# Quantifying the hydrological implications of pre- and post-installation willowed engineered log jams in the Pennine Uplands, NW England

Norbury, Michael; Phillips, Hazel; Macdonald, Neil; Brown, David; Boothroyd, Richard; Wilson, Catherine; Quinn, Paul; Shaw, David

*DOI:*
10.1016/j.jhydrol.2021.126855

*License:*
Creative Commons: Attribution-NonCommercial-NoDerivs (CC BY-NC-ND)

*Document Version*
Peer reviewed version

*Citation for published version (Harvard):*
Norbury, M, Phillips, H, Macdonald, N, Brown, D, Boothroyd, R, Wilson, C, Quinn, P & Shaw, D 2021, 'Quantifying the hydrological implications of pre- and post-installation willowed engineered log jams in the Pennine Uplands, NW England', *Journal of Hydrology*, vol. 603, 126855. https://doi.org/10.1016/j.jhydrol.2021.126855

Link to publication on Research at Birmingham portal

**General rights**
Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

- •Users may freely distribute the URL that is used to identify this publication.
- •Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
- •User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
- •Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

**Take down policy**
While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

Download date: 25. Apr. 2024

Click here to view linked References

# Quantifying the hydrological implications of pre- and post-installation willowed engineered log jams in the Pennine Uplands, NW England

## Authors and affiliations

Michael Norbury[1, 2], Hazel Phillips[1, 2], Neil Macdonald[1] David Brown[3], Richard Boothroyd[4], Catherine Wilson[5], Paul Quinn[6], David Shaw[1]

[1] Department of Geography and Planning, School of Environmental Science, University of Liverpool, Roxby Building, Liverpool, L69 7ZT, UK

[2] The Mersey Forest Offices, Risley Moss, Ordnance Avenue, Birchwood, Warrington, WA3 6QX, UK

[3] The Environment Agency, Richard Fairclough House, Knutsford Road, Latchford, Warrington WA4 1HT, UK

[4] School of Geographical and Earth Sciences, University of Glasgow, Glasgow, G12 8QQ, UK

[5] Cardiff School of Engineering, Cardiff University, Cardiff, CF24 3AA, UK

[6] School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK

Corresponding Author: E-mail: M.Norbury@liverpool.ac.uk; Telephone Number: +44 (0)151 794 2000

## Highlights

- Willowed log jams (~dams) have been installed frequently to reduce flood risk.
- Few studies have assessed pre- and post- installation changes to watercourse flows.
- Discharge data shows an average 27.3% reduction on peaks, following installation.
- River-reach (0-130m) wildlife camera photos and levels confirm attenuation.
- Willowed log jams re-naturalise flows, locally alleviating floods and droughts.

## - Abstract

Nature Based Solutions (NBS), including Natural Flood Management (NFM) schemes are becoming an important component of many governmental and organisation responses to increases in flood and aridity risk. NFM structures may take multiple forms to slow, store, disconnect and filter distributed overland flow pathways within a catchment that coalesce to generate a flood-wave downstream and runoff rather than infiltrate groundwaters. To date few studies have conducted observations pre- and post-installation monitoring at river reach-scales, despite widespread and frequent installation, to investigate the efficacy of willowed engineered log jams (WELJs) interventions used in abating flood-flows, through backing-up flood-pulses with consequent reductions in downstream discharges. This paper examines the efficiency, before and after installation of five 1 metre high WELJs incorporating 1,000 Bay willow (*Salix pentandra*) saplings supporting the dead horizontal timber, across a total of 130 linear metres spanning the floodplain of a decommissioned reservoir. One rain gauge, two fixed point time-lapse wildlife cameras and three water level stations were installed: upstream-of; within, and downstream-of all WELJs. The findings demonstrate a substantial reduction is achieved for most events, with an average of 27.3% reduction in peak discharge being achieved post-installation. The time to peak is little impacted, however there is demonstrable evidence of a longer and higher recessional limb to the events. These findings quantify for the first time the role that WELJs can play in a move towards re-naturalisation of water level regimes, with lower peak water flows achieved, and waters released from the river-reach more slowly. Furthermore, baseflow during dry periods is also elevated by 27.1%, offering greater resilience to dry periods and droughts. Consequently, over the river-reach scale (0-130 m), WELJs play an important role in alleviating flood and drought risk through suppressing flood peaks and increasing baseflow during low flows; steps towards improved hydro-morphological quality overall.

## Keywords

Natural flood management, flooding; hydrological connectivity; willow; engineered log jams.

58

# Quantifying the hydrological implications of pre- and post-installation willowed engineered log jams in the Pennine Uplands, NW England

## 1. Introduction

### 1.1. Natural Flood Management in policy

Globally, 74% of disasters between 2001 – 2018 were water related, with the number of deaths exceeding 166,000 from floods and droughts, a trend which is set to rise (United Nations World Water Development Report, 2020), and in the European Union annual flood loses are projected to exceed €23 billion by 2050 (Jongman *et al.*, 2014). Traditional flood and drought protection measures have largely focused on engineered structures which are costly to construct and maintain (Thorne, 2014); however, increasingly natural approaches to retaining water in the landscape are considered alongside traditional engineered approaches (Pitt, 2008; Waylen, 2017).

Natural Flood Management (NFM) is a holistic approach based on an earth system engineering principal that uses natural processes to slow the flow of water across landscapes (Werritty, 2006). In 2019, at the UN Climate Action Summit, A Nature Based Solutions (NBS) for Climate Manifesto was launched, supported by 70 governments, private sector, and international organizations, and accompanied by nearly 200 initiatives of best practice combating all water security needs (United Nations, 2019). The aspiration of NFM is to create a holistic catchment wide network of interventions that produce single site improvements that collectively reduce downstream flood risk alongside a range of additional benefits. Whilst flood management has traditionally been the focus, the benefits of NFM are much greater, what Barlow *et al.* (2014) calls 'multiple benefits', with improvements in biodiversity (Cook *et al.*, 2016), groundwater recharge (Hut *et al.,* 2008), carbon sequestration (WWAP, 2018), public health (Postnote, 2016), water quality (Barber and Quinn, 2012), and the provision of recreational areas.

## 1.2. Natural Flood Management in practice

In the UK, current and future flood risks are being compounded by a combination of climate and land use change; with peak runoff flows being observed to increase at a rate of over 5% per decade, while 10% of new homes are being built in areas of significant flood risk – land with a ≤ 1:100-year probability of flooding (Putro *et al.,* 2016; DEFRA, 2018; Blöschl *et al.,* 2019; Ministry of Housing, Communities and Local Government, 2020). Studies have highlighted how some 12,200 km$^2$ of UK land is at risk of flooding, including 1 in 6 properties, which in total implicates circa 5 million people (Hall *et al.,* 2003; Environment Agency, 2009; House of Commons, 2016). Climate change and land use scenarios predict that flood risk will increase in real terms; in frequency, magnitude and effect (Committee on Climate Change, 2012; House of Commons, 2016). A family of scenarios for: climate change impact; long-term increasing development on the floodplain (Committee on Climate Change, 2012); and increasingly impermeable catchments will cumulatively result in more property exposure to flood risk from increasingly flashy watercourses, with impaired groundwater recharge (Hut *et al.,* 2008; Kendon *et al.,* 2014; Putro *et al.,* 2016). The Department for Environment, Food and Rural Affairs' (DEFRA) 'Making Space for Water' (2004) approach has been trialled in several places on an *ad hoc* basis for some time (Burgess-Gamble *et al.,* 2017; Nicholson *et al.,* 2020). In the UK 4,185 NFM assets have been created with woody leaky barriers make up 69% of all measures (JBA Trust, 2020; DEFRA, 2021A). To-date, a dearth of pre-installation observations exist that would permit a pre- and post-installation assessment to be undertaken (Arnott *et al*., 2018). Ellis *et al.,* (2021) provide a useful empirical scale-based assessment of NFM data to date, whilst Black *et al.*, (2020) observes catchment-scale lags of 2.6 – 7.3 hours where leaky woody structures and other measures occurred. As Leakey *et al.,* (2020:1) observe these "barriers have been implemented widely, there is still resistance to their use at the scales required to impact significantly on flood risk, at least partially due to an evidence gap". Consequently, since modelling and evidence is the basis to much NFM development, without a determination of the impact on observed flows and levels, which can be used to calibrate models (Hankin *et al.,* 2016; 2017), many schemes may not progress. This paper addresses this research and understanding gap, by demonstrating reach scale level and discharge change, for both floods and low flows (see Hut *et al.*, 2008).

The data and analysis presented in this paper are based on a series five willowed log jam structures installed in late 2019 in the Smithills Estate, near Bolton in North West England led by the Mersey Forest, Woodland Trust, Environment Agency and installed by specialist contractors – Pownall Plant Ltd. Water harvesting and retention techniques have been used since 9,000 BC (Oweis *et al.*, 2001), whilst human uses of willow pre-date stone age technology (> 3,300 BC; Kuzovkina and Quigley, 2005). Yet no studies *prima facie* document the effects of WELJs on flow, despite abundant distribution water tolerant willows (*Salix sp.*) across arid and temperate regions of the world – totalling 450 species across all continents bar Antarctica (Zhen-Fu, 1987; Kuzovkina and Quigley, 2005). Consequently, the evidence and approach documented is likely to have international application to similar headwater reaches, where water retention by substrate are infeasible. No two catchments are the same, presenting heterogeneity in form, pattern and process, which is problematic to map and predict at finite scales under a reductionist approach, which may seek to specify the details of heterogeneity through spatial distributions (Sivapalan, 2018). By taking an earth system science approach, which acknowledges commonality in hydro- eco- geo- pedo-logical processes across all catchments, the conceptual opportunity to apply the WELJ approach to first and second stream orders in similar climatic and geomorphological settings is presented (*ibid)*.

### 1.3. **Natural Flood Management**

Where practiced, NFM often seeks to address quick-flow/direct runoff propagation. NFM techniques are defined as the alteration, restoration of use of landscape features to spatially engineer measures to slow, store, disconnect and filter river and overland flows in sufficient volume to alleviate downstream flood risk (Wilkinson *et al.,* 2010; Burgess-Gamble *et al.,* 2017). NFM draws upon multiple sets of expertise including natural scientists, hydrologists, engineers, and social scientists, combined with knowledge from local communities (Bark *et al.*, 2021). Proponents of this holistic and often partnership-based approach advocate that "These practices could be taken up more widely in the UK, and internationally, to manage floods, droughts and pollution" (Quinn *et al.,* 2016:1). Yet despite wide advocacy of the multi-function benefits to the natural and human worlds, Wingfield *et al*. (2019) note the lack of widespread adoption could reflect a focus on research and resources aimed at increasing the evidence base; a lengthy and complex goal, if NFM is not holistically applied at the catchment-scale. Furthermore, the Agricultural Act of 2020 which is in its implementation phase via UK Environmental Land Management schemes (DEFRA, 2021B) will, in the future, allow funding of a wider-range of public ecosystem service actions, including NFM (Holstead *et al.*, 2014; Green Alliance, 2017).

### 1.4. The Runoff Attenuation Feature (RAF) approach

Natural flood management encompasses a gamut of measures, including tree planting, peatland, agricultural soil and river restoration techniques. One approach focused on addressing rapid rainfall-to-runoff responses, or flashiness, is through Runoff Attenuation Features (RAFs) (after Nicholson *et al.,* 2012). The hydrological premise is that, if a sufficient number of features are deployed around a river catchment, targeting multiple sources and pathways of quick-flow, then runoff can be attenuated at numerous spatial-scales, diffusing and retaining the tributary flood-pulses, before they coalesce to create peak flow synchronicities, and hence, flood the urban receptor (Wilkinson *et al.,* 2010; Nicholson *et al.,* 2012; Figure 1 in Norbury *et al.,* 2019). Whilst the wider gamut of NFM techniques offer multi-functional benefits (e.g., Burgess-Gamble *et al.,* 2017), the ability to indicatively quantify their efficacy in business case terms is often problematic (Hankin *et al.*, 2017). Many communities at flood risk are covered by hydraulic models which can be assessed to determine return period spill volume over bank into floodplain and dwellings (Norbury *et al.,* 2019). This floodplain spill volume can then become a catchment attenuation requirement above the community at flood risk, and hence, RAFs which can be monitored readily and volumetrically calculated, individually or as a collectively across a catchment, and frequently present a best available technique to alleviate risk (Nicholson *et al.,* 2012; Hankin *et al.,* 2017:4; Norbury *et al.,* 2019).

Areas characterised by intense drainage density, over-grazing and high livestock densities, soil compaction, and steepness of slope, are commonplace in many uplands, sites prime for RAFs (Bracken and Croke 2007; Wilkinson *et al.,* 2010; Marshall *et al.*, 2014). RAFs are interventions that alter pluvial and fluvial pathways; physically restricting the passing-forward of downstream flood-flow, and hence, reduce peak runoff and velocity, but convey baseflow (Wilkinson *et al.,* 2010; Nicholson *et al.,* 2012). RAFs can include drained earth and stone bunds (~embankments), ditches often perpendicular to the watercourse, attenuation ponds and scrapes, excavations of pluvial hollows or floodplains, leaky barriers, including live willowed log jams or sawn treated timber barriers and woodland planting (Wilkinson *et al.,* 2010; Nicholson *et al.,* 2012; Burgess-Gamble *et al.,* 2017). The physical backing-up of water by these measures, for temporary periods, often 0 – 80 hrs (storm dependant), also results in increased infiltration and probable groundwater recharge (Hut *et al.*, 2008; Wilkinson *et al.,* 2010; Wainwright *et al.,* 2011; Norbury *et al.,* 2020). RAFS fall into two categories: offline, which attenuate water off the floodplain and online which holds water on the floodplain (Nicholson *et al.,* 2012).

One of the most cost-effective and frequently used measures is the introduction of willowed log jams in the upper and middle reaches of a catchment, such interventions intercept propagating flood-waves heading down-channel and attenuate floodwater behind the dam on floodplains (Burgess-Gamble *et al.,* 2017; Muhawenimana *et al.,* 2021). Willowed engineered log jams often consist of tree trunks, 2.5 times stream-width keyed into the riverbanks to allow sufficient passage of base flow through the obstruction, then during high-flows the logs trap and attenuate water behind the log-jam. To avoid bypass, willow-woven trunks can be planted across the floodplain perpendicular to flow. Planting behind the logs makes the structure a living bio-filter, resilient to movement and increases structural stability and longevity.

## 2.0. Methodology

### 2.1. Study Site: Two Lads and the Woodland Trusts Smithills Estate, Bolton

Recognising the need to trial NFM, the UK Government launched a fund for bids to deliver £15m of NFM from 2017 – 2021 (Wentworth *et al.*, 2020). Locally, the Environment Agency opened-up a £1m competition, and following a bid from the Woodland Trust, the Smithills Estate was successful in a partnership project with the Environment Agency to deliver a NFM project starting in 2019. The focus was predominantly on capital interventions over detailed monitoring. Two Lads was one of 11 locations selected to site 44 NFM installations on the Woodland Trust's Smithills Estate, and it is part of a wider programme of NFM interventions regionally. The study site is a headwater stream of Dean Brook, a tributary of the River Irwell which discharges to the Mersey (Figure 1, 2 and Video SM1). Dean Brook is situated above Smithills, Bolton, in the northwest of England, and rises at approximately 456 meters on the peatlands of Winter Hill. The site consists of peat sitting on a course-grained feldspathic sandstone, except in incised sections which have an alluvium bed. At its rural source, Dean Brook flows off the West Pennine Moor Site of Special Scientific Interest, via an extensive grip network, into the Clough Woodlands and Dean Brook before reaching Smithills, a suburb of Bolton, Greater Manchester. The settlement at Smithills is at flood risk, with 12,300 $m^3$ of water predicted to spill into the floodplain during a 1 in 100-year event, potentially affecting 53 properties (Figure SM2; See Hankin *et al.,* 2017:4 and Norbury *et al.*, 2019 for flood volume appraisal techniques). Smithills Estate is being used to trial a range of landscape-scale restoration techniques, including re-wilding, led by the Woodland Trust see Bridges *et al.,* (2021:180) for further background.

The Dean Brook catchment has a long legacy of industrialisation, with several abandoned mine shafts (predominantly coal), mill ponds/impoundment structures to support the upland early industry (17th and 18th century brick works) and subsequent reservoirs (three, of which two have been decommissioned) constructed to support the emerging textile industry and associated bleach works in the lower valley in the 19th century. During the early 20th century the area was extensively drained, with the industrial structures of previous centuries abandoned, however this has left a legacy of hydrological manipulation, with many channels straightened and canalised with a focus on increased drainage efficiency downstream. The catchment provides the spatial unit (0.72 $km^2$ upstream of WELJ5) and offers an opportunity to deliver innovative ways of alleviating flooding through NFM, based on flood modelling of the area. Five willowed engineered log jam (WELJ) interventions were trialled at the Two Lads site, situated in a former reservoir bed, which was last active in the 1840s adjacent to the Hole Bottom ‘Kiln’ and ‘Hall’, situated in the NW corner of Figure 1A.

## 2.2. Pre-installation monitoring: apparatus and methodology

A decommissioned reservoir presents an opportune site to attenuate flood-flow, as they are often flat and wide, hence relatively short structures may retain a large volume of water compared to a steeply incised landscape-setting (See Case Study 17 in Burgess-Gamble *et al.,* 2017 and Norbury *et al.,* 2020 for example efficacy; Video SM1 and 2). On 8th August 2019 three water level stations (WLS1-3) were installed across five willowed engineered log jams (WELJ001-005). WLS1 was situated 85m upstream of the final WELJ (005) and beyond the attenuation area, WLS2 was installed within the area of inundation behind the second to last log jam (WELJ002) and WLS3 was placed 100 linear metres downstream of all log jams (Figure 1A). An EML ARG 3 rain-gauge was discretely installed 90m to the NE of the WELJs (not visible from the footpath that runs adject to the site), a Tempcon HOBO U20L-04 atmospheric pressure logger was placed adjacent to WLS3 and two Crenova wildlife cameras were installed looking downstream over the log jams WELJ001-4 and the second provides a side view of WELJ002 (Figure 1A). Typical level accuracy is at ±0.1% or 4 mm and for rainfall it is above the 99% confidence level up to 120mm $hr^{-1}$. Together these instruments served to provide simultaneous 15-minute precipitation (mm) and water level (m) data along with hourly time-lapsed photos of the willowed log jams. HOBO pressure loggers were hung in a perforated stilling well situated at the base of the entrenched channels; an atmospheric pressure logger served to compensate the water level loggers using Tempcons Hoboware software. Additional precipitation data has been accessed from the Environment Agency (EA), with the nearest meteorological station situated at Lower Rivington (Stn. Num. 569723, 53°36'15.5"N, 2°33'32.2"W), annual average precipitation 1,174.5 mm (1981-2010), <5km away from the Two Lads site and provides quality control and supplemental data. The EA rain-gauge has been used to infill missing precipitation data arising from a technical fault on the Two Lads rain-gauge (28th Oct. - 7th Dec. 2019; Figure 1A).

### 2.3. Willowed engineered log jam interventions

Specialist contractors started and completed the five willowed log jam build between August 21st – 30th 2019, with a total length of 130 linear metres (Figure 1, 2 and Video SM1), offering a total attenuation capacity of ~3,000 $m^3$ across the suite of WELJs, with increasing capacity moving downstream. Figure 1B provides a schematisation of the WELJs, these are horizontal felled timbers, staked front and back every two linear metres with strainer posts ($\Sigma = 103$) bay willow (*Salix pentandra*) planted at 8 per linear metre ($\Sigma = 1{,}040$), to create a living thicket of live shrubs. In total, 54 tonnes of locally sustainably harvested timber was used in the WELJs, approximately 130 stems of whole tree at 9m L and 300mm maximum diameter. The timber was a mixture of native, European and North American softwoods including Scots- (*Pinus sylvestris*), Logepole- (*Pinus contorta*) and Corsican pine (*Pinus nigra*) derived from thinning from Burnt Edge legacy plantation inappropriately located on dry heathland (53°36′26″N, 002°30′02″W). Since not all log jams are created equal (Dixon

2015A, 2015B); WELJs advance the longevity and structural performance compared to conventional log jams. The use of willow to create a thicket both, holds-up the horizontal deadwoods which are set to heavily decayed by 2029 (Burgess-Gamble *et al.,* 2017; Dixon *et al.,* 2018; Thomas and Nisbet, 2020) and provides immediate resource to add to the horizontal timber (Figure 1B). In stacking timbers, as the horizontals saturate and descend into the floodplain, those horizontals on top in the stack provide a continued vertical barrier to attenuate a head of water.  A new planation of broadleaves nearby, can be sustainably harvested to do this, also (Figure 1A).

## 2.4. Post installation monitoring

A difference in minimum baseflow between WLS1 and WLS3 was identified during the pre-instrumental period (08-29/08/2019; ~0.165 $m^3s^{-1}$), which is replicated post-installation with a longer observation window (30/08/2019-02/10/2020; ~0.15 $m^3s^{-1}$), a negligible difference between the two. During analysis $WLS3^{adj}$ is used to represent the WLS3 measurements with baseflow removed (0.165 $m^3s^{-1}$). WLS3 is situated within a bedrock gorge, ~100m downstream of the last WELJ, at 344 mAOD, this represents a fall in elevation of 15 m from WLS1, with both surface and subsurface flows channelled into the bedrock gorge from the sub-catchment. During intense precipitation events additional lateral surface flow channelled along the adjacent footpath enters downstream of the installations, but upstream of WLS3, this has only been observed during high flows >0.5 $m^3s^{-1}$ @WLS1 arising from intense precipitation (>4mm/15min) and/or during snowmelt events; spot gauging during high lateral flows (14/01/2021) determined an addition of ~0.2 $m^3s^{-1}$. During low and normal conditions no lateral inflow is presented, this additional lateral inflow was not identified during site selection or during the early instrumentation phase (Figure 1 and Video SM4).

# 3.0. Results

## 3.1. Rainfall-runoff analysis

Precipitation and water level data from the three pressure transducers (WLS1-3; Figure 3A - D) demonstrate that whilst the pre-installation period was relatively short, a range of precipitation events of varying magnitude, frequency and duration were captured, with comparable events pre- and post-installation of the WELJs. The reduction in precipitation in late-March 2020 to mid-June 2020 is captured within the water level stations at the three sites, with little flow reaching the WELJs during the dry months March-June (Figure 3B-D), demonstrating a typical hydrological response for an upland peat-moorland. The annual precipitation pattern in 2020 reflects the long-term pattern (1971-2010), with February to July average monthly precipitation <100 mm and all other months receiving >100 mm. Notably April has the lowest average monthly precipitation (74.3 mm), whereas October has the highest (129.1 mm).

Analysis of comparable isolated events, where precipitation and discharges exceeded 7.5 mm hr$^{-1}$ and 0.5 m$^3$s$^{-1}$, indicates a reduction in water level at WLS3 relative to WLS1 (Figures 4A-H), with greater reductions in water level for higher magnitude precipitation events (Figure 4C-D, G-H). Comparison of events under comparable catchment antecedent conditions demonstrates a similar pattern (10:00-22:00 16/08/2019 compared to 05:00-17:00 09/10/2019), with a reduction in water level and discharge achieved at WLS3 post-WELJ installation relative to pre-installation (Figure 3; Figure 4C). Lateral inflow was observed (Figure 1A; Video SM4) and spot gauging estimated at 0.2 m$^3$s$^{-1}$, an equivalent the 27% higher flow noted during Storm Ciara. The lag time pre- and post-WELJ installation is typically around 135 minutes from peak precipitation to peak discharge at WLS1, with no discernible difference in the timing peak precipitation and peak flow pre- and post-WELJ installation. The efficiency of the WELJs during the two events are demonstrated by Figure 4D and 4H (also see supplementary material SM3), which demonstrate the elevated water levels present in WELJ002 throughout the period of analysis, with a higher base water level retained in the installation during the winter months, with a return to pre-installation levels only during dry periods (Figure 4C).

## 3.2. Comparable pre- and post- engineered log jam hydrographs

In assessing the hydrological efficiency of the five willowed WELJs, comparative analysis of pre- and post- installation discharges between WLS1 and WLS3 are undertaken (Figure 5A). A demonstrable difference is achieved post-WELJ installation, with a reduction in discharge at WLS3 for most events, the reduction is relatively stable above 0.6 $m^3s^{-1}$ (WLS3), with no discernible reduction in capacity or attenuation effect for the events captured irrespective of volume, with increasing storage above 0.45 m post WELJ installation (WLS3; Figure 4B-C). Higher baseflow (level) at WLS3 is achieved for low flows (<0.1 $m3s^{-1}$ @WLS1) post-WELJ installation, a previously poorly documented benefit of NFM structures. Further analysis of these changes in low baseflow (inflows of <0.1 m) show an increase of ~0.03 m post-WELJ installation at WLS3 (Figure 5D).

Analysis of a series of precipitation events (>7.5 mm $hr^{-1}$) and associated peak discharges at WLS1 (>0.5 $m^3s^{-1}$) and WLS3 pre- and post- installation identifies an average reduction in peak discharge of 27.3% across the river-reach at a range of event sizes (Table 1). Pre-installation events across the river-reach witness percentage change differences between a 10.5-102.6% increase, with an average of +42.1%; whereas post-installation sees a percentage change of -11.4-124.8%, with an average of +14.8% (Table 1; Figure 6). The reduction of 27.3% typically equates to a reduction of ~0.2 $m^3s^{-1}$ on peak flows at $WLS3^{adj}$ (Figure 6).

## 3.3. February 2020 flooding: storm Ciara and Dennis hydrography

The period of analysis captures several precipitation events and subsequent run-off responses for both pre- and post-WELJ installation, including the notable storms Ciara (8-

10th Feb. 2020) and Dennis (15-16th Feb. 2020) (Figure 7). Storms Ciara and Dennis brought intense and prolonged rainfall to northern England in February 2020, with North West England experiencing 321% on its 1981-2010 long-term February average and recording the wettest February on record since 1910 (Sefton *et al*., 2020; Simon *et al*., 2020). Three people died in storm-related incidents with 3,000 properties flooded, more flood warnings and alerts were issued across the UK within a 24hr (16th Feb.) period since records began (2006-present; (*ibid*). Close inspection of storm Ciara reveals a double rainfall peak, which coalesced into a single peak in water level/discharge (Figure 7A). The hydrograph structures through the log jam structures (WELJ002, WLS2) and after the log jams ($WLS3^{adj}$) show a delaying in peak and attenuation of the flow against the inflow (WLS1, Figure 7 A-B). No identifiable reduction in peak discharge is achieved during storm Ciara (percentage change increase of 27%), in part arising from lateral inflow along the footpath during the intense precipitation phase (see supplementary material SM4), which exacerbates peak discharge at WLS3 relative to discharges at WLS1 and WLS2 (Table 1). Elevated discharges are identified in the recessional limb, with $WLS3^{adj}$ demonstrating higher discharges compared to WLS1, with the shape of the recessional limb reflecting that of the water level recorded at WLS2. However, it is notable that the water level in WLS2 does increase and the photographic evidence indicates water retention was occurring during storm Ciara, even if no discernible reduction in peak flow is documented at WLS3.

The subsequent storm Dennis reveals a more-prolonged less-intense precipitation event, with peak discharge at WLS3 being reduced by ~0.2 $m^3s$-1, with a percentage change decrease of -4.3% (WLS1-$WLS3^{adj}$), with demonstrable storage within WELJ002 (Table 1; Figure 7B). Water levels in the log jam reservoir reveal attenuation and a release of flood waters after the peak has passed, with $WLS3^{adj}$ initially below WLS1 on the recessional limb (Figure 7A).

The different hydrograph responses to the two events suggest that the WELJs had a greater attenuation role during storm Dennis compared to Ciara, likely reflecting the lower intensity more prolonged nature of the precipitation, though for both events the peak was reduced with storage and attenuation evident in WELJ002 (Figure 7). Whilst the cameras captured both events, images are of relatively poor quality because of poor visibility at the site, with storm Dennis floodwaters peaking at night. With continued monitoring a larger sample of higher-magnitude events will improve understanding of peak flow through the WELJs and provide a clearer depiction of the reductions afforded during peak flows.

## 4.0. Discussion

### 4.1. Reach-scale flow regime change

At the Two Lads site, the WELJs result in an average peak level reduction of 27.3% against the pre-installation peaks (Figure 3 and 5). Pre-installation, the channel was entrenched, with dominant processes being narrowing and degradation, with low biotic interaction and high erosion resistance - a stage two (channelized) or Rosgen A channel present (after Rosgen, 1996; Cluer and Thorne, 2014). These channel types are sometimes so-called “fire-hose” channels, since few fluvial forms exist to slow the flow of passing waters. The installation of the WELJs induced disturbance to the hydromorphology, and with it ameliorated the flood propagating elements over the reach. The introduction of a physical barrier has resulted in greater trapping of flood waters, where the flow exceedance of porosity and orifice space in the barrier results in backing-up and attenuation (Figure 2 and Video SM1). Trapping of peak flood waves reduces the passage of the peak discharges through the reach (Figure 3). The wildlife camera photos show filling and emptying of the structures, and since Q = V*A (Q=discharge rate, A=area, V=velocity), a velocity rate change can be observed meaning that the reduction in peak discharge passing through the reach can be established causally, rather than associatively. This is further reaffirmed by the changes longitudinally presented in the data from the stations, from upstream, within and downstream of the WELJs (Figure 3 and 4). All conversions of water level to discharges are based on ratings derived from repeat spot gauging at sites WLS1 and WLS3, with all level data (pre- and post-instillation) converted to discharge.

WELJs enable assisted natural recovery (Burgess-Gamble *et al.,* 2017) of the reach with consequent process change discerned from time-lapse photos, from degradation and narrowing to widening and aggradation, which in time will lead to an anastomosing wet woodland (stage a stage 0 channel) as the WELJs separate single channel belts into multiple channels (Figure 2 and Video SM1; Dixon, 2015A, 2015B; Burgess-Gamble *et al.*, 2017; Dixon *et al.*, 2018; Norbury *et al.*, 2020).

To-date, the findings presented of reduced flood peak during events at all scales (once the impact of the lateral inflow is accounted for at WLS3) would appear *prima facie* contrary to the proposition by Dadson *et al.* (2017) and Wilby and Dadson (2020) that NFM is only operable during their so-called 'nuisance' flooding and would be overwhelmed during extreme flows (Figures 1, SM2 and SM3; Video SM4). The Two Lads WELJs have undergone storm Ciara, Dennis and Christoph, with the wildlife camera (Figure 2 and Video SM1) and level stations (Figure 3 and 7) showing no overwhelming – with no evidence of WELJ overtopping.

As a comparison to reach-scale discharge reductions presented here, Dixon *et al.* (2016) determined that restoring riparian forest cover over 20-40% of catchment area reduced flood peak magnitude by up to 19%, yet restoration can take 25+ years to introduce large woody debris into the channel sufficient to effect runoff rates.  The physical morphology of the channel will evolve to a more naturalised state, but the physical properties of the WELJ structure will adjust through time, likely increasing flood-flow trapping efficiency (Section 2.3). The growth of the willow, and coppicing of it, will lead to increase trunk diameter over the 1,080 whips, plus self-seeding, will increase the WELJ blockage and hydraulic roughness, particularly during summer foliation. This is predicted to enhance the trapping of peak flows and prolong the recessional limb which is already notable in the data (Figures 3, 4 and 7).  The increase in baseflow during low flow/drought events is nominal (27.1%; ~0.05

$m^3s^{-1}$). However, a baseflow increase may have important implications for the local hydroecology, suggesting woody structures such as those installed at Two Lads may have an important role in landscape wetting, supporting the findings by Wilson *et al.,* (2011) who have identified similar responses following drain blocking of peatlands in upland mid-Wales. The absence of a discernible change in time to peak across the site may simply be reflective of site size (130 m between WLS1 and WLS3, as such no clearly definable change is achieved and flood events are relatively small and responsive ‘flashy’ events.

### 4.2. Future WELJ research agendas

Greater understanding of how the combination of the five WELJs are hydraulically interacting would be advantageous, with results aggregating the efficiency of the structures on flood peak attenuation. High-resolution repeat topographic surveys (e.g., Spreitzer *et al.,* 2019), physical experiments (e.g., Follett *et al.,* 2019; Follett and Wilson, 2020; Muhawenimana *et al.,* 2021) and numerical modelling studies (e.g., Boothroyd *et al.,* 2016; Xu and Liu, 2017) could further improve understanding of flow-structure interactions and sediment dynamics associated with willowed engineered log jams and represent opportunities for further enhanced understanding at the site. The site at Two Lads was not intended or designed as a demonstration site, rather an opportunity was grasped to instrument the site prior to the installation of the working structures.

The exact impact of WELJs would be sensitive to site specific context, however the findings identified within this study are comparable (23-50% reduction) to those considering natural woody dams created by beavers (Puttock *et al*., 2020), without the challenges that reintroduction brings (Auster *et al*., 2019). The potential role of WELJs in mimicking natural processes is considerable and could be an important tool in catchment-based flood risk management that combines both hard engineering and NFM interventions as advocated by Hewett *et al* (2020). This research provides valuable additional information to the evidence base for NFM adoption; however, as Wingfield *et al*. (2019) note we should continue to embrace such holistic measures in developing more resilient natural systems.

Pre-installation monitoring is often challenging but crucial in providing an evidence-led approach, as recognised by CaBA (2017); as funding schemes used to support NFM installation are varied and often have short timescales with limited funding assigned to pre- or post- installation monitoring (Robins *et al.*, 2017). In undertaking this research on a working site, it is evident that a longer pre-installation dataset would be optimal, however the timescales between funding being received, permissions of work gained, and installation to begin were short, therefore a longer window was unavailable, this continues to represent challenges for data acquisition.

Whilst this study used Bay Willow *(Salix pentandra) within the WELJ,* a species considered native across much of northern Europe and Asia that favours damp environments, and therefore are ideal for use in living WELJ, alternative species could be used to achieve similar impacts (see Zhen-Fu, 1987; Kuzovkina and Quigley, 2005).

### 4.3. Strategic flood risk alleviation

Understanding the efficacy of WELJs in abating flood-flow at the reach scale is important, since to alleviate flood risk in Smithills for the 1 in 100-year event, flows over >13 $m^3s^{-1}$ require retention in the upper catchment, corresponding to 12,300 $m^3$ of water being removed from the flood hydrograph peak, a depth reduction of 910 mm; representing 5% of the total storm discharge (Figure SM2; Hankin *et al.,* 2017; Norbury *et al*., 2019). This is equivalent to a 19% reduction of the peak water level and hence if NFM can be exercised at sufficient scale it is hypothesized that the 1:100 year risk could be alleviated. At Smithills, the interventions at Two Lads and the other 25 locations equate to that target volume of 12, 300 $m^3$. Furthermore 65 Ha of woodland planting (130,000 trees), 60% of the river catchment, are also ongoing on the Estate. Dixon *et al.* (2016) predict that for a 20-40% catchment riparian woodland uplift, a 19% catchment outlet level reduction. In combination, the downstream flood risk reduction at Smithills should be tangible. As a comparison, the Holnicote NFM project which installed 41 log jams, 5 attenuation bunds, 5 ha of woodland, 5 fields of arable reversion, wet woodland and pond restoration in the 40ha catchment experienced a 10% reduction in flood peak during a 1 in 75 year event – the December 2013 floods – with none of the 98 at risk properties being flooded (Case Study 20 in Burgess-Gamble *et al.,* 2017).

Along with the NFM distributed across the catchment as shown in Figure SM2 further works include peatland restoration on the headwaters including circa 100 stone dams, 50 peat bunds, 200 linear metres of reprofiling and surface contour bunds over 70,000 square metres of the catchment (Gresty, 2020; see https://www.moorsforthefuture.org.uk/). Moorland restoration is noted to delay stormflow and reduce peak flows, with Shuttleworth *et al.* (2019) observing delays of 106% and reductions of 27%. Consequently, the inflows to Two Lads, particularly at WLS1, are predicted to be less flashy. Future research is urgently needed for further catchment outlet monitoring, particularly as joined-up catchment-scale restoration projects like this are uncommon. The data and findings on WELJ level induced reach changes will contribute to 1 and 2 dimensional hydraulic models, in particular unit development and structural representation, which are used to predict flood benefits that often underpin flood scheme prefeasibility and options assessment (see Hewett *et al.*, 2020; Leakey *et al.,*2020).

## 5.0. Conclusion

This research demonstrably identifies a 27.3% reduction in the average peak flow, with retention achieved in the WELJ structures (Figure 3). During storms Ciara and Dennis in February 2020, a comparable discharge at WLS1 to WLS3$^{adj}$, is achieved during storm Ciara accounting for baseflow and lateral inflows and during storm Dennis a reduction of 4.3% in peak flow was achieved between WLS1 and WLS3$^{adj.}$ Whilst these present modest reductions in peak flow, they represent a small sample, further high-magnitude events will enhance understanding of WELJ capacity to reduce peak flows during high magnitude events. Generally, discharges between precipitation events are increased with installations slowly releasing waters long after flood-waves have passed, suggesting WELJs can play a role in increased water residence. The impact of these five WELS is more than holding water in the landscape for longer, with the effect of more naturalised flow regimes, slower more sluggish water over flashier flows and reduced flood peaks. Together the findings demonstrate the role these measures can play in flood and drought alleviation objectives as guided by legislation.

**Acknowledgements**

This work was in part supported by an intensive 3-month monitoring period made possible by a NPIF Placement with the Mersey Forest supporting the Engineering and Physical Research Sciences Council Funding (EPSRC) PhD studentship to HP (*EP/L015927/1 – P90791D*). The Natural Flood Management Works were made possible by Environment Agency and Treasury Flood Defence Grant in Aid Funds (ITQ 0219 CW-NFM Smithills Estate) and Heritage Lottery Fund. The engineered log-jams were installed by the Mersey Forest in conjunction with the Environment Agency, Woodland Trust, Heritage Lottery Fund, Pownall Plant Limited, Bolton Council and Natural England. Other partners who have contributed to the project include: Bolton Council, Natural England, Ribble Rivers Trust, the University of Glasgow and Newcastle. The EU Natural Course Project (*LIFE14 IPE/UK/027*) contributed to resourcing this papers dissemination and the Unmanned Aerial Vehicle and Differential Global Positioning Surveys that are shown in Figure 1, with Paragon Surveys being awarded the work following competitive quoting.

## Contributions

Michael Norbury was the project manager, led project design and contributed to data analysis and writing. Hazel Phillips undertook installation monitoring and data analysis and contributed to writing. Neil Macdonald led the writing and contributed to field and data analysis and project design. David Brown secured funding and contributed to project design, data analysis and writing. Richard Boothroyd undertook field monitoring and UAV site work and contributed to writing. Catherine Wilson, Paul Quinn and Dave Shaw supported in developing the paper. Wilson is undertaking further modelling of the interventions, Quinn has visited site and provided independent quality assurance to the Environment Agency and Shaw is a Trustee of the Community Forest which has supported this project and many others like it.

## Conflicts of Interests

There are no conflicts of interest.

## Data Access

The data from the site is continuing to be collected. As part of the funding requirements, data will be uploaded onto the NERC repository once a substantial volume is collected/completed. Earlier access may be gained through contacting Hazel Phillips.

## References

Arnott, S., Burgess-Gamble, L., Dunsford, D., Webb, L., Johnson, D., Andison, E., … Maslen, S. (2018). Monitoring and evaluating the DEFRA funded Natural Flood Management projects. Bristol: Environment Agency. Available at: https://catchmentbasedapproach.org/wp-content/uploads/2018/11/NFM-MonitoringObjectivesFINAL-v18.pdf (Accessed: 2nd February 2019).

Auster, R., Puttock, A., Brazier, R.E. (2019). Unravelling perceptions of Eurasian beaver reintroduction in Great Britain. *Area*, 52, 364-375. https://doi.org/10.1111/area.12576

Barber, NJ., Quinn, P.F. (2012). Mitigating diffuse water pollution from agriculture using soft-engineered runoff attenuation features. *Area*, 44, 454-462. https://doi.org/10.1111/j.1475-4762.2012.01118.x

Bark, R.H., Martin-Ortega, J., Waylen, K.A. (2021). Stakeholders' views on natural flood management: Implications for the nature-based solutions paradigm shift?, *Environmental Science and Policy*, 115, 91-98. https://doi.org/10.1016/j.envsci.2020.10.018

Barlow. J., Moore, F., Burgess-Gamble, L. (2014). Working with natural processes to reduce flood risk: R and D framework.

Black, A., Peskett, L., MacDonald, A., Young, A., Spray, C., Ball, T., … Werritty, A. (2021) Natural flood management, lag time and catchment scale: Results from an empirical nested catchment study, *Journal of flood risk management,* e12717, 1 – 16. https://doi.org/10.1111/jfr3.12717

Boothroyd, RJ., Hardy, RJ., Warburton, J.  Marjoribanks, TI. (2016). The importance of accurately representing submerged vegetation morphology in the numerical prediction of complex river flow. *Earth Surface Processes and Landforms*, 41, 567-576. https://doi.org/10.1002/esp.3871

Bracken, LJ., Croke, J. (2007). The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. *Hydrological Processes*, 21, 1749-1763. https://doi.org/10.1002/hyp.6313

Bridges, T.S., Bourne, E.M., Suedel, B.C., Moynihan, E.B., King, J.K. (2021). Engineering With Nature: An Atlas, Volume 2. ERDC SR-21-2. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://dx.doi.org/10.21079/11681/40124.

Burgess-Gamble, L., Ngai, R., Wilkinson, M., Nisbet, T., Pontee, N., Harvey, R., … Quinn, P. (2017). Working with Natural Processes – Evidence Directory (SC150005). Bristol: Environment Agency. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/654431/Working_with_natural_processes_evidence_directory.pdf (Accessed: 2nd February 2018).

Cluer, B.L., Thorne, C.R. (2014). A stream evolution model integrating habitat and ecosystem benefits. *River Research and Applications*, 30, 135-154. https://doi.org/10.1002/rra.2631

Committee on Climate Change. (2012) Adaptation sub-committee report: Chapter 2: Flooding indicators. Available at: https://www.theccc.org.uk/flooding-indicators/ (Accessed: 12th February 2017).

Cook, B., Forrester, J., Bracken, L., Spray, C., Oughton, E. (2016). Competing paradigms of flood management in the Scottish/English borderlands. *Disaster Prevention and Management: An International Journal*, 25, 314-328. https://doi.org/10.1108/DPM-01-2016-0010

Dadson, S.J., Hall. J.W., Murgatroyd, A., Acreman, M., Bates, P., Beven, K., … Wilby, R. (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: 20160706. http://dx.doi.org/10.1098/rspa.2016.0706

DEFRA. (2004). Making space for water: Developing a new Government strategy for flood and coastal erosion risk management in England. Available at: https://www.lookup.org.uk/2013/wp-content/uploads/2014/02/Making-space-for-water.pdf (Accessed: 2nd February 2018)

DEFRA. (2018). *A green future: Our 25 year plan to improve the environment*. Available at: https://www.gov.uk/government/publications/25-year-environment-plan (Accessed: 2nd February 2018)

DEFRA. (2021A) NFM Projects Monitoring and Evaluation Tool v2.501. Available at: https://www.arcgis.com/apps/MapSeries/index.html?appid=5086d50ee3bc49f1bd25b039c7129c1a (Accessed: 2nd January 2021)

DEFRA. (2021B). Guidance Environmental land management schemes: overview. Available at: https://www.gov.uk/government/publications/environmental-land-management-schemes-overview (Accessed: 2nd January 2021)

Dixon, S.J. (2015A). A dimensionless statistical analysis of log jam form and process. *Ecohydrology*, 9, 1117-1129. https://doi.org/10.1002/eco.1710

Dixon, S.J. (2015B). The River Management Blog: Not all logjams are created equal. Available at: https://therivermanagementblog.wordpress.com/2015/11/30/not-all-logjams-are-created-equal/ (Accessed: 2nd January 2021)

Dixon, S. J., Sear, D.A., Nislow, K.H. (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., Sear, D.A., Odoni, N.A., T. Sykes, Lane, S., (2016). The effects of river restoration on catchment-scale flood risk and flood hydrology. *Earth Surface Processes and Landforms*, 41, 997-1008. https://doi.org/10.1002/esp.3919

Ellis, N., Anderson, K., Brazier, R. (2021). Mainstreaming natural flood management: A proposed research framework derived from a critical evaluation of current knowledge. *Progress in Physical Geography*. XX (x), 1 – 23. https://doi.org/10.1177/0309133321997299

Follett, E., Wilson, C.A.M.E. (2020). Bedload sediment transport induced by channel-spanning instream structures. In: *Proceedings of the 10th Conference on Fluvial Hydraulics* (Delft, Netherlands, 7-10 July 2020), 735-742.

Follett, E., Schalko, I., Nepf, H. (2020). Momentum and energy predict the backwater rise generated by a large wood jam. Geophysical Research Letters, 47: e2020GL089346. https://doi.org/10.1029/2020GL089346

Green Alliance. (2017). Natural infrastructure schemes in practice: How to create new markets for ecosystem services from land. Available at: http://www.green-alliance.org.uk/resources/Natural_infrastructure_schemes_in_practice.pdf (Accessed: 2nd February 2018)

Gresty, J. (2020). Site of Special Scientific Interest Notice of works: West Pennine Moors, Unit 81. *Submitted to Natural England for works December 2020 – March 2021.*

Hall, J.W., Dawson, R.J., Sayers, D.B., Rosu, C., Chatterton, J.B., Deaton, R. (2003). A methodology for national-scale flood risk assessment. Proceedings of the Institution of Civil Engineers: *Water and Maritime Engineering*, 156, 235-247. https://doi.org/10.1680/wame.2003.156.3.235

Hankin, B., Craigen, I., Chappell, N.A., Page, T., Metcalfe, P., Rose, S. (2016). Strategic Investigation of Natural Flood Management in Cumbria. Skipton: Jeremy Benn Associates. Available at: http://naturalcourse.co.uk/uploads/2017/04/2016s4667-Rivers-Trust-Life-IP-NFM-Opportunities-Technical-Report-v8.0.pdf (Accessed: 2nd February 2018).

Hankin, B., Arnott, S., Whiteman, M., Burgess-Gamble, L., Rose, S. (2017). Research and analysis: Working with Natural Processes – Using the evidence base to make the case for Natural Flood Management (SC150005). Bristol: Environment Agency. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/654435/Working_with_natural_processes_using_the_evidence_base.pdf (Accessed: 2nd February 2018).

Hewett, C.J.M., Wilkinson, M.E., Jonczyk, J, Quinn, P. (2020) Catchment systems engineering: An holistic approach to catchment management. *WIREs Water*. 3 (3), e1417, 1 – 14. https://doi.org/10.1002/wat2.1417

Holstead, K., Kenyon, W., Rouillard, J., Hopkins, J., Galán-Díaz, C. (2017). Natural flood management from the farmer's perspective. *Journal of Flood Risk Management*, 10, 205-218. https://doi.org/10.1111/jfr3.12129

House of Commons. (2016). Environment, Food and Rural Affairs Committee: Future Flood Prevention: Second Report of Session 2016-17. HC 115. Available at: https://www.parliament.uk/business/committees/committees-a-z/commons-select/environment-food-and-rural-affairs-committee/inquiries/parliament-2015/inquiry/ (Accessed: 12th February 2017).

Hut, R., Ertsen, M., Joeman, N., Vergeer, N., Winsemius, H., Van de Giesen, N. (2008). Effects of sand storage dams on groundwater levels with examples from Kenya. *Physics and Chemistry of the Earth*, 33, 56-66. https://doi.org/10.1016/j.pce.2007.04.006

JBA Trust, Lancaster Environment Centre and Lancaster University. (2020). Working With Natural Processes. Catalogue of nature-based flood risk management projects in the UK. Available at: http://naturalprocesses.jbahosting.com/#6/43.918/7.861 (Accessed: 29th December 2020).

Jongman, B., Hochrainer-Stigler, S., Feyen, L., Aerts, J.C.J.H., Mechler, R., Botzen, W.J. W., …  Ward, P. J. (2014). Increasing stress on disaster-risk finance due to large floods. *Nature Climate Change*, 4, 264-268. https://doi.org/10.1038/nclimate2124

Kendon, E.J., Roberts, N.M., Fowler, H.J., Roberts, M.J., Chan, S.C., Senior, C.A. (2014). Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nature Climate Change*, 4, 570-576. https://doi.org/10.1038/nclimate2258

Kuzovkina, Y.A., Quigley, M.F. (2005) Willows beyond wetlands: Uses of *Salix L.* species for environmental projects. *Water, Air and Soil Pollution*, 162, 183–204

Leakey, S, Hewett, C.J.M., Glenis, V., Quinn, P.F. (2020). Modelling the Impact of Leaky Barriers with a 1D Godunov-Type Scheme for the Shallow Water Equations. *Water*. 12(2), 371, 1 – 28. https://doi.org/10.3390/w12020371

Marshall, M.R., Ballard, C.E., Frogbrook, Z.L., Solloway, I., McIntyre, N., Reynolds, B., Wheater, H.S. (2014). The impact of rural land management changes on soil hydraulic properties and runoff processes: results from experimental plots. *Hydrological Processes*, 28, 2617-2629. https://doi.org/10.1002/hyp.9826

Ministry of Housing, Communities and Local Government. (2020). Statistical data set: Live tables on land use change statistics. UK Government website. Available at: https://www.gov.uk/government/statistical-data-sets/live-tables-on-land-use-change-statistics (Accessed: 29th December 2020).

Muhawenimana, V., Wilson, C.A.M.E., Nefjodova, J., Cable, J., (2021). Flood attenuation hydraulics of channel-spanning leaky barriers. *Journal of Hydrology*, 596, 125731. https://doi.org/10.1016/j.jhydrol.2020.125731

Nicholson, A.R., Wilkinson, M.E., O'Donnell, G.M., Quinn, P.F. (2012). Runoff attenuation features: a sustainable flood mitigation strategy in Belford catchment, UK. *Area*, 44, 1-7. https://doi.org/10.1111/j.1475-4762.2012.01099.x

Nicholson, A.R., O'Donnell, G.M., Wilkinson, M.E., Quinn, P.F. (2020). The potential of runoff attenuation features as a Natural Flood Management approach. *Journal of Flood Risk Management,* 13, e12565. https://doi.org/10.1111/jfr3.12565

Norbury, M., Shaw, D., Jones, P. (2019). Combining hydraulic modelling with partnership working: towards practical natural flood management. *Proceedings of the Institution of Civil Engineers: Engineering Sustainability*, 172, 372-384. https://doi.org/10.1680/jensu.17.00025

Norbury, M., Bracken, L., Burt, T. (in press). The effect of riparian pool-riffle bedforms on hyporheic hydrochemistry and biodiversity: The River Esk, Yorkshire, UK. *Ecohydrology, ECO-20-0163*

Oweis, T., Prinz, D., Hachum, A. (2001). Water harvesting. In: *Indigenous Knowledge for the Future of Drier Environments*. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria.

Pescott, O., Wentworth, J. (2011). Natural flood management: Parliamentary office of science and technology note. POST Note: 396. Available at: http://researchbriefings.parliament.uk/ResearchBriefing/Summary/POST-PN-396 (Accessed: 12th February 2017).

Pitt, M. (2008). Learning lessons from the 2007 floods – June 2008. Available at: http://webarchive.nationalarchives.gov.uk/20100702215619/http://archive.cabinetoffice.gov.uk/pittreview/thepittreview/final_report.html (Accessed: 12th February 2017).

Postnote. (2016). Green space and health. Retrieved from: https://researchbriefings.parliament.uk/ResearchBriefing/Summary/POST-PN-0538

Puttock, A., Graham, H.A., Ashe, J., Luscombe, D.J., Brazier, R.E. (2021). Beaver dams attenuate flow: A multi-site study. *Hydrological Processes,* 35, e14017. https://doi.org/10.1002/hyp.14017

Putro, B., Kjeldsen, T.R., Hutchins, M.G., Miller, J.D. (2016). An empirical investigation of climate and land-use effects on water quantity and quality in two urbanising catchments in the southern United Kingdom. *Science of the Total Environment*, 548-549, 164-172. https://doi.org/10.1016/j.scitotenv.2015.12.132

Pyayt, A.L., Mokhov, I.I., Kozionov, A.P., Kusherbeava, V.T., Lang, B., Krzhizhanovskaya, V.V., Meijer, RJ. (2013). Data-driven modelling for flood defence structure analysis. In F.

Klijn, T. Schweckendiek (Eds.) *Comprehensive flood risk management: research for policy and practice*. 301-306. Boca Raton, FL: CRC Press.

Quinn, P.F., O'Donnell, G., Nicholson, A., Wilkinson, M., Owen, G., Jonczyk, J., … Davies, G. (2013). The Potential Use of Runoff Attenuation Features in Small Rural Catchments for Flood Mitigation. Available at: https://research.ncl.ac.uk/proactive/belford/newcastlenfmrafreport/reportpdf/ (Accessed: 12th February 2017).

Quinn, P.F., Wilkinson, M.E., Strutter, M. (2016). Policy note: Working with nature to ease floods and droughts. Newcastle University: Institute for Sustainability. Available at: http://research.ncl.ac.uk/proactive/holdingwater/Holding%20Water%20Briefing%20Note.pdf (Accessed: 12th February 2017).

Robins, L., Burt, T.P., Bracken, L.J., Boardman, J., Thompson, D.B.A. (2017). Making water policy work in the United Kingdom: A case study of practical approaches to strengthening complex, multi-tiered systems of water governance. *Environmental Science and Policy*, 71, 41-55. https://doi.org/10.1016/j.envsci.2017.01.008

Rosgen, D.L. (1996). *Applied river morphology*. Pagosa Springs, Colorado: Wildland Hydrology.

Sefton, C., Bronwyn, M., Melinda, L., Sandie, C. (2020). Hydrological summary for the United Kingdom: February 2020. Wallingford, UK: UK Centre for Ecology and Hydrology, 12pp. (UKCEH Project no. C04954) Available at: http://nora.nerc.ac.uk/id/eprint/527499/ (Accessed: 2nd January 2021).

Shuttleworth, E.L., Evans, M.G., Pilkington, M., Spencer, T., Walker, J., Milledge, D., Allott, T.E.H. (2019). Restoration of blanket peat moorland delays stormflow from hillslopes and reduces peak discharge. *Journal of Hydrology X, 2, 100006.* https://doi.org/10.1016/j.hydroa.2018.100006

Simon, P., Barker, L., Sefton, C., Hannaford, J., Turner, S., Muchan, K., … Pennington, C. (2020). *Briefing Note: Severity of the February 2020 floods -- preliminary analysis.* Wallingford, UK: UK Centre for Ecology and Hydrology, 8pp Available at: https://nrfa.ceh.ac.uk/sites/default/files/Briefing_Note_V6.pdf (Accessed: 2nd January 2021).

Sivapalan, M. (2018). From engineering hydrology to Earth system science: milestones in the transformation of hydrologic science. *Hydrology and Earth System Science*. 22, 1665 – 1693. https://doi.org/10.5194/hess-2017-670-AC3

Spreitzer, G., Tunnicliffe, J., Friedrich, H. (2019). Using Structure from Motion photogrammetry to assess large wood (LW) accumulations in the field. *Geomorphology*, 346, 106851. https://doi.org/10.1016/j.geomorph.2019.106851

The Flood Reinsurance (Scheme Funding and Administration) Regulations. (2015). Available at: https://www.legislation.gov.uk/ukdsi/2015/9780111137307/contents (Accessed: 2nd January 2021).

The Water Act (2014). C. 5. Available at: https://www.legislation.gov.uk/ukpga/2014/21/contents/enacted (Accessed: 2nd January 2021).

Thomas, H., Nisbet, T. (2020) Assessing the Decay and Integrity of Timber Structures used for Natural Flood Management. Forest Research Paper (Forestry Commission). Available at: https://www.forestresearch.gov.uk/research/can-forestry-reduce-flooding/assessing-decay-and-integrity-timber-structures-used-natural-flood-management/ (Accessed: 13th April 2021).

Thorne, C. (2014). Geographies of UK flooding in 2013/2014. *The Geographical Journal,* 180, 297-309. https://doi.org/10.1111/geoj.12122

United Nations. (2019). Nature-Based Solutions for Climate. United Nations Environment Programme. Available at: https://www.unenvironment.org/nature-based-solutions-climate (Accessed: 29th December 2020).

United Nations. (2020). The United Nations World Water Development Report 2020: Water and Climate Change. Paris: UNESCO. Available at: https://www.unwater.org/publications/world-water-development-report-2020/ (Accessed: 29th December 2020).

Wainwright, J., Turnbull, L., Ibrahim, T.G., Lexartza-Artza, I., Thornton, S.F., Brazier, R.E. (2011). Linking environmental regimes, space and time: Interpretations of structural and functional connectivity. *Geomorphology*, 126, 387-404. http://dx.doi.org/10.1016/j.geomorph.2010.07.027

Waylen, K.A., Holstead, K.L., Colley, K., Hopkins, J. (2017). Challenges to enabling and implementing Natural Flood Management in Scotland. *Journal of Flood Risk Management,* 11, 1-12. https://doi.org/10.1111/jfr3.12301

Werritty, A. (2006). Sustainable flood management: oxymoron or new paradigm?. *Area,* 38, 16-23. https://doi.org/10.1111/j.1475-4762.2006.00658.x

Wentworth, J., Ermgassen, S. Z. (2020). Natural Mitigation of Flood Risk. POST Note: 623. Available at: https://post.parliament.uk/research-briefings/post-pn-0623/#:~:text=NFM%20is%20an%20approach%20to,landscape%20features%20to%20reduce%20flooding.&text=NFM%20can%20help%20mitigate%20the,flood%20risk%20for%20smaller%20communities (Accessed: 29th December 2020).

Wilby, R., Dadson, S (2020). ‘Natural’ flood management would be overwhelmed by Britain’s winter super-floods. The Conversation. Available at: https://theconversation.com/natural-flood-management-would-be-overwhelmed-by-britains-winter-super-floods-132150 (Accessed: 29th December 2020).

Wilkinson, M.E., Quinn, P.F., Welton, P. (2010). Runoff management during the September 2008 floods in the Belford catchment, Northumberland. *Journal of Flood Risk Management*, 3, 285-295. https://doi.org/10.1111/j.1753-318X.2010.01078.x

Wilson, L., Wilson, J., Holden, J., Johnstone, I., Armstrong, A., Morris, M., (2011). The impact of drain blocking on an upland blanket bog during storm and drought events, and the importance of sampling-scale. *Journal of Hydrology*, 404, 198-208. https://doi.org/10.1016/j.jhydrol.2011.04.030

Wingfield, T., Macdonald, N., Peters, K., Spees, J., Potter, K. (2019). Natural Flood Management: Beyond the evidence debate. *Area*. 51, 743-751. https://doi.org/10.1111/area.12535

WWAP (United Nations World Water Assessment Programme)/UN-Water. (2018). *Nature-Based solutions for water:* WWDR 2018. UNESCO. http://unesdoc.unesco.org/images/0026/002614/261424e.pdf (Accessed: 29th December 2020).

Xu, Y., Liu, X. (2017). Effects of Different In-Stream Structure Representations in Computational Fluid Dynamics Models—Taking Engineered Log Jams (ELJ) as an Example. *Water*. 9, 110. https://doi.org/10.3390/w9020110

Zhen-Fu, F., (1987) On the Distribution and Origin of Salix in the World. *Journal of Systematics and Evolution*, 25(4): 307-313.

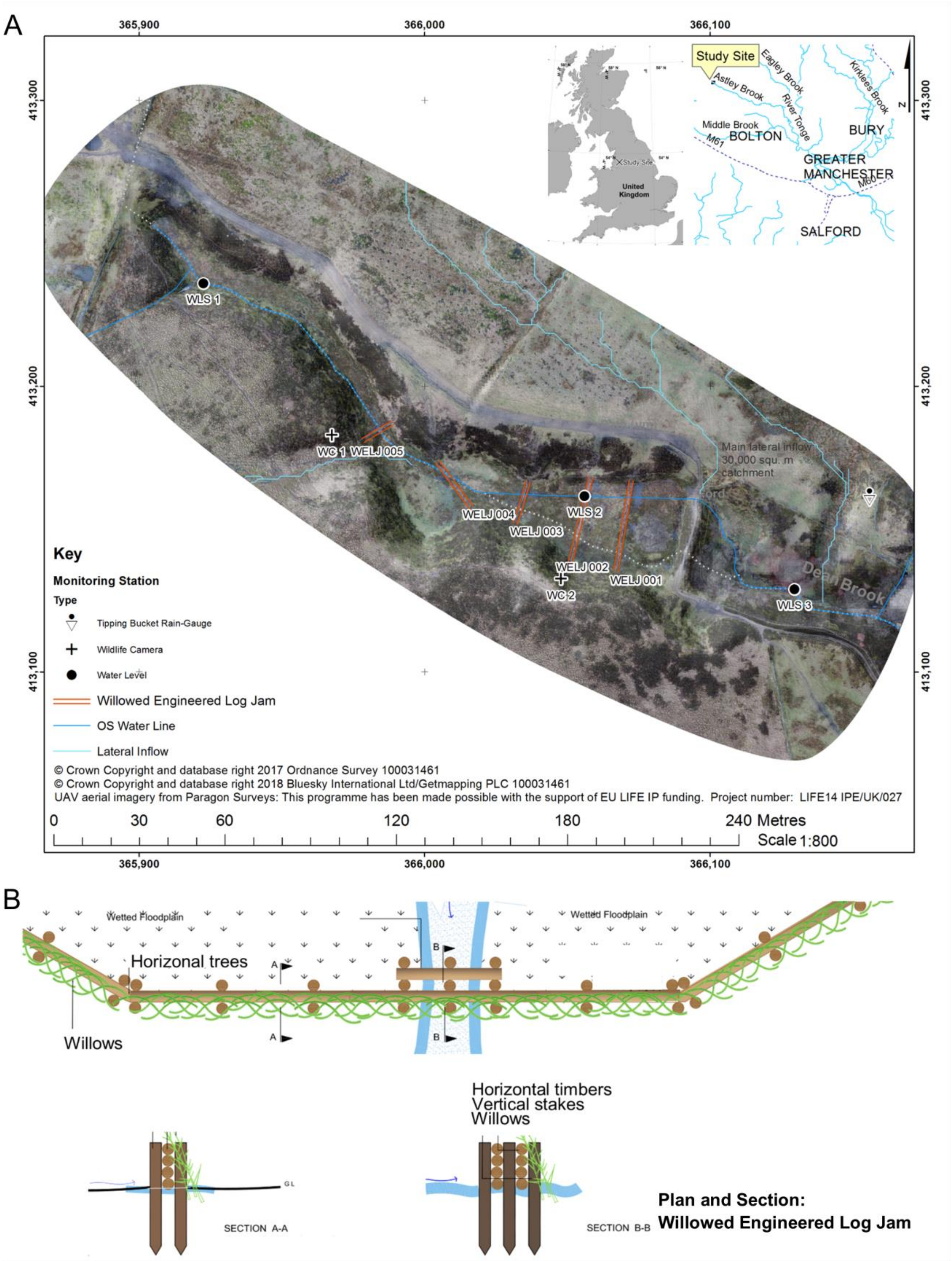

**Figure 1:** A) Two Lads study site map showing location of monitoring equipment in relation to WELJs; B) engineering schematic cross section of the WELJ.

**Figure 2:** A) Two Lads Study Site Photographs Prior to WELJ installation; B) the site following WELJ installation

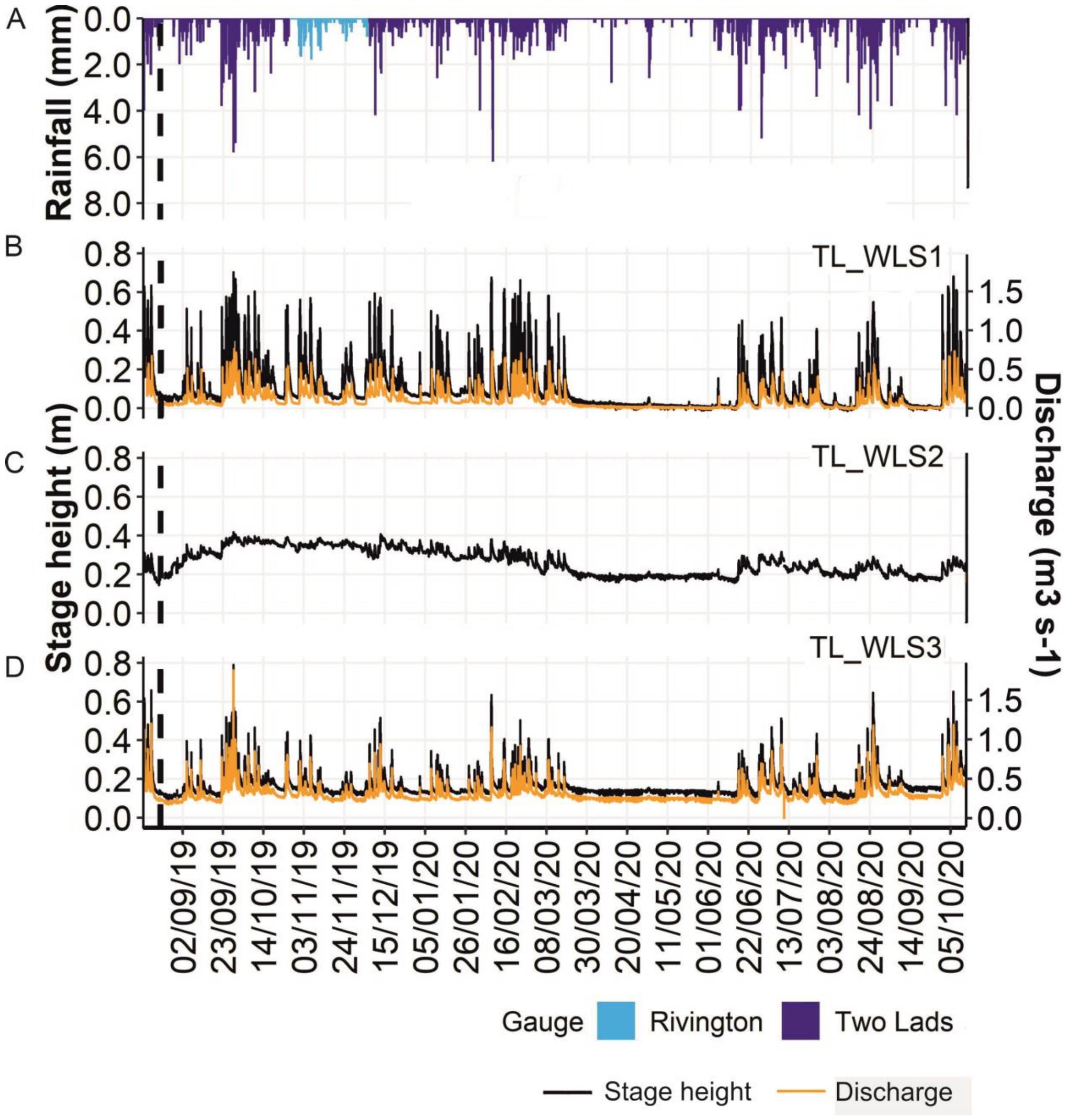

**Figure 3:** A) Daily precipitation at the Two Lads rain gauge and Rivington meteorological station; B) continuous water levels for WLS1 (08/08/2019 - 02/10/2020); C) WLS (08/08/2019 - 02/10/2020); and, D) WLS3 (08/08/2019 - 02/10/2020). The dashed vertical line marks the installation of the five WELJ (19-30 August 2019).

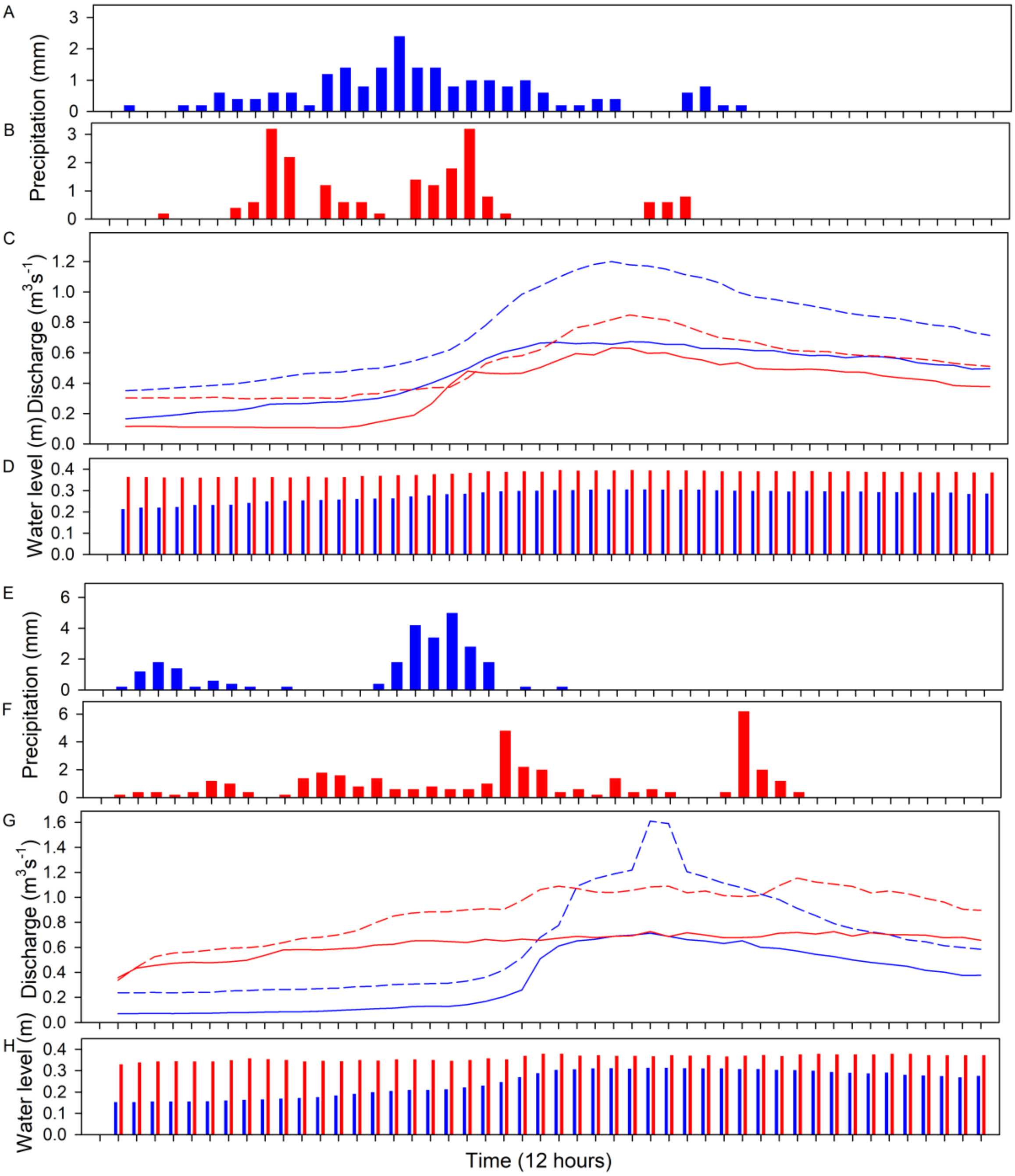

**Figure 4:** Comparison of similar magnitude pre- and post-WELJ installation 12-hour events, A) precipitation (10:00-22:00 16/08/2019, blue), B) precipitation 05:00-17:00 09/10/2019, red), C) respective hydrographs at WLS1 (solid) and WLS3$^{adj}$ (dashed) for the two events (a-b), D) comparative water levels in WELJ002 from WLS2 for each event; E) precipitation (05:00-17:00 09/08/2019, blue), F) precipitation 02:00-14:00 02/09/2020, red), G) respective hydrographs at WLS1 (solid) and WLS3$^{adj}$ (dashed) for the two events, and H) comparative water levels in WELJ002 from WLS2 for each event (E-F).

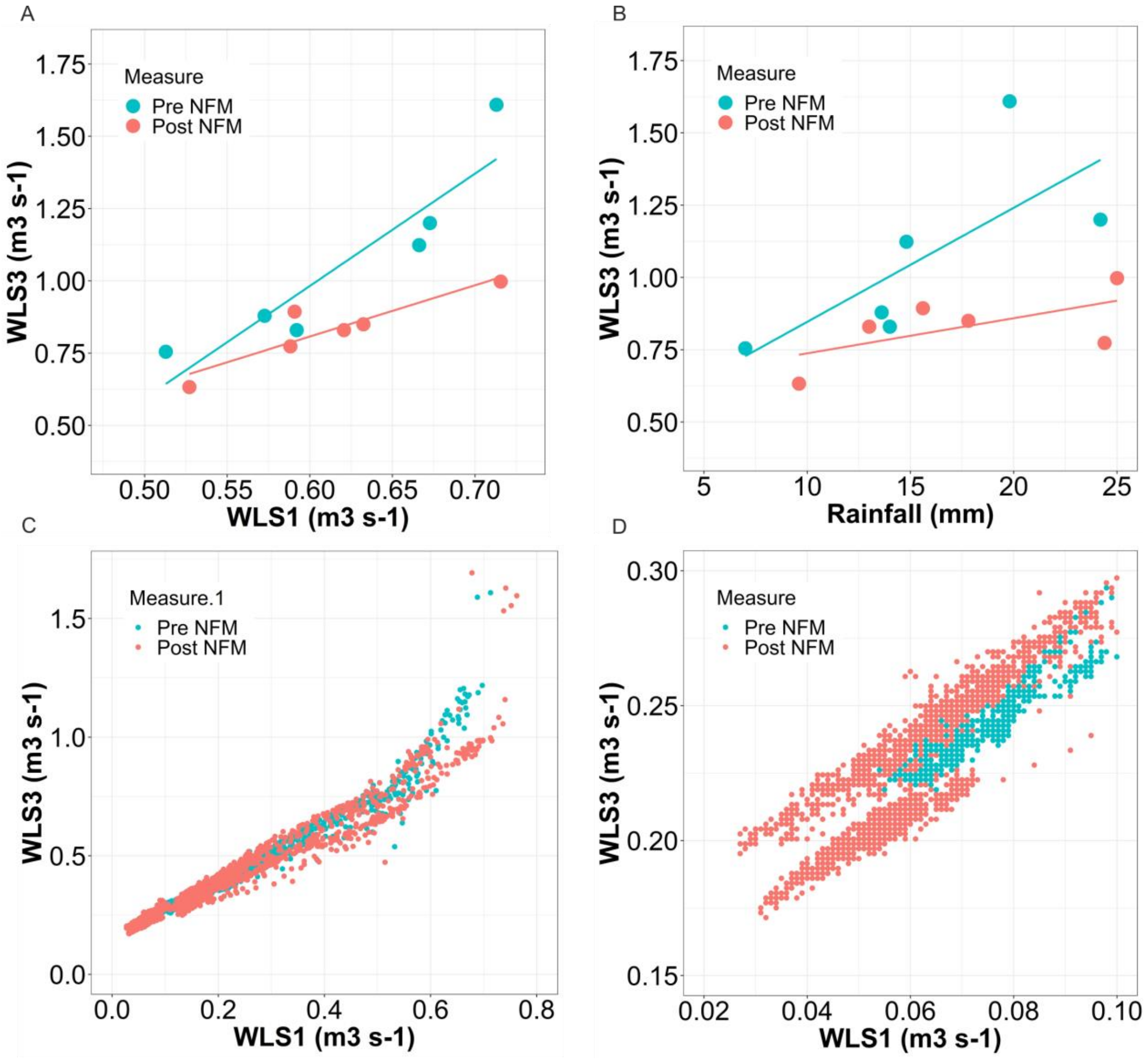

**Figure 5:** A) Peak inflow (WLS1) compared to peak outflow (WLS3) for comparable precipitation events (>10 mm per 0.25 hours) pre- (08/08/2019 - 18/08/2019) and post-WELJ installation (30/09/2020 - 10/10/2020); B) Total rainfall and peak discharge at WLS3 for comparable rainfall events pre- and-post WELJ installation; C); pre- and post-discharge relationship between inflow (WLS1) and outflow (WLS3); and, D) comparison of baseflow events (<0.1 m$^3$s$^{-1}$ @WLS1) between WLS1 and WLS3 for pre- and post-WELJ installation.

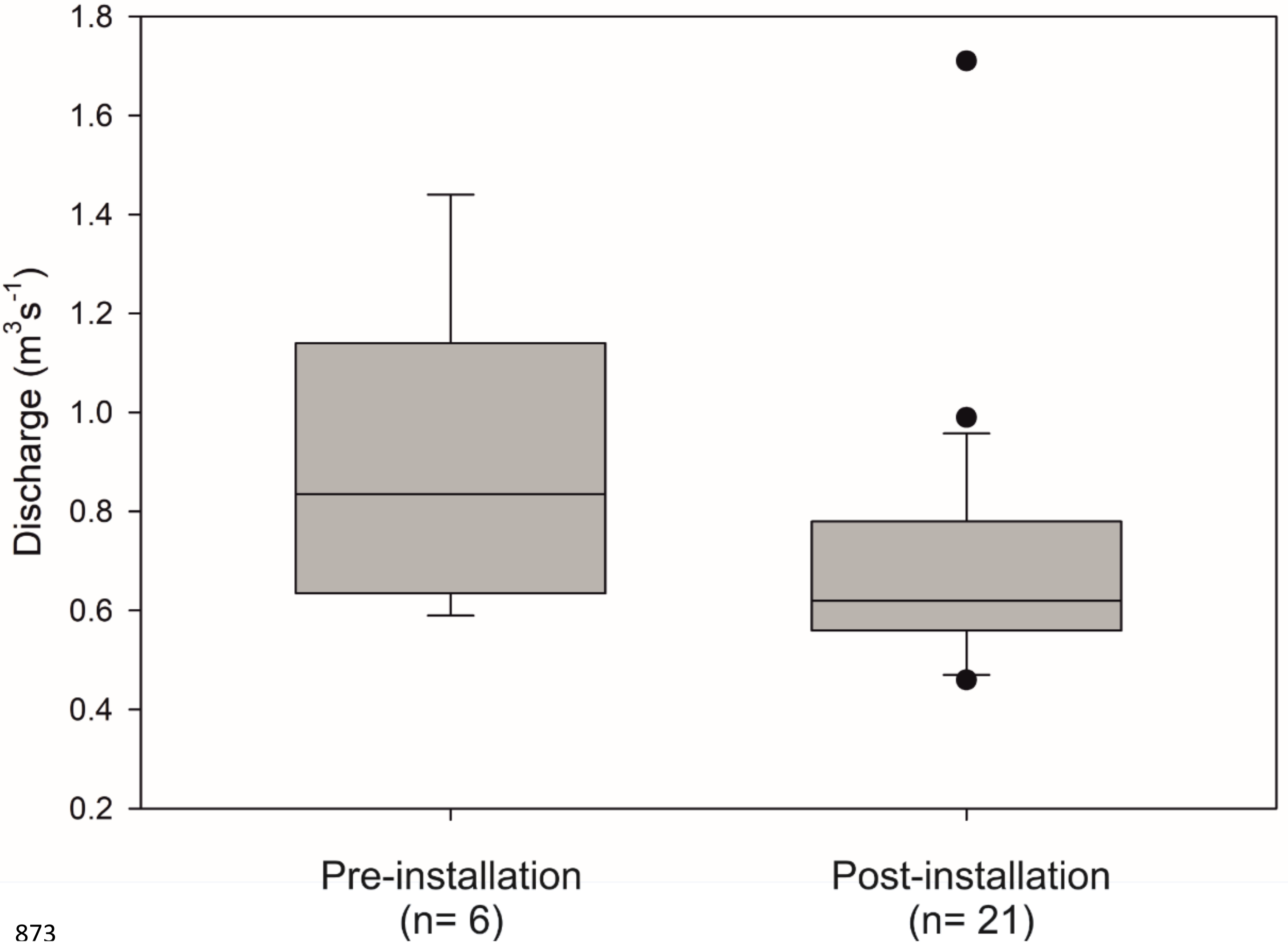

**Figure 6:** WLS3$^{adj}$ discharge pre- (08/08/2019-21/08/2019) and post- (22/08/2019-16/02/2020) installation for events where WLS1 >0.5 m$^3$s$^{-1}$ and events precipitation >7.5mm hr$^{-1}$.

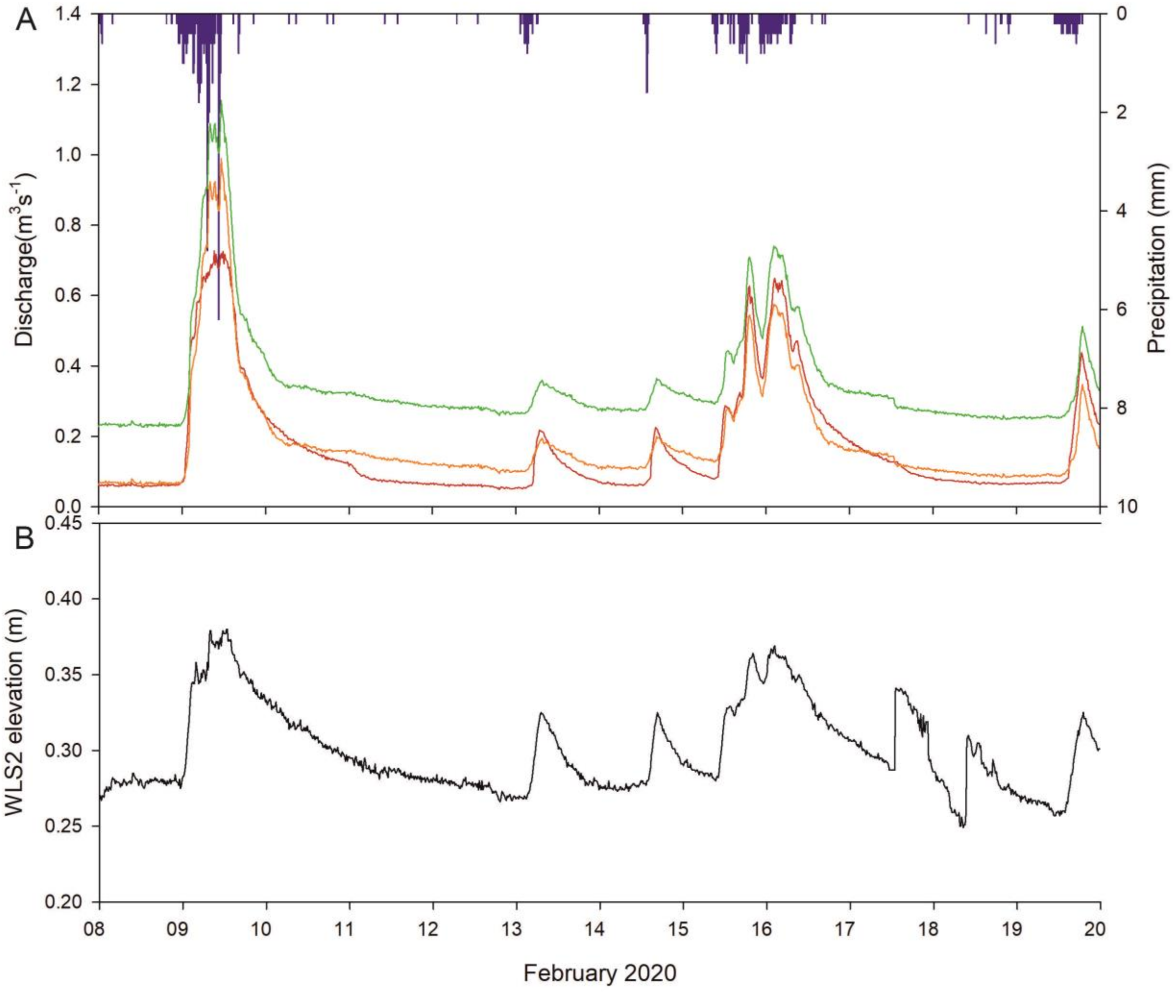

**Figure 7:** A) Precipitation (blue) and discharges at WLS1 (red) and WLS3 (green) respectively for storms Ciara and Dennis during February 2020 (15min resolution), WLS3$^{adj.}$ (where minimum baseflow is removed 0.165 m$^3$s$^{-1}$; gold) provided to aid comparison; B) water level within WELJ2 at WLS2 (15 min resolution).

**Table 1:** Comparison of differing events pre- and post-WELJ installation, where WLS1 $>0.5 m^3s^{-1}$ and events precipitation >7.5mm. Storm Ciara and Dennis data highlighted.

| **Date** | **Precipitation (mm)** | **WLS1** | **WLS2** | **WLS3$^{adj}$** | **Percentage change between WLS1 and WLS3$^{adj}$** |
|---|---|---|---|---|---|
| | | **($m^3s^{-1}$)** | **($m^3s^{-1}$)** | **($m^3s^{-1}$)** | |
| **Pre-installation** | | | | | |
| **09-08-19** | 19.8 | 0.71 | 0.31 | 1.44 | 102.6 |
| **10-08-19** | 14.2 | 0.59 | 0.31 | 0.65 | 10.5 |
| **11-08-19** | 7.6 | 0.5 | 0.3 | 0.59 | 17.2 |
| **13-08-19** | 14.8 | 0.67 | 0.31 | 0.96 | 43.9 |
| **14-08-19** | 13.6 | 0.57 | 0.3 | 0.71 | 24.7 |
| **16-08-19** | 24.2 | 0.67 | 0.31 | 1.04 | 53.9 |
| **Post-installation** | | | | | |
| **04-09-19** | 8.6 | 0.52 | 0.35 | 0.56 | 7.5 |
| **11-09-19** | 8.6 | 0.5 | 0.34 | 0.57 | 13.7 |
| **22-09-19** | 18.8 | 0.53 | 0.37 | 0.61 | 15.1 |
| **24-09-19** | 12.6 | 0.6 | 0.39 | 0.78 | 30.6 |
| **26-09-19** | 15 | 0.59 | 0.39 | 0.62 | 5.4 |
| **27-09-19** | 21.4 | 0.61 | 0.4 | 0.83 | 34.7 |
| **28-09-19** | 33.6 | 0.76 | 0.42 | 1.71 | 124.8 |
| **29-09-19** | 24.8 | 0.72 | 0.4 | 0.83 | 16.4 |
| **06-10-19** | 18 | 0.6 | 0.4 | 0.63 | 4.3 |
| **09-10-19** | 17.6 | 0.63 | 0.4 | 0.68 | 8.3 |
| **26-10-19** | 20.6 | 0.54 | 0.39 | 0.64 | 18.4 |
| **01-11-19** | 10.4 | 0.58 | 0.36 | 0.56 | -2.8 |
| **07-11-19** | 24.4 | 0.59 | 0.37 | 0.61 | 3.4 |
| **08-12-19** | 11.2 | 0.56 | 0.36 | 0.53 | -6.5 |
| **10-12-19** | 15 | 0.62 | 0.35 | 0.66 | 7.1 |
| **12-12-19** | 10.4 | 0.53 | 0.35 | 0.47 | -11.2 |
| **13-12-19** | 15.8 | 0.59 | 0.41 | 0.78 | 31.4 |
| **19-12-19** | 8 | 0.51 | 0.38 | 0.47 | -6.5 |
| **09-01-20** | 11.8 | 0.5 | 0.37 | 0.46 | -8 |
| **09-02-20** | 46.2 | 0.73 | 0.38 | 0.99 | 36.3 |
| **16-02-20** | 11.6 | 0.65 | 0.37 | 0.58 | -11.4 |
| **Storm Ciara** | **46.2** | **0.72** | **1.15** | **0.99** | **27** |
| **Storm Dennis** | **11.2** | **0.65** | **0.74** | **0.58** | **-4.3** |

## Supplementary Material

Video SM1: An Un-crewed Aerial Vehicle (UAV) fly through the Willowed Engineered Log Jams (WELJs) at two lads, accessible at: https://www.youtube.com/watch?v=1gyfPbp4I_Y

Figure SM2: A) Catchment map of the natural flood management measures and location of the Smithills Community at flood risk, accessible at: https://themerseyforest.sharefile.com/d-sfb38c2cbc03543be9b1f82cd0aa76a16, B) An interactive edition of the map in A, accessible at:https://www.arcgis.com/apps/MapSeries/index.html?appid=5086d50ee3bc49f1bd25b039c7129c1a (Under: NFM Asset Map, Smithills area nr, Bolton, N.W. England)

Figure SM3: Wildlife camera series for 28th September 07:30 – 30th September 12:30 event, demonstrating inundation and attenuation with multiple channel belting, downloadable at: https://themerseyforest.sharefile.com/d-sfa38519ebde9419f8b1cce17b85ef1c1

Video SM4: lateral inflow during high flow events (greater than approximately 0.5 $m^3s^{-1}$ @WLS1 as in Fig 1A), downloadable at: https://themerseyforest.sharefile.com/d-s93dfa13ee83e4355accc23189e364e5e