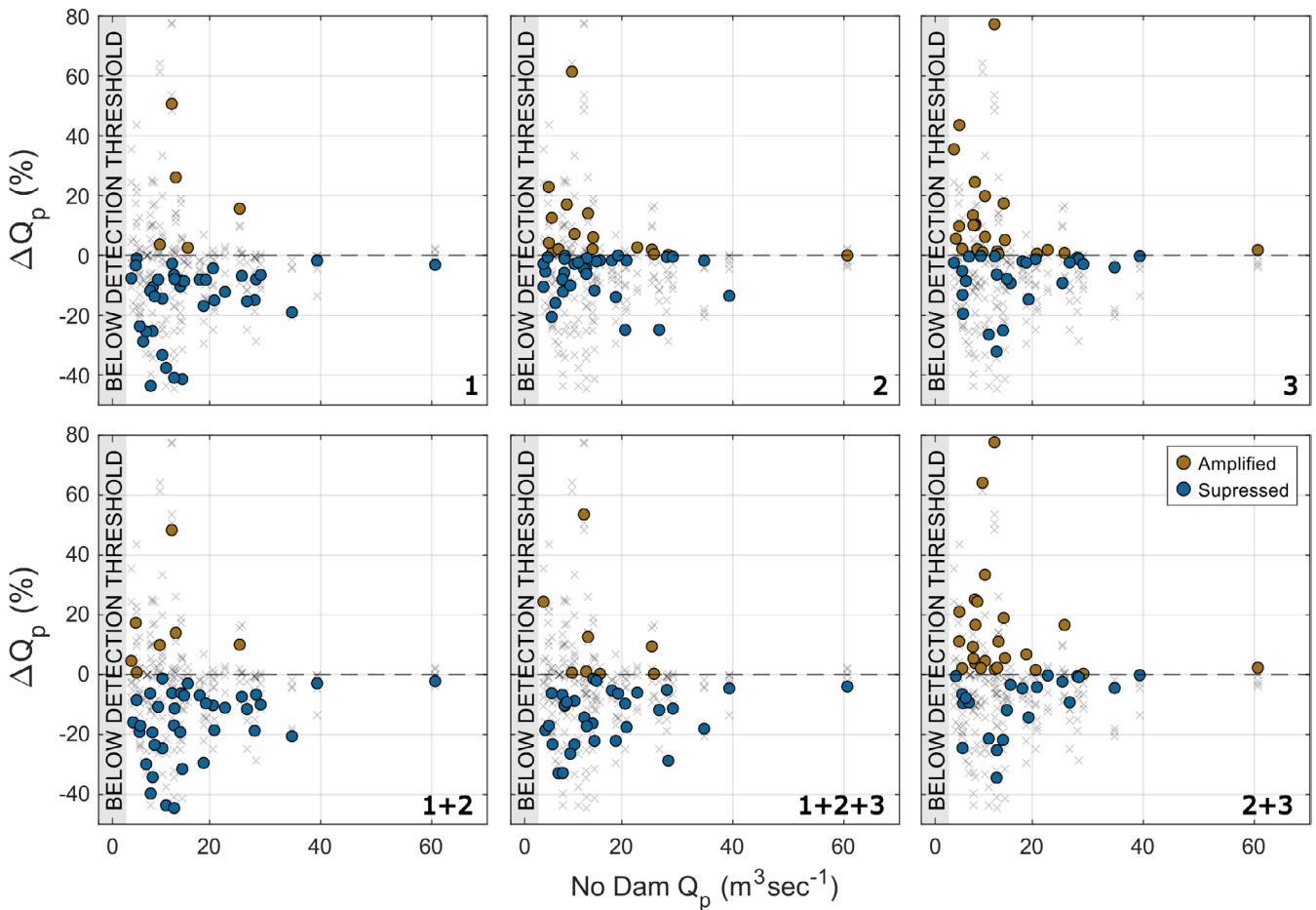


FIGURE 6 | ΔQ_p compared to the no dam peak. Stream order denoted by number in the bottom right of each plot. All simulations shown by grey 'x'.

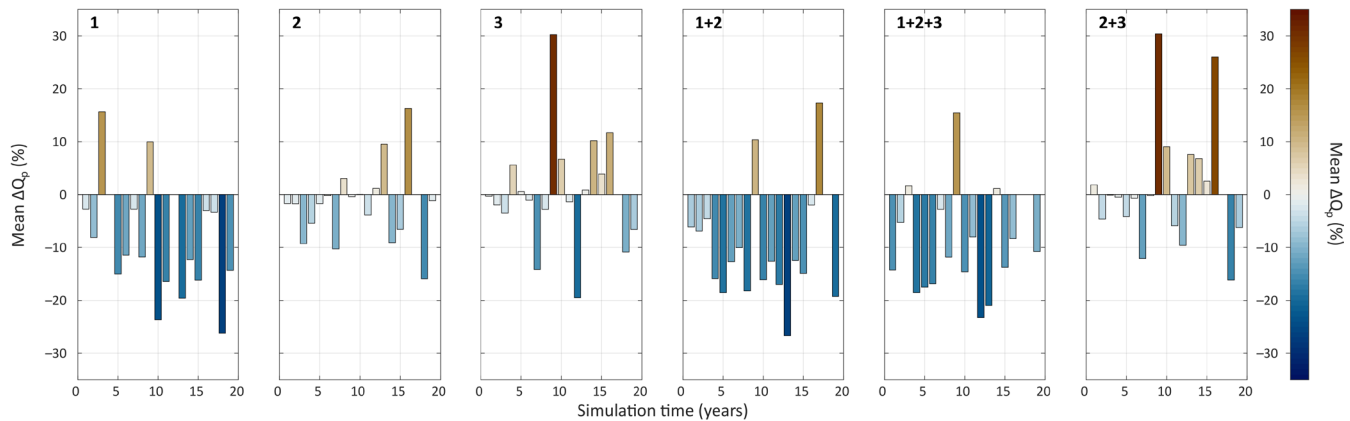


FIGURE 7 | Mean annual change in peak discharge (ΔQ_p) for each stream order combination throughout model simulation time. Mean annual ΔQ_p was calculated through averaging the normalised peak change presented in Figure 6 for each model year.

change surrounding individual LWD structures for experiments S1, S2 and S3, illustrating how the upstream/downstream asymmetry captured in the CDFs manifests spatially at the reach scale. For S1, scour up to the erosion limit (1 m) was reached immediately downstream of the LWD, with erosion either side of the structure suggesting localised bank erosion. Flow acceleration through the LWD gap increases local bed shear stress beyond the threshold for sediment entrainment, driving scour immediately

downstream, while flow deflection around the structure drives lateral bank erosion either side (Lo et al. 2022; Muhawenimana et al. 2023; Wolstenholme et al. 2025b). Deposition was evident in the second cell downstream, reaching up to 0.75 m in the example shown in Figure 9, consistent with flow deceleration and sediment settling as the energy from accelerated discharge under the LWD dissipates (Schalko et al. 2023; Wenzel et al. 2014). For S2, scour immediately downstream of the LWD

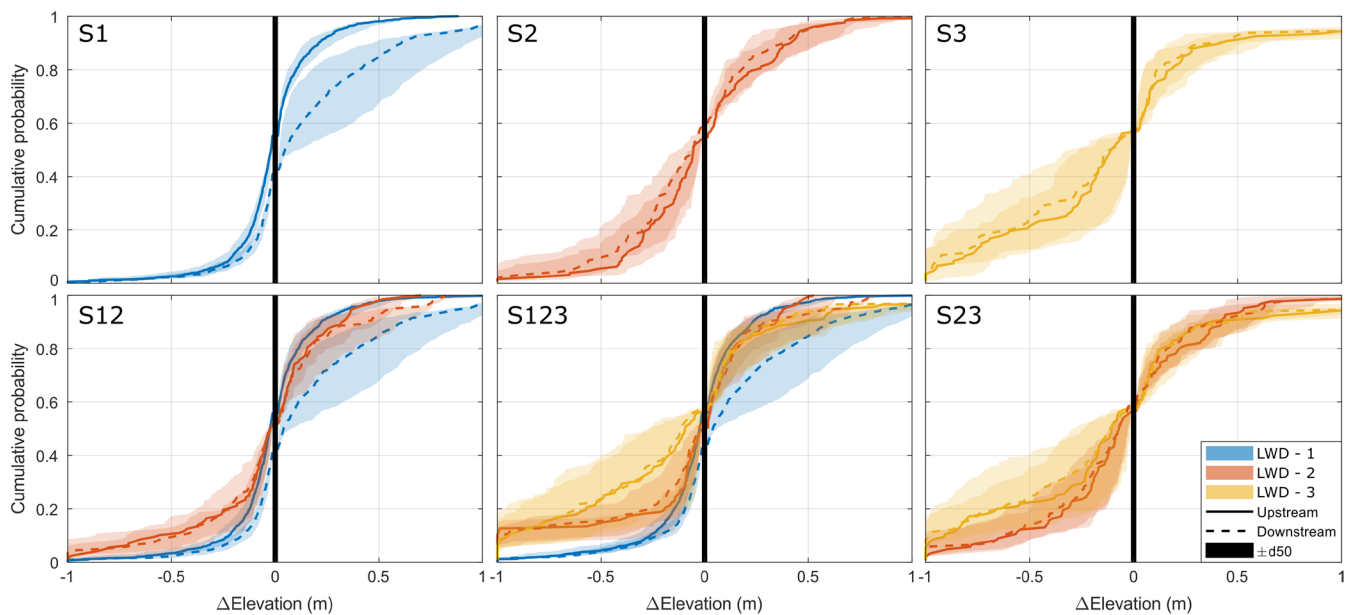


FIGURE 8 | Cumulative density function of median elevation change localised to LWD distributed throughout the catchment. Experimental setup denoted by Sn. Shaded area represents minimum and maximum values for each percentile. Elevation change $\pm d_{50}$ (12.8 mm; Wolstenholme et al. 2025b) and deposition > 1 m omitted to highlight substantial elevation change.

also reached the erosion limit, but was more spatially extensive than S1, extending across multiple downstream cells. Bank erosion was similarly more widespread, spanning up to six cells in the representative example. Downstream deposition was more diffuse, distributed across several cells rather than concentrated immediately below the structure. In contrast, the influence of S3 LWDs on localised elevation change was less distinct, reflecting the predominantly erosive character of the third-order channel. Scour remained below the erosion limit (up to 0.7 m) and deposition was more localised to cells immediately surrounding the structure, reaching up to 0.75 m. These mechanistic signatures are consistent across stream orders but diminish in clarity at higher orders where the background erosive regime increasingly dominates the localised LWD signal. It should be noted that at the 10 m grid resolution used herein, localised scour and deposition magnitudes are likely overestimated relative to finer-resolution simulations, as demonstrated by Wolstenholme et al. (2025a); however, the order of magnitude and directionality of elevation change are consistent across resolutions, and the spatial patterns described above should therefore be interpreted in a behavioural rather than absolute sense. These patterns are consistent with the upstream deposition and downstream scour observed in field measurements at equivalent structures in the same catchment (Wolstenholme et al. 2025b), providing confidence that the simulated geomorphic responses are physically plausible rather than artefacts of parameterisation.

4 | Discussion

This paper uses a heuristic approach to simulate the impact of sequences of leaky wooden dams (LWD) on the hydrologic and geomorphic response of a synthetic catchment based loosely on an upland catchment in Northern England. In this discussion, we focus on exploring how LWD placement, stream order configuration, and spatial interactions within the channel network

influence flood peak attenuation, sediment transport, and geomorphic variability over decadal timescales. To do this, we evaluate the results presented herein in terms of the relative effectiveness of different LWD arrangements, examine the trade-offs between hydrological benefits and potential flood peak amplification, and consider how evolving geomorphic feedbacks shape long-term performance. These insights are then framed in the context of natural flood management design and modelling assumptions, and implications for implementing LWDs as part of wider catchment-scale strategies are suggested.

4.1 | Hydrological Response to Leaky Dam Installation

All LWD placement scenarios reduced the total number of identified flood peaks. The greatest reduction occurred for LWD placed in all three stream orders in combination (scenario S123), where 11 fewer peaks were identified compared to the baseline, likely due to the LWDs working as designed in the headwaters and intercepting and desynchronising flood peaks (Pattison et al. 2014). The use of a long timeseries in this analysis additionally revealed that LWDs on first order streams can reduce flood peak Q_p of individual storms by up to 80%. Since most numerical studies only evaluate on a single event basis (potentially spread over multiple days; e.g., Addy and Wilkinson 2019; Hankin et al. 2019; Senior et al. 2022; Wenzel et al. 2014), this omits the potential for LWDs to reach capacity and become ineffective at reducing flood peaks, with the risk that they increase the flood hazard and not represent potential temporal changes nor the impact of storm sequencing. Indeed, year-on-year mean flow peaks were reduced by up to 49% when LWDs were installed on first order streams, while other stream orders were less effective at reducing peaks and there were more years where peaks were amplified compared to the baseline scenario. Conversely, 13%–57% of flow peaks $< 20 \text{ m}^3\text{s}^{-1}$ were exacerbated

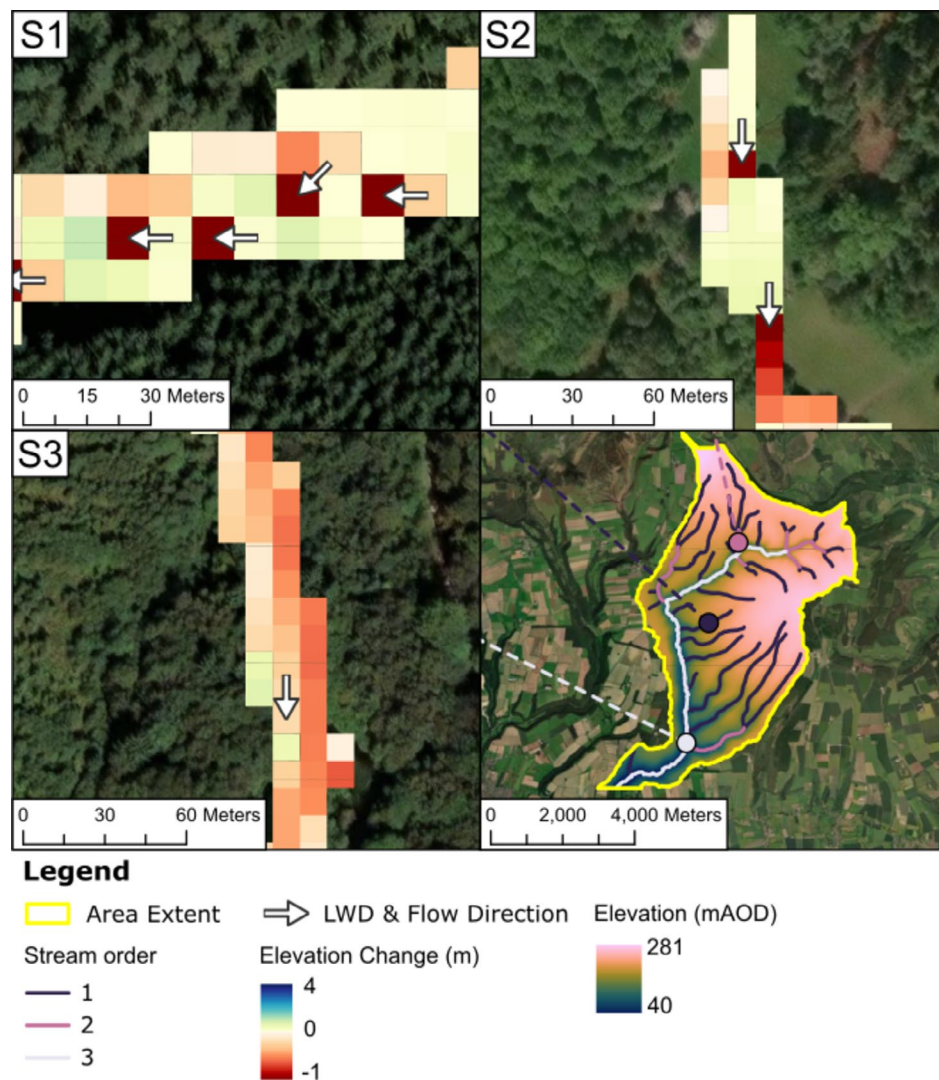


FIGURE 9 | Representative examples of localised elevation change surrounding LWDs through the catchment on first, second and third order streams. Imagery: Microsoft, Vantor and Earthstar Geographics.

by LWDs. However, it is important to note that the rainfall data used in this study may influence the simulated impact of LWDs. The first 10 years consist of 17 peak flow events which are relatively regularly distributed (approximately one peak per year exceeding the simulation mean of $15.15 \text{ m}^3 \text{ s}^{-1}$), whereas the second half of the sequence contains almost double the number of peaks (37), which are predominantly below the simulation mean despite no clear change in average rainfall. The majority of the drastic changes to sediment efflux occurred between 8 and 12.5 years, when there were 20 relatively low magnitude flood peaks with close temporal proximity to one another, resulting in significant erosion and channel expansion whilst exacerbating Q_p by up to 77% during this time. As such, LWDs amplified a greater proportion of the flow peaks in the first 10 years than the second half of the 20-year scenario, when they were generally more effective at reducing the number of peaks, and peak discharge, of larger storms.

The results of this study therefore agree with the findings of Wenzel et al. (2014) and van Leeuwen et al. (2024), who showed that natural large wood can attenuate small flood peaks, but highlight how temporal variability and storm sequencing can

reduce or amplify LWD effectiveness at reducing flow peaks. They, alongside others (Thomas and Nisbet 2007; Barnes et al. 2023), recommended that LWDs form part of the catchment management approach alongside land use change and afforestation. Over much longer timeframes, this would also encourage wood to reach maturity and contribute to the natural wood cycle (Dixon et al. 2018; Lo et al. 2022; Muhawenimana et al. 2023; Wolstenholme et al. 2025b).

4.2 | Temporal Variability of Catchment Response

The initial discharge reductions for scenarios including higher-order installations (S123, S3 and S23) reflect the greater median storage capacity per structure in higher-order channels (S3: 881 m^3 ; S2: 198 m^3 ; Table 1), which provide substantial but short-lived storage that was rapidly filled or bypassed during the simulation due to the greater discharges conveyed by these channels. Over the full simulation period, the presence of first-order LWDs emerges as the critical control on sustained water retention, with scenarios lacking first-order installations all converging toward positive $\Delta \Sigma Q$. This reflects the cumulative effect of distributed

headwater structures gradually modifying catchment-scale hydrological connectivity, rather than the immediate hydraulic effect of individual high-capacity structures. S123 produced the most sustained reduction despite increased network complexity suggesting that distributed installation across all stream orders outweighs tributary connections over longer timescales, consistent with spatially distributed interventions being more effective at desynchronising flood peaks and water storage than concentrated interventions (Dadson et al. 2017).

The divergence of all scenarios from the baseline at approximately year 10 coincides with a cluster of closely spaced flow peaks (Figure 3) suggests that storm sequencing exerts an important control on long-term LWD effectiveness. Closely spaced events likely prevent storage recovery between storms whilst simultaneously driving progressive geomorphic adjustment throughout the network. Tributary junctions act as pre-existing sediment and hydraulic discontinuities (Rice 1998), and LWD installations alter the longitudinal connectivity of the sediment cascade at these junctions in ways that are sensitive to successive event frequency and magnitude (Fryirs 2013; Pattison et al. 2014). The interaction between these discontinuities and LWD-induced connectivity changes may therefore amplify system sensitivity to storm sequencing, particularly where LWDs span multiple stream orders simultaneously (van Leeuwen et al. 2024; Wenzel et al. 2014).

The disproportionate increase in $\Delta\Sigma Q_s$ for S23 at simulation year 3 relative to any concurrent change in water efflux indicates that a geomorphic threshold was crossed rather than a purely hydraulic response. As higher-order LWD storage becomes saturated and flow overtops or bypasses structures, the transition from net deposition to net erosion drives rapid sediment remobilisation that is decoupled from the discharge signal. This threshold behaviour reflects the non-linear nature of sediment (dis)connectivity, where progressive changes to connections between channel stream orders can produce sudden disproportionate responses in sediment flux (Dixon et al. 2016; Fryirs 2013). Localised scour and deposition patterns in Figure 9 provide direct evidence of how LWD placement modifies connectivity and geomorphic roughness, and critically demonstrate that outlet sediment efflux alone is insufficient to characterise internal geomorphic evolution.

4.3 | Interconnectivity of Sub-Catchments

The impact on both discharge and sediment efflux varied when LWD were placed on multiple stream orders simultaneously. LWDs placed on streams of orders 1 and 2 in combination (scenario S12), were less effective at reducing both the number of flood peaks and Q_p than when they were placed only on streams of order 1 (scenario S1). Placement of LWDs on streams of orders 1, 2, and 3 simultaneously (scenario S123) increased flood risk relative to both the scenario with LWDs only on order-1 streams (S1) and the scenario with LWDs on order-1 and order-2 streams combined (S12). In scenario S123, fewer flood peaks were reduced and the magnitude of reduction was also lower (−35% vs. −44%) compared with the baseline scenario. We note that these differences reflect the combined influence of LWD number and spatial configuration which are inherently coupled in the

experimental design. This presents an interesting observation regarding how the connectivity of tributaries can increase flood risk and agrees with the findings of Pattison et al. (2014) and Dixon et al. (2016). Tributaries can have a substantial impact on both morphology and sediment transport (Consoli et al. 2022; Rice 1998) through forming environmental discontinuities (Rice et al. 2001). Therefore, the interaction between these discontinuities and the additional disconnectivity induced by LWDs may lead to more frequent deposition events and greater variability. Nevertheless, the contrasting behaviour between scenarios (e.g., S1, S12 and S123) indicates that spatial arrangement within the network exerts an important control beyond installation number alone. However, the backwater effect may be useful for water resource management, and LWDs could also be used to mitigate against the risk of low flows for local habitats. Additionally, new enhancements to CL such as sediment (Xie et al. 2022) or water tracing (Wilson and Coulthard 2023) would further this work by enabling the calculation of the residence time of sediment or water in a LWD sequence.

The results presented herein provide quantitative bounds on the hydrological and geomorphic response to LWD placement that can inform catchment-scale management decisions. First-order installations consistently reduced peak discharge by up to 44% and suppressed up to 21% of identified flood peaks over a 20-year period, whilst higher-order installations alone risk amplifying peaks by up to 77% under certain conditions. Water storage of 7500–15,000 m³ was achieved for first-order scenarios, whilst higher-order installations reduced net storage over the simulation period. These ranges provide order-of-magnitude expectations for LWD performance under varying placement strategies, whilst acknowledging that absolute values will vary with catchment characteristics. Caution should be exercised when interpreting these outputs in isolation from geomorphic context, as the temporal evolution of LWD effectiveness demonstrated herein highlights that single-event assessments may substantially over- or under-estimate long-term performance.

5 | Conclusions

This study demonstrates that the spatial placement of leaky wooden dams (LWDs), and the geomorphic changes they induce, are critical determinants of their long-term effectiveness. Continuous, multi-year simulations revealed patterns that would be overlooked by event-based analyses: LWDs placed on first-order streams consistently attenuated high flows, whereas installations on second- and third-order streams could amplify peaks, particularly in reaches regularly conveying high flows. Across most scenarios, sediment retention was lower than the no-LWD baseline simulation, indicating greater sediment mobilisation, while geomorphic variability increased throughout the network. In some cases, higher-order placements raised local base levels, reducing degradation and sediment export from tributaries, thus highlighting the complex, spatially dependent nature of hydro-geomorphic feedbacks.

Geomorphic change emerged as a major driver of LWD performance over time, underscoring the need for sediment transport to be explicitly incorporated into both modelling and appraisal of LWD. Crucially, the results show that the hydrological benefits

of LWDs cannot be fully understood without accounting for evolving topography, channel connectivity, and storm sequencing. Single-event assessments risk overlooking the potential for LWDs to reach a sediment storage capacity and become ineffective or counterproductive, particularly where higher-order installations are rapidly saturated by successive flood events, creating conditions under which further flood peaks may become amplified rather than attenuated. A continuous simulation approach is therefore essential to capture the cumulative, interacting effects of multiple events and landscape change, rather than relying solely on single-storm or shorter-term assessments of efficacy and longer-term performance.

From an operational perspective, these findings have direct implications for flood scheme appraisal. They suggest that current practice that is often focused on hydraulic metrics from isolated events risks over- or under-estimating the benefits of LWD schemes, especially when geomorphic adjustments over time are ignored. While the detailed, process-based modelling applied here may be considered disproportionate to the budgets of most NFM schemes, the insights provided point to simple but critical considerations for design: prioritising first-order stream placements, anticipating potential flood peak amplification on higher-order channels, and recognising that performance, and thus flood mitigation benefits, may shift over time.

Ultimately, robust appraisal of LWDs as part of integrated, catchment-scale flood risk management requires acknowledging their dynamic, interconnected behaviour. By embedding spatial configuration, temporal variability, and geomorphic feedbacks into scheme design, practitioners can better ensure that NFM interventions deliver sustained hydrological and sediment management benefits over the long term.

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Data Availability Statement

The current version of CAESAR-Lisflood is available from Coulthard et al. (2022; <https://sourceforge.net/projects/caesar-lisflood/>) under the GNU General Public Licence version 3.0 (GPLv3). The exact version of the model used to produce the results used in this paper is archived on Zenodo and available at <https://doi.org/10.5281/zenodo.12795495> (Wolstenholme et al. 2024), as are input data and scripts to run the model for simulations presented in this paper.

References

- Addy, S., and M. E. Wilkinson. 2019. "Representing Natural and Artificial In-Channel Large Wood in Numerical Hydraulic and Hydrological Models." *WIREs Water* 6: 1–20. <https://doi.org/10.1002/wat2.1389>.
- Baar, A. W., M. Boechat Albernaz, W. M. van Dijk, and M. G. Kleinans. 2019. "Critical Dependence of Morphodynamic Models of Fluvial and Tidal Systems on Empirical Downslope Sediment Transport." *Nature Communications* 10, no. 1: 4903. <https://doi.org/10.1038/s41467-019-12753-x>.
- Banks, S. 1993. "Exploratory Modeling for Policy Analysis." *Operations Research* 41, no. 3: 435–449. <https://doi.org/10.1287/opre.41.3.435>.
- Barnes, M. S., J. C. Bathurst, E. Lewis, and P. F. Quinn. 2023. "Leaky Dams Augment Afforestation to Mitigate Catchment Scale Flooding." *Hydrological Processes* 37, no. 6: 1–19. <https://doi.org/10.1002/hyp.14920>.
- Barnes, R. 2016. "RichDEM: Terrain Analysis Software." <http://github.com/r-barnes/richdem>.
- Barnsley, I. 2022. *Quantifying the Benefits of Natural Flood Management Methods in Groundwater-Dominated River Systems*. University of Southampton.
- Bates, P. D., J. Savage, O. Wing, et al. 2023. "A Climate-Conditioned Catastrophe Risk Model for UK Flooding." *Natural Hazards and Earth System Sciences* 23, no. 2: 891–908. <https://doi.org/10.5194/nhess-23-891-2023>.
- Black, A., L. Peskett, A. MacDonald, et al. 2021. "Natural Flood Management, Lag Time and Catchment Scale: Results From an Empirical Nested Catchment Study." *Journal of Flood Risk Management* 14, no. 3: 1–16. <https://doi.org/10.1111/jfr3.12717>.
- Bond, S., T. Willis, J. Johnston, et al. 2022. "The Influence of Land Management and Seasonal Changes in Surface Vegetation on Flood Mitigation in Two UK Upland Catchments." *Hydrological Processes* 36, no. 12: e14766. <https://doi.org/10.1002/hyp.14766>.
- Burgess-Gamble, L., R. Ngai, M. Wilkinson, et al. 2017. *Working With Natural Processes-Evidence Directory SC150005*, 294. Environment Agency. <https://www.gov.uk/government/organisations/environment-agency/about/research>.
- Carrick, J., M. S. A. B. Abdul Rahim, C. Adjei, et al. 2018. "Is Planting Trees the Solution to Reducing Flood Risks?" *Journal of Flood Risk Management* 12, no. S2: 1–10. <https://doi.org/10.1111/jfr3.12484>.
- Chen, Y., A. Paschalis, E. Kendon, D. Kim, and C. Onof. 2021. "Changing Spatial Structure of Summer Heavy Rainfall, Using Convection-Permitting Ensemble." *Geophysical Research Letters* 48, no. 3: e2020GL090903. <https://doi.org/10.1029/2020GL090903>.
- Consoli, G., R. M. Haller, M. Doering, S. Hashemi, and C. T. Robinson. 2022. "Tributary Effects on the Ecological Responses of a Regulated River to Experimental Floods." *Journal of Environmental Management* 303: 114122. <https://doi.org/10.1016/j.jenvman.2021.114122>.
- Coulthard, T. J., J. C. Neal, P. D. Bates, J. Ramirez, G. A. M. de Almeida, and G. R. Hancock. 2013. "Integrating the LISFLOOD-FP 2D Hydrodynamic Model With the CAESAR Model: Implications for Modelling Landscape Evolution." *Earth Surface Processes and Landforms* 38, no. 15: 1897–1906. <https://doi.org/10.1002/esp.3478>.
- Coulthard, T. J., J. C. Neal, P. D. Bates, J. Ramirez, G. A. de Almeida, and G. R. Hancock. 2022. "CAESAR Lisflood Download-1.9j, Sourceforge [code]." <https://sourceforge.net/projects/caesar-lisflood/>. (last access: 30 September 2022).
- Coulthard, T. J., and C. J. Skinner. 2016. "The Sensitivity of Landscape Evolution Models to Spatial and Temporal Rainfall Resolution." *Earth Surface Dynamics* 4, no. 3: 757–771. <https://doi.org/10.5194/esurf-4-757-2016>.
- Dadson, S. J., J. W. Hall, A. Murgatroyd, et al. 2017. "A Restatement of the Natural Science Evidence Concerning Catchment-Based 'Natural' Flood Management in the UK." *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* 473, no. 2199: 20160706. <https://doi.org/10.1098/rspa.2016.0706>.
- Dixon, S. J., D. A. Sear, and K. H. Nislow. 2018. "A Conceptual Model of Riparian Forest Restoration for Natural Flood Management." *Water and Environment Journal* 33: 329–341. <https://doi.org/10.1111/wej.12425>.
- Dixon, S. J., D. A. Sear, N. A. Odoni, T. Sykes, and S. N. Lane. 2016. "The Effects of River Restoration on Catchment Scale Flood Risk and Flood Hydrology." *Earth Surface Processes and Landforms* 41, no. 7: 997–1008. <https://doi.org/10.1002/esp.3919>.

- Ely, L. L., A. DeMott, B. J. Free, and A. C. Ritchie. 2025. "Decadal-Scale Effects of a Dam Removal on Channel Geomorphology, Sediment and Large Wood on the Elwha River, Washington, USA." *Geomorphology* 478: 109676. <https://doi.org/10.1016/j.geomorph.2025.109676>.
- Environment Agency. 2022. "Spatial Prioritisation of Catchments Suitable for Using Natural Flood Management." <https://www.data.gov.uk/dataset/2a4bcf6e-3880-4c0b-9986-6cafbec89faf/spatial-prioritisation-of-catchments-suitable-for-using-natural-flood-management>.
- Ferguson, C., and R. Fenner. 2020. "Evaluating the Effectiveness of Catchment-Scale Approaches in Mitigating Urban Surface Water Flooding." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 378, no. 2168: 20190203. <https://doi.org/10.1098/rsta.2019.0203>.
- Fosser, G., E. J. Kendon, D. Stephenson, and S. Tucker. 2020. "Convection-Permitting Models Offer Promise of More Certain Extreme Rainfall Projections." *Geophysical Research Letters* 47, no. 13: e2020GL088151. <https://doi.org/10.1029/2020GL088151>.
- Fryirs, K. 2013. "(Dis)connectivity in Catchment Sediment Cascades: A Fresh Look at the Sediment Delivery Problem." *Earth Surface Processes and Landforms* 38, no. 1: 30–46. <https://doi.org/10.1002/esp.3242>.
- Hancock, G. R., T. J. Coulthard, C. Martinez, and J. D. Kalma. 2011. "An Evaluation of Landscape Evolution Models to Simulate Decadal and Centennial Scale Soil Erosion in Grassland Catchments." *Journal of Hydrology* 398, no. 3–4: 171–183. <https://doi.org/10.1016/j.jhydrol.2010.12.002>.
- Hankin, B., I. Hewitt, G. Sander, et al. 2020. "A Risk-Based, Network Analysis of Distributed In-Stream Leaky Barriers for Flood Risk Management." *Natural Hazards and Earth System Sciences* 2, no. January: 1–22. <https://doi.org/10.5194/nhess-2019-394>.
- Hankin, B., P. Metcalfe, K. Beven, and N. A. Chappell. 2019. "Integration of Hillslope Hydrology and 2D Hydraulic Modelling for Natural Flood Management." *Hydrology Research* 50, no. 6: 1535–1548. <https://doi.org/10.2166/nh.2019.150>.
- Hankin, B., T. J. C. Page, N. A. Chappell, et al. 2021. "Using Micro-Catchment Experiments for Multi-Local Scale Modelling of Nature-Based Solutions." *Hydrological Processes* 35, no. 11: e14418. <https://doi.org/10.1002/hyp.14418>.
- Hewett, C. J. M., M. E. Wilkinson, J. Jonczyk, and P. F. Quinn. 2020. "Catchment Systems Engineering: An Holistic Approach to Catchment Management." *WIREs Water* 7, no. 3: e1417. <https://doi.org/10.1002/wat2.1417>.
- Kendon, E. J., G. Fosser, J. Murphy, et al. 2019. "UKCP Convection-Permitting Model Projections: Science Report."
- Lo, H. W., M. Smith, M. Klaar, and C. Woulds. 2021. "Potential Secondary Effects of In-Stream Wood Structures Installed for Natural Flood Management: A Conceptual Model." *WIREs Water* 8, no. 5: e1546. <https://doi.org/10.1002/wat2.1546>.
- Lo, H. W., Z. van Leeuwen, M. Klaar, C. Woulds, and M. Smith. 2022. "Geomorphic Effects of Natural Flood Management Woody Dams in Upland Streams." *River Research and Applications* 38, no. 10: 1787–1802. <https://doi.org/10.1002/rra.4045>.
- Lockwood, T., J. Freer, K. Michaelides, R. E. Brazier, and G. Coxon. 2022. "Assessing the Efficacy of Offline Water Storage Ponds for Natural Flood Management." *Hydrological Processes* 36: e14618. <https://doi.org/10.1002/hyp.14618>.
- Lowe, J. A., D. Bernie, P. Bett, et al. 2019. *UKCP18 Science Overview Report*, 1–73. Met Office.
- Marston, C., C. S. Rowland, A. W. O'Neil, and R. D. Morton. 2022. *Land Cover Map 2021 (10m Classified Pixels, GB)*. NERC EDS Environmental Information Data Centre. <https://doi.org/10.5285/a22baa7c-5809-4a02-87e0-3cf87d4e223a>.
- Met Office. 2019. "UKCP18 Factsheet: UKCP Local (2.2km) Projections." (Met Office, Ed.).
- Monger, F., S. Bond, D. V. Spracklen, and M. J. Kirkby. 2022. "Overland Flow Velocity and Soil Properties in Established Semi-Natural Woodland and Wood Pasture in an Upland Catchment." *Hydrological Processes* 36, no. 4: e14567. <https://doi.org/10.1002/hyp.14567>.
- Muhawenimana, V., E. Follett, I. Maddock, and C. A. M. E. Wilson. 2023. "Field-Based Monitoring of Instream Leaky Barrier Backwater and Storage During Storm Events." *Journal of Hydrology* 622: 129744. <https://doi.org/10.1016/j.jhydrol.2023.129744>.
- Nisbet, T., S. Marrington, H. Thomas, S. Broadmeadow, and G. Valantin. 2011. "Project RMP5455: Slowing the Flow at Pickering—Phase 1." In *Forestry Research*, 29. Forestry Research.
- Ordnance Survey. 2020. "OS Terrain 5 DTM [ASC Geospatial Data], Scale 1:20000, Tile(s): Dalby Forest, Updated: April 2020 (Vol. 2020, Number 07/2021)." <http://digimap.edina.ac.uk/>.
- Pattison, I., S. N. Lane, R. J. Hardy, and S. M. Reaney. 2014. "The Role of Tributary Relative Timing and Sequencing in Controlling Large Floods." *Water Resources Research* 50, no. 7: 5444–5458. <https://doi.org/10.1002/2013wr014067>.
- Pearson, E. G. 2020. *Modelling the Interactions Between Geomorphological Processes and Natural Flood Management*. University of Leeds.
- Peleg, N., C. Skinner, J. A. Ramirez, and P. Molnar. 2021. "Rainfall Spatial-Heterogeneity Accelerates Landscape Evolution Processes." *Geomorphology* 390: 107863. <https://doi.org/10.1016/j.geomorph.2021.107863>.
- Pidoto, R., N. Bezak, H. Müller-Thomy, et al. 2022. "Comparison of Rainfall Generators With Regionalisation for the Estimation of Rainfall Erosivity at Ungauged Sites." *Earth Surface Dynamics* 10, no. 4: 851–863. <https://doi.org/10.5194/esurf-10-851-2022>.
- Rice, S. 1998. "Which Tributaries Disrupt Downstream Fining Along Gravel-Bed Rivers?" *Geomorphology* 22, no. 1: 39–56. [https://doi.org/10.1016/S0169-555X\(97\)00052-4](https://doi.org/10.1016/S0169-555X(97)00052-4).
- Rice, S., M. T. Greenwood, and C. B. Joyce. 2001. "Tributaries, Sediment Sources, and the Longitudinal Organisation of Macroinvertebrate Fauna Along River Systems." *Canadian Journal of Fisheries and Aquatic Sciences* 58, no. 4: 824–840. <https://doi.org/10.1139/f01-022>.
- Roberts, M. T., J. Geris, P. D. Hallett, and M. E. Wilkinson. 2023. "Mitigating Floods and Attenuating Surface Runoff With Temporary Storage Areas in Headwaters." *WIREs Water* 10, no. 3: 1–18. <https://doi.org/10.1002/wat2.1634>.
- Robinson, E. L., E. M. Blyth, D. B. Clark, E. Comyn-Platt, and A. C. Rudd. 2020. *Climate Hydrology and Ecology Research Support System Potential Evapotranspiration Dataset for Great Britain (1961–2017) [CHESS-PE]*. NERC Environmental Information Data Centre. <https://doi.org/10.5285/9116e565-2c0a-455b-9c68-558fdd9179ad>.
- Sayers, P., L. Yuanyuan, G. Galloway, et al. 2013. *Flood Risk Management: A Strategic Approach*. Asian Development Bank, GIWP, UNESCO and WWF-UK.
- Schalko, I., E. Follett, and H. Nepf. 2023. "Impact of Lateral Gap on Flow Distribution, Backwater Rise, and Turbulence Generated by a Logjam." *Water Resources Research* 59, no. 10: e2023WR034689. <https://doi.org/10.1029/2023WR034689>.
- Senior, J. G., M. A. Trigg, and T. Willis. 2022. "Physical Representation of Hillslope Leaky Barriers in 2D Hydraulic Models: A Case Study From the Calder Valley." *Journal of Flood Risk Management* 15, no. 3: e12821. <https://doi.org/10.1111/jfr3.12821>.
- Skinner, C. J., T. J. Coulthard, W. Schwanghart, M. J. Van De Wiel, and G. Hancock. 2018. "Global Sensitivity Analysis of Parameter Uncertainty in Landscape Evolution Models." *Geoscientific Model Development* 11, no. 12: 4873–4888. <https://doi.org/10.5194/gmd-11-4873-2018>.

- Skinner, C. J., N. Peleg, N. Quinn, T. J. Coulthard, P. Molnar, and J. Freer. 2020. "The Impact of Different Rainfall Products on Landscape Modelling Simulations." *Earth Surface Processes and Landforms* 45, no. 11: 2512–2523. <https://doi.org/10.1002/esp.4894>.
- Slater, L. J., M. B. Singer, and J. W. Kirchner. 2015. "Hydrologic Versus Geomorphic Drivers of Trends in Flood Hazard." *Geophysical Research Letters* 42, no. 2: 370–376. <https://doi.org/10.1002/2014GL062482>.
- Smith, J. A., A. J. Miller, M. L. Baeck, P. A. Nelson, G. T. Fisher, and K. L. Meierdiercks. 2005. "Extraordinary Flood Response of a Small Urban Watershed to Short-Duration Convective Rainfall." *Journal of Hydrometeorology* 6, no. 5: 599–617. <https://doi.org/10.1175/JHM426.1>.
- Stevens, A. J., D. Clarke, and R. J. Nicholls. 2016. "Trends in Reported Flooding in the UK: 1884–2013." *Hydrological Sciences Journal* 61, no. 1: 50–63. <https://doi.org/10.1080/02626667.2014.950581>.
- Strahler, A. N. 1952. "Hypsometric (Area-Altitude) Analysis of Erosional Topography." *GSA Bulletin* 63, no. 11: 1117–1142. [https://doi.org/10.1130/0016-7606\(1952\)63\[1117:HAAOET\]2.0.CO;2](https://doi.org/10.1130/0016-7606(1952)63[1117:HAAOET]2.0.CO;2).
- Thomas, H., and T. R. Nisbet. 2007. "An Assessment of the Impact of Floodplain Woodland on Flood Flows." *Water and Environment Journal* 21, no. 2: 114–126. <https://doi.org/10.1111/j.1747-6593.2006.00056.x>.
- van Leeuwen, Z. R., M. J. Klaar, M. W. Smith, and L. E. Brown. 2024. "Quantifying the Natural Flood Management Potential of Leaky Dams in Upland Catchments, Part II: Leaky Dam Impacts on Flood Peak Magnitude." *Journal of Hydrology* 628: 130449. <https://doi.org/10.1016/j.jhydrol.2023.130449>.
- Walsh, P., A. Jakeman, and C. Thompson. 2020. "Modelling Headwater Channel Response and Suspended Sediment Yield to In-Channel Large Wood Using the Caesar-Lisflood Landscape Evolution Model." *Geomorphology* 363: 107209. <https://doi.org/10.1016/j.geomorph.2020.107209>.
- Wenzel, R., C. Reinhardt-Imjela, A. Schulte, and J. Bölscher. 2014. "The Potential of In-Channel Large Woody Debris in Transforming Discharge Hydrographs in Headwater Areas (Ore Mountains, Southeastern Germany)." *Ecological Engineering* 71: 1–9. <https://doi.org/10.1016/j.ecoleng.2014.07.004>.
- Wilson, M. D., and T. J. Coulthard. 2023. "Tracing and Visualisation of Contributing Water Sources in the LISFLOOD-FP Model of Flood Inundation (Within CAESAR-Lisflood Version 1.9j-WS)." *Geoscientific Model Development* 16, no. 9: 2415–2436. <https://doi.org/10.5194/GMD-16-2415-2023>.
- Wolstenholme, J. M., C. J. Skinner, D. Milan, R. E. Thomas, and D. R. Parsons. 2024. "CAESAR-Lisflood 1.9j LD, Zenodo [Code and Data Set]." <https://doi.org/10.5281/zenodo.12795495>.
- Wolstenholme, J. M., C. J. Skinner, D. Milan, R. E. Thomas, and D. R. Parsons. 2025a. "Hydro-Geomorphological Modelling of Leaky Wooden Dam Efficacy From Reach to Catchment Scale With CAESAR-Lisflood 1.9j." *Geoscientific Model Development* 18, no. 5: 1395–1411. <https://doi.org/10.5194/gmd-18-1395-2025>.
- Wolstenholme, J. M., C. J. Skinner, D. Milan, R. E. Thomas, and D. R. Parsons. 2025b. "Localised Geomorphic Response to Channel-Spanning Leaky Wooden Dams." *Earth Surface Dynamics* 13, no. 4: 647–663. <https://doi.org/10.5194/esurf-13-647-2025>.
- Wren, E., M. Barnes, A. Kitchen, et al. 2022. *The Natural Flood Management Manual*. Vol. C802. CIRIA.
- Xie, J., T. J. Coulthard, and S. J. McLelland. 2022. "Modelling the Impact of Seismic Triggered Landslide Location on Basin Sediment Yield, Dynamics and Connectivity." *Geomorphology* 398: 108029. <https://doi.org/10.1016/j.geomorph.2021.108029>.