



24 **Highlights**

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

30

31 - **Abstract**

32 Nature Based Solutions (NBS), including Natural Flood Management (NFM) schemes are  
33 becoming an important component of many governmental and organisation responses to  
34 increases in flood and aridity risk. NFM structures may take multiple forms to slow, store,  
35 disconnect and filter distributed overland flow pathways within a catchment that coalesce to  
36 generate a flood-wave downstream and runoff rather than infiltrate groundwaters. To date  
37 few studies have conducted observations pre- and post-installation monitoring at river reach-  
38 scales, despite widespread and frequent installation, to investigate the efficacy of willowed  
39 engineered log jams (WELJs) interventions used in abating flood-flows, through backing-up  
40 flood-pulses with consequent reductions in downstream discharges. This paper examines  
41 the efficiency, before and after installation of five 1 metre high WELJs incorporating 1,000  
42 Bay willow (*Salix pentandra*) saplings supporting the dead horizontal timber, across a total of  
43 130 linear metres spanning the floodplain of a decommissioned reservoir. One rain gauge,  
44 two fixed point time-lapse wildlife cameras and three water level stations were installed:  
45 upstream-of; within, and downstream-of all WELJs. The findings demonstrate a substantial  
46 reduction is achieved for most events, with an average of 27.3% reduction in peak discharge  
47 being achieved post-installation. The time to peak is little impacted, however there is  
48 demonstrable evidence of a longer and higher recessional limb to the events. These findings  
49 quantify for the first time the role that WELJs can play in a move towards re-naturalisation of  
50 water level regimes, with lower peak water flows achieved, and waters released from the  
51 river-reach more slowly. Furthermore, baseflow during dry periods is also elevated by  
52 27.1%, offering greater resilience to dry periods and droughts. Consequently, over the river-  
53 reach scale (0-130 m), WELJs play an important role in alleviating flood and drought risk  
54 through suppressing flood peaks and increasing baseflow during low flows; steps towards  
55 improved hydro-morphological quality overall.

56 **Keywords**

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





## 85 1.2. Natural Flood Management in practice

86 In the UK, current and future flood risks are being compounded by a combination of climate  
87 and land use change; with peak runoff flows being observed to increase at a rate of over 5%  
88 per decade, while 10% of new homes are being built in areas of significant flood risk – land  
89 with a  $\leq 1:100$ -year probability of flooding (Putro *et al.*, 2016; DEFRA, 2018; Blöschl *et al.*,  
90 2019; Ministry of Housing, Communities and Local Government, 2020). Studies have  
91 highlighted how some 12,200 km<sup>2</sup> of UK land is at risk of flooding, including 1 in 6 properties,  
92 which in total implicates circa 5 million people (Hall *et al.*, 2003; Environment Agency, 2009;  
93 House of Commons, 2016). Climate change and land use scenarios predict that flood risk  
94 will increase in real terms; in frequency, magnitude and effect (Committee on Climate  
95 Change, 2012; House of Commons, 2016). A family of scenarios for: climate change impact;  
96 long-term increasing development on the floodplain (Committee on Climate Change, 2012);  
97 and increasingly impermeable catchments will cumulatively result in more property exposure  
98 to flood risk from increasingly flashy watercourses, with impaired groundwater recharge (Hut  
99 *et al.*, 2008; Kendon *et al.*, 2014; Putro *et al.*, 2016). The Department for Environment, Food  
100 and Rural Affairs' (DEFRA) 'Making Space for Water' (2004) approach has been trialled in  
101 several places on an *ad hoc* basis for some time (Burgess-Gamble *et al.*, 2017; Nicholson *et*  
102 *al.*, 2020). In the UK 4,185 NFM assets have been created with woody leaky barriers make  
103 up 69% of all measures (JBA Trust, 2020; DEFRA, 2021A). To-date, a dearth of pre-  
104 installation observations exist that would permit a pre- and post-installation assessment to  
105 be undertaken (Arnott *et al.*, 2018). Ellis *et al.*, (2021) provide a useful empirical scale-based  
106 assessment of NFM data to date, whilst Black *et al.*, (2020) observes catchment-scale lags  
107 of 2.6 – 7.3 hours where leaky woody structures and other measures occurred. As Leakey *et*  
108 *al.*, (2020:1) observe these “barriers have been implemented widely, there is still resistance  
109 to their use at the scales required to impact significantly on flood risk, at least partially due to  
110 an evidence gap”. Consequently, since modelling and evidence is the basis to much NFM  
111 development, without a determination of the impact on observed flows and levels, which can

112 be used to calibrate models (Hankin *et al.*, 2016; 2017), many schemes may not progress.  
113 This paper addresses this research and understanding gap, by demonstrating reach scale  
114 level and discharge change, for both floods and low flows (see Hut *et al.*, 2008).

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

133

### 134 1.3. **Natural Flood Management**

135 Where practiced, NFM often seeks to address quick-flow/direct runoff propagation. NFM  
136 techniques are defined as the alteration, restoration of use of landscape features to spatially  
137 engineer measures to slow, store, disconnect and filter river and overland flows in sufficient  
138 volume to alleviate downstream flood risk (Wilkinson *et al.*, 2010; Burgess-Gamble *et al.*,

139 2017). NFM draws upon multiple sets of expertise including natural scientists, hydrologists,  
140 engineers, and social scientists, combined with knowledge from local communities (Bark *et*  
141 *al.*, 2021). Proponents of this holistic and often partnership-based approach advocate that  
142 “These practices could be taken up more widely in the UK, and internationally, to manage  
143 floods, droughts and pollution” (Quinn *et al.*, 2016:1). Yet despite wide advocacy of the multi-  
144 function benefits to the natural and human worlds, Wingfield *et al.* (2019) note the lack of  
145 widespread adoption could reflect a focus on research and resources aimed at increasing  
146 the evidence base; a lengthy and complex goal, if NFM is not holistically applied at the  
147 catchment-scale. Furthermore, the Agricultural Act of 2020 which is in its implementation  
148 phase via UK Environmental Land Management schemes (DEFRA, 2021B) will, in the fu-  
149 ture, allow funding of a wider-range of public ecosystem service actions, including NFM  
150 (Holstead *et al.*, 2014; Green Alliance, 2017).

151

#### 152 **1.4. The Runoff Attenuation Feature (RAF) approach**

153 Natural flood management encompasses a gamut of measures, including tree planting,  
154 peatland, agricultural soil and river restoration techniques. One approach focused on  
155 addressing rapid rainfall-to-runoff responses, or flashiness, is through Runoff Attenuation  
156 Features (RAFs) (after Nicholson *et al.*, 2012). The hydrological premise is that, if a sufficient  
157 number of features are deployed around a river catchment, targeting multiple sources and  
158 pathways of quick-flow, then runoff can be attenuated at numerous spatial-scales, diffusing  
159 and retaining the tributary flood-pulses, before they coalesce to create peak flow  
160 synchronicities, and hence, flood the urban receptor (Wilkinson *et al.*, 2010; Nicholson *et al.*,  
161 2012; Figure 1 in Norbury *et al.*, 2019). Whilst the wider gamut of NFM techniques offer  
162 multi-functional benefits (e.g., Burgess-Gamble *et al.*, 2017), the ability to indicatively  
163 quantify their efficacy in business case terms is often problematic (Hankin *et al.*, 2017).  
164 Many communities at flood risk are covered by hydraulic models which can be assessed to  
165 determine return period spill volume over bank into floodplain and dwellings (Norbury *et al.*,

166 2019). This floodplain spill volume can then become a catchment attenuation requirement  
167 above the community at flood risk, and hence, RAFs which can be monitored readily and  
168 volumetrically calculated, individually or as a collectively across a catchment, and frequently  
169 present a best available technique to alleviate risk (Nicholson *et al.*, 2012; Hankin *et al.*,  
170 2017:4; Norbury *et al.*, 2019).

171 Areas characterised by intense drainage density, over-grazing and high livestock densities,  
172 soil compaction, and steepness of slope, are commonplace in many uplands, sites prime for  
173 RAFs (Bracken and Croke 2007; Wilkinson *et al.*, 2010; Marshall *et al.*, 2014). RAFs are  
174 interventions that alter pluvial and fluvial pathways; physically restricting the passing-forward  
175 of downstream flood-flow, and hence, reduce peak runoff and velocity, but convey baseflow  
176 (Wilkinson *et al.*, 2010; Nicholson *et al.*, 2012). RAFs can include drained earth and stone  
177 bunds (~embankments), ditches often perpendicular to the watercourse, attenuation ponds  
178 and scrapes, excavations of pluvial hollows or floodplains, leaky barriers, including live  
179 willowed log jams or sawn treated timber barriers and woodland planting (Wilkinson *et al.*,  
180 2010; Nicholson *et al.*, 2012; Burgess-Gamble *et al.*, 2017). The physical backing-up of  
181 water by these measures, for temporary periods, often 0 – 80 hrs (storm dependant), also  
182 results in increased infiltration and probable groundwater recharge (Hut *et al.*, 2008;  
183 Wilkinson *et al.*, 2010; Wainwright *et al.*, 2011; Norbury *et al.*, 2020). RAFS fall into two  
184 categories: offline, which attenuate water off the floodplain and online which holds water on  
185 the floodplain (Nicholson *et al.*, 2012).

186 One of the most cost-effective and frequently used measures is the introduction of willowed  
187 log jams in the upper and middle reaches of a catchment, such interventions intercept  
188 propagating flood-waves heading down-channel and attenuate floodwater behind the dam  
189 on floodplains (Burgess-Gamble *et al.*, 2017; Muhawenimana *et al.*, 2021). Willowed  
190 engineered log jams often consist of tree trunks, 2.5 times stream-width keyed into the  
191 riverbanks to allow sufficient passage of base flow through the obstruction, then during high-  
192 flows the logs trap and attenuate water behind the log-jam. To avoid bypass, willow-woven

193 trunks can be planted across the floodplain perpendicular to flow. Planting behind the logs  
194 makes the structure a living bio-filter, resilient to movement and increases structural stability  
195 and longevity.

196

## 197 **2.0. Methodology**

### 198 **2.1. Study Site: Two Lads and the Woodland Trusts Smithills Estate, Bolton**

199 Recognising the need to trial NFM, the UK Government launched a fund for bids to deliver  
200 £15m of NFM from 2017 – 2021 (Wentworth *et al.*, 2020). Locally, the Environment Agency  
201 opened-up a £1m competition, and following a bid from the Woodland Trust, the Smithills  
202 Estate was successful in a partnership project with the Environment Agency to deliver a  
203 NFM project starting in 2019. The focus was predominantly on capital interventions over  
204 detailed monitoring. Two Lads was one of 11 locations selected to site 44 NFM installations  
205 on the Woodland Trust's Smithills Estate, and it is part of a wider programme of NFM  
206 interventions regionally. The study site is a headwater stream of Dean Brook, a tributary of  
207 the River Irwell which discharges to the Mersey (Figure 1, 2 and Video SM1). Dean Brook is  
208 situated above Smithills, Bolton, in the northwest of England, and rises at approximately 456  
209 meters on the peatlands of Winter Hill. The site consists of peat sitting on a coarse-grained  
210 feldspathic sandstone, except in incised sections which have an alluvium bed. At its rural  
211 source, Dean Brook flows off the West Pennine Moor Site of Special Scientific Interest, via  
212 an extensive grip network, into the Clough Woodlands and Dean Brook before reaching  
213 Smithills, a suburb of Bolton, Greater Manchester. The settlement at Smithills is at flood risk,  
214 with 12,300 m<sup>3</sup> of water predicted to spill into the floodplain during a 1 in 100-year event,  
215 potentially affecting 53 properties (Figure SM2; See Hankin *et al.*, 2017:4 and Norbury *et al.*,  
216 2019 for flood volume appraisal techniques). Smithills Estate is being used to trial a range of  
217 landscape-scale restoration techniques, including re-wilding, led by the Woodland Trust see  
218 Bridges *et al.*, (2021:180) for further background.

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

232

## 233 **2.2. Pre-installation monitoring: apparatus and methodology**

234 A decommissioned reservoir presents an opportune site to attenuate flood-flow, as they are  
235 often flat and wide, hence relatively short structures may retain a large volume of water  
236 compared to a steeply incised landscape-setting (See Case Study 17 in Burgess-Gamble *et*  
237 *al.*, 2017 and Norbury *et al.*, 2020 for example efficacy; Video SM1 and 2). On 8<sup>th</sup> August  
238 2019 three water level stations (WLS1-3) were installed across five willowed engineered log  
239 jams (WELJ001-005). WLS1 was situated 85m upstream of the final WELJ (005) and  
240 beyond the attenuation area, WLS2 was installed within the area of inundation behind the  
241 second to last log jam (WELJ002) and WLS3 was placed 100 linear metres downstream of  
242 all log jams (Figure 1A). An EML ARG 3 rain-gauge was discretely installed 90m to the NE of  
243 the WELJs (not visible from the footpath that runs adject to the site), a Tempcon HOBO  
244 U20L-04 atmospheric pressure logger was placed adjacent to WLS3 and two Crenova  
245 wildlife cameras were installed looking downstream over the log jams WELJ001-4 and the

246 second provides a side view of WELJ002 (Figure 1A). Typical level accuracy is at  $\pm 0.1\%$  or  
247 4 mm and for rainfall it is above the 99% confidence level up to  $120\text{mm hr}^{-1}$ . Together these  
248 instruments served to provide simultaneous 15-minute precipitation (mm) and water level  
249 (m) data along with hourly time-lapsed photos of the willowed log jams. HOBO pressure  
250 loggers were hung in a perforated stilling well situated at the base of the entrenched  
251 channels; an atmospheric pressure logger served to compensate the water level loggers  
252 using Tempcons Hoboware software. Additional precipitation data has been accessed from  
253 the Environment Agency (EA), with the nearest meteorological station situated at Lower  
254 Rivington (Stn. Num. 569723,  $53^{\circ}36'15.5''\text{N}$ ,  $2^{\circ}33'32.2''\text{W}$ ), annual average precipitation  
255 1,174.5 mm (1981-2010), <5km away from the Two Lads site and provides quality control  
256 and supplemental data. The EA rain-gauge has been used to infill missing precipitation data  
257 arising from a technical fault on the Two Lads rain-gauge (28<sup>th</sup> Oct. - 7<sup>th</sup> Dec. 2019; Figure  
258 1A).

259

### 260 **2.3. Willowed engineered log jam interventions**

261 Specialist contractors started and completed the five willowed log jam build between August  
262 21<sup>st</sup> – 30<sup>th</sup> 2019, with a total length of 130 linear metres (Figure 1, 2 and Video SM1), offering  
263 a total attenuation capacity of  $\sim 3,000\text{ m}^3$  across the suite of WELJs, with increasing capacity  
264 moving downstream. Figure 1B provides a schematisation of the WELJs, these are  
265 horizontal felled timbers, staked front and back every two linear metres with strainer posts ( $\Sigma$   
266 = 103) bay willow (*Salix pentandra*) planted at 8 per linear metre ( $\Sigma = 1,040$ ), to create a  
267 living thicket of live shrubs. In total, 54 tonnes of locally sustainably harvested timber was  
268 used in the WELJs, approximately 130 stems of whole tree at 9m L and 300mm maximum  
269 diameter. The timber was a mixture of native, European and North American softwoods  
270 including Scots- (*Pinus sylvestris*), Logepole- (*Pinus contorta*) and Corsican pine (*Pinus*  
271 *nigra*) derived from thinning from Burnt Edge legacy plantation inappropriately located on dry  
272 heathland ( $53^{\circ}36'26''\text{N}$ ,  $002^{\circ}30'02''\text{W}$ ). Since not all log jams are created equal (Dixon

273 2015A, 2015B); WELJs advance the longevity and structural performance compared to  
274 conventional log jams. The use of willow to create a thicket both, holds-up the horizontal  
275 deadwoods which are set to heavily decayed by 2029 (Burgess-Gamble *et al.*, 2017; Dixon  
276 *et al.*, 2018; Thomas and Nisbet, 2020) and provides immediate resource to add to the  
277 horizontal timber (Figure 1B). In stacking timbers, as the horizontals saturate and descend  
278 into the floodplain, those horizontals on top in the stack provide a continued vertical barrier  
279 to attenuate a head of water. A new plantation of broadleaves nearby, can be sustainably  
280 harvested to do this, also (Figure 1A).

281

#### 282 **2.4. Post installation monitoring**

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

297

298

299 **3.0. Results**

300 **3.1. Rainfall-runoff analysis**

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

312 Analysis of comparable isolated events, where precipitation and discharges exceeded 7.5  
313 mm hr<sup>-1</sup> and 0.5 m<sup>3</sup>s<sup>-1</sup>, indicates a reduction in water level at WLS3 relative to WLS1  
314 (Figures 4A-H), with greater reductions in water level for higher magnitude precipitation  
315 events (Figure 4C-D, G-H). Comparison of events under comparable catchment antecedent  
316 conditions demonstrates a similar pattern (10:00-22:00 16/08/2019 compared to 05:00-17:00  
317 09/10/2019), with a reduction in water level and discharge achieved at WLS3 post-WELJ  
318 installation relative to pre-installation (Figure 3; Figure 4C). Lateral inflow was observed  
319 (Figure 1A; Video SM4) and spot gauging estimated at 0.2 m<sup>3</sup>s<sup>-1</sup>, an equivalent the 27%  
320 higher flow noted during Storm Ciara. The lag time pre- and post-WELJ installation is  
321 typically around 135 minutes from peak precipitation to peak discharge at WLS1, with no  
322 discernible difference in the timing peak precipitation and peak flow pre- and post-WELJ  
323 installation. The efficiency of the WELJs during the two events are demonstrated by Figure  
324 4D and 4H (also see supplementary material SM3), which demonstrate the elevated water  
325 levels present in WELJ002 throughout the period of analysis, with a higher base water level

326 retained in the installation during the winter months, with a return to pre-installation levels  
327 only during dry periods (Figure 4C).

328

### 329 **3.2. Comparable pre- and post- engineered log jam hydrographs**

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

340 Analysis of a series of precipitation events ( $>7.5 \text{ mm hr}^{-1}$ ) and associated peak discharges at  
341 WLS1 ( $>0.5 \text{ m}^3\text{s}^{-1}$ ) and WLS3 pre- and post- installation identifies an average reduction in  
342 peak discharge of 27.3% across the river-reach at a range of event sizes (Table 1). Pre-  
343 installation events across the river-reach witness percentage change differences between a  
344 10.5-102.6% increase, with an average of +42.1%; whereas post-installation sees a  
345 percentage change of -11.4-124.8%, with an average of +14.8% (Table 1; Figure 6). The  
346 reduction of 27.3% typically equates to a reduction of  $\sim 0.2 \text{ m}^3\text{s}^{-1}$  on peak flows at WLS3<sup>adj</sup>  
347 (Figure 6).

348

### 349 **3.3. February 2020 flooding: storm Ciara and Dennis hydrography**

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

352 10<sup>th</sup> Feb. 2020) and Dennis (15-16<sup>th</sup> Feb. 2020) (Figure 7). Storms Ciara and Dennis brought  
353 intense and prolonged rainfall to northern England in February 2020, with North West  
354 England experiencing 321% on its 1981-2010 long-term February average and recording the  
355 wettest February on record since 1910 (Sefton *et al.*, 2020; Simon *et al.*, 2020). Three  
356 people died in storm-related incidents with 3,000 properties flooded, more flood warnings  
357 and alerts were issued across the UK within a 24hr (16<sup>th</sup> Feb.) period since records began  
358 (2006-present; (*ibid*). Close inspection of storm Ciara reveals a double rainfall peak, which  
359 coalesced into a single peak in water level/discharge (Figure 7A). The hydrograph structures  
360 through the log jam structures (WELJ002, WLS2) and after the log jams (WLS3<sup>adj</sup>) show a  
361 delaying in peak and attenuation of the flow against the inflow (WLS1, Figure 7 A-B). No  
362 identifiable reduction in peak discharge is achieved during storm Ciara (percentage change  
363 increase of 27%), in part arising from lateral inflow along the footpath during the intense  
364 precipitation phase (see supplementary material SM4), which exacerbates peak discharge at  
365 WLS3 relative to discharges at WLS1 and WLS2 (Table 1). Elevated discharges are  
366 identified in the recessional limb, with WLS3<sup>adj</sup> demonstrating higher discharges compared to  
367 WLS1, with the shape of the recessional limb reflecting that of the water level recorded at  
368 WLS2. However, it is notable that the water level in WLS2 does increase and the  
369 photographic evidence indicates water retention was occurring during storm Ciara, even if no  
370 discernible reduction in peak flow is documented at WLS3.

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

377 The different hydrograph responses to the two events suggest that the WELJs had a greater  
378 attenuation role during storm Dennis compared to Ciara, likely reflecting the lower intensity

379 more prolonged nature of the precipitation, though for both events the peak was reduced  
380 with storage and attenuation evident in WELJ002 (Figure 7). Whilst the cameras captured  
381 both events, images are of relatively poor quality because of poor visibility at the site, with  
382 storm Dennis floodwaters peaking at night. With continued monitoring a larger sample of  
383 higher-magnitude events will improve understanding of peak flow through the WELJs and  
384 provide a clearer depiction of the reductions afforded during peak flows.

385

## 386 **4.0. Discussion**

### 387 **4.1. Reach-scale flow regime change**

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

405 based on ratings derived from repeat spot gauging at sites WLS1 and WLS3, with all level  
406 data (pre- and post-instillation) converted to discharge.

407 WELJs enable assisted natural recovery (Burgess-Gamble *et al.*, 2017) of the reach with  
408 consequent process change discerned from time-lapse photos, from degradation and  
409 narrowing to widening and aggradation, which in time will lead to an anastomosing wet  
410 woodland (stage a stage 0 channel) as the WELJs separate single channel belts into  
411 multiple channels (Figure 2 and Video SM1; Dixon, 2015A, 2015B; Burgess-Gamble *et al.*,  
412 2017; Dixon *et al.*, 2018; Norbury *et al.*, 2020).

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

421 As a comparison to reach-scale discharge reductions presented here, Dixon *et al.* (2016)  
422 determined that restoring riparian forest cover over 20-40% of catchment area reduced flood  
423 peak magnitude by up to 19%, yet restoration can take 25+ years to introduce large woody  
424 debris into the channel sufficient to effect runoff rates. The physical morphology of the  
425 channel will evolve to a more naturalised state, but the physical properties of the WELJ  
426 structure will adjust through time, likely increasing flood-flow trapping efficiency (Section  
427 2.3). The growth of the willow, and coppicing of it, will lead to increase trunk diameter over  
428 the 1,080 whips, plus self-seeding, will increase the WELJ blockage and hydraulic  
429 roughness, particularly during summer foliation. This is predicted to enhance the trapping of  
430 peak flows and prolong the recessional limb which is already notable in the data (Figures 3,  
431 4 and 7). The increase in baseflow during low flow/drought events is nominal (27.1%; ~0.05

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

439

#### 440 **4.2. Future WELJ research agendas**

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

451 The exact impact of WELJs would be sensitive to site specific context, however the findings  
452 identified within this study are comparable (23-50% reduction) to those considering natural  
453 woody dams created by beavers (Puttock *et al.*, 2020), without the challenges that  
454 reintroduction brings (Auster *et al.*, 2019). The potential role of WELJs in mimicking natural  
455 processes is considerable and could be an important tool in catchment-based flood risk  
456 management that combines both hard engineering and NFM interventions as advocated by  
457 Hewett *et al* (2020). This research provides valuable additional information to the evidence

458 base for NFM adoption; however, as Wingfield *et al.* (2019) note we should continue to  
459 embrace such holistic measures in developing more resilient natural systems.

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

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

472

### 473 **4.3. Strategic flood risk alleviation**

474 Understanding the efficacy of WELJs in abating flood-flow at the reach scale is important,  
475 since to alleviate flood risk in Smithills for the 1 in 100-year event, flows over  $>13 \text{ m}^3\text{s}^{-1}$   
476 require retention in the upper catchment, corresponding to 12,300  $\text{m}^3$  of water being  
477 removed from the flood hydrograph peak, a depth reduction of 910 mm; representing 5% of  
478 the total storm discharge (Figure SM2; Hankin *et al.*, 2017; Norbury *et al.*, 2019). This is  
479 equivalent to a 19% reduction of the peak water level and hence if NFM can be exercised at  
480 sufficient scale it is hypothesized that the 1:100 year risk could be alleviated. At Smithills, the  
481 interventions at Two Lads and the other 25 locations equate to that target volume of 12, 300  
482  $\text{m}^3$ . Furthermore 65 Ha of woodland planting (130,000 trees), 60% of the river catchment,  
483 are also ongoing on the Estate. Dixon *et al.* (2016) predict that for a 20-40% catchment

484 riparian woodland uplift, a 19% catchment outlet level reduction. In combination, the  
485 downstream flood risk reduction at Smithills should be tangible. As a comparison, the  
486 Holnicote NFM project which installed 41 log jams, 5 attenuation bunds, 5 ha of woodland, 5  
487 fields of arable reversion, wet woodland and pond restoration in the 40ha catchment  
488 experienced a 10% reduction in flood peak during a 1 in 75 year event – the December 2013  
489 floods – with none of the 98 at risk properties being flooded (Case Study 20 in Burgess-  
490 Gamble *et al.*, 2017).

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

504

## 505 **5.0. Conclusion**

506 This research demonstrably identifies a 27.3% reduction in the average peak flow, with  
507 retention achieved in the WELJ structures (Figure 3). During storms Ciara and Dennis in  
508 February 2020, a comparable discharge at WLS1 to WLS3<sup>adj</sup>, is achieved during storm Ciara  
509 accounting for baseflow and lateral inflows and during storm Dennis a reduction of 4.3% in  
510 peak flow was achieved between WLS1 and WLS3<sup>adj</sup>. Whilst these present modest

511 reductions in peak flow, they represent a small sample, further high-magnitude events will  
512 enhance understanding of WELJ capacity to reduce peak flows during high magnitude  
513 events. Generally, discharges between precipitation events are increased with installations  
514 slowly releasing waters long after flood-waves have passed, suggesting WELJs can play a  
515 role in increased water residence. The impact of these five WELS is more than holding water  
516 in the landscape for longer, with the effect of more naturalised flow regimes, slower more  
517 sluggish water over flashier flows and reduced flood peaks. Together the findings  
518 demonstrate the role these measures can play in flood and drought alleviation objectives as  
519 guided by legislation.

520

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535 **Contributions**

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

546

547 **Conflicts of Interests**

548 There are no conflicts of interest.

549 **Data Access**

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

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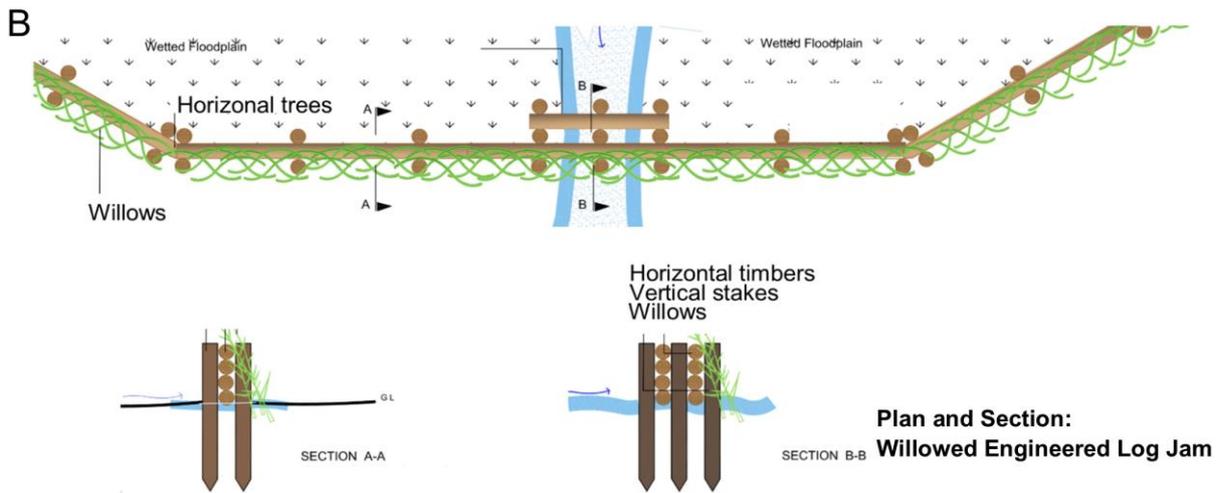
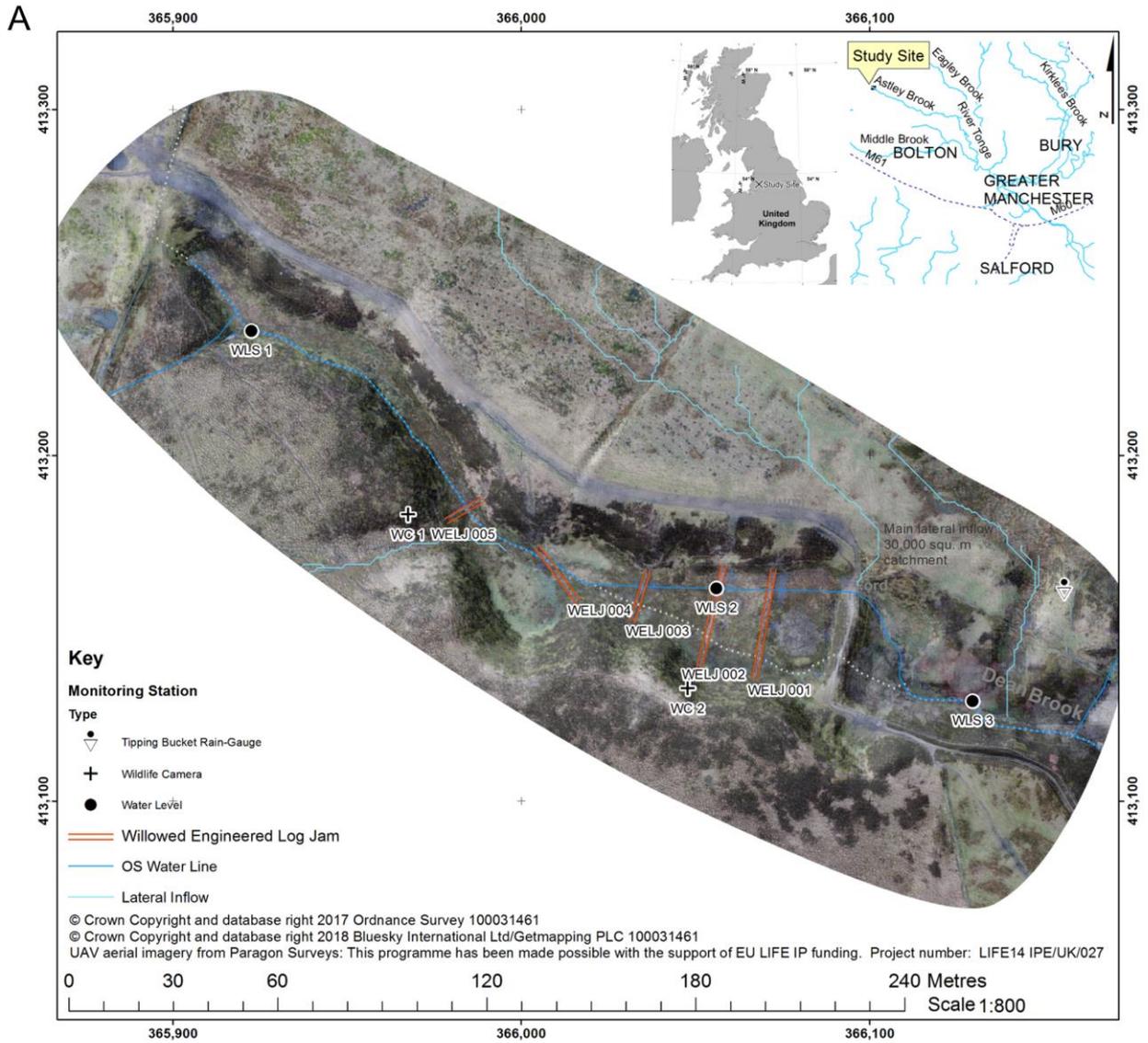
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**Figure 1:** A) Two Lads study site map showing location of monitoring equipment in relation to WELJs; B) engineering schematic cross section of the WELJ.

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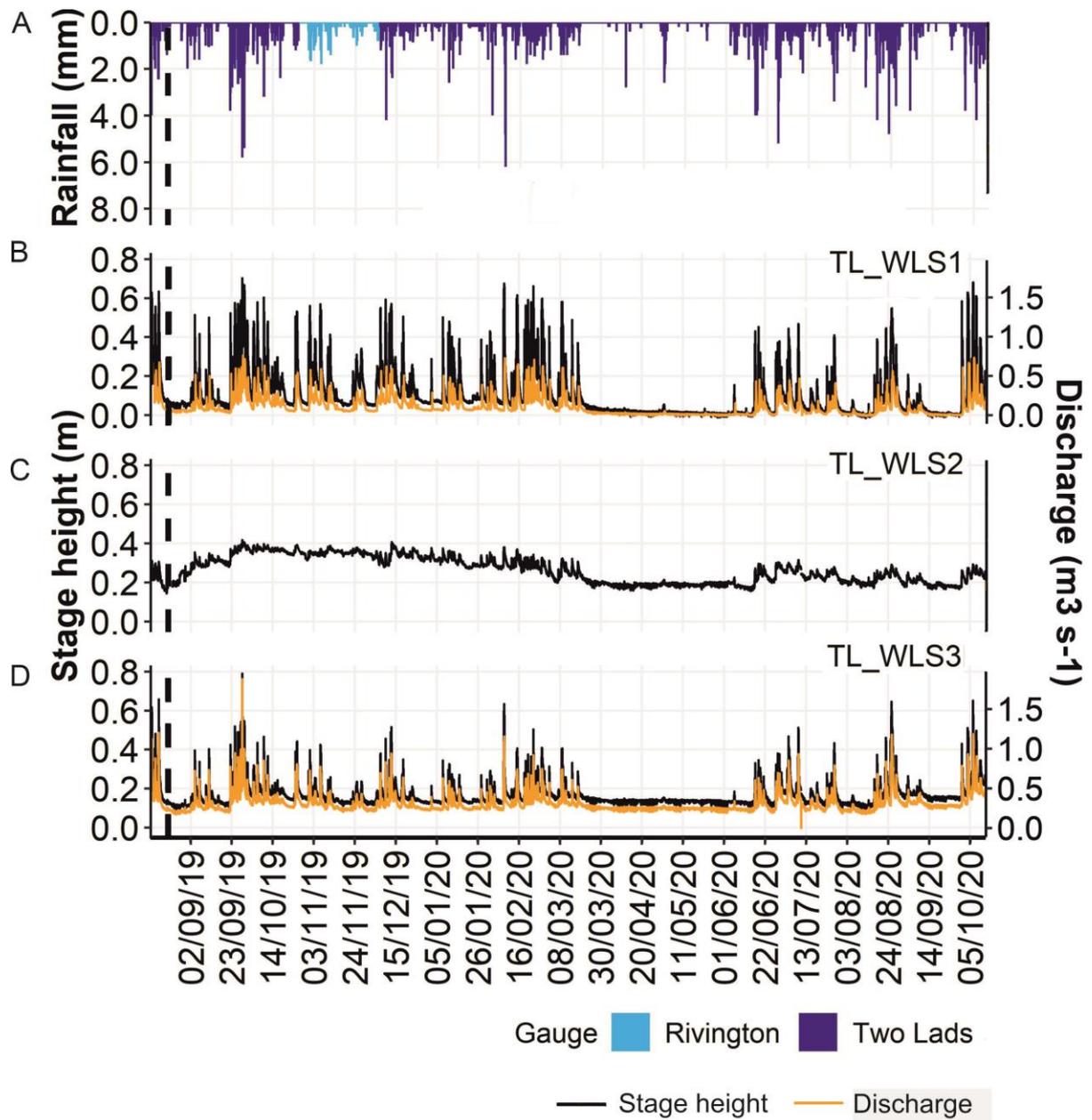


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824 **Figure 2:** A) Two Lads Study Site Photographs Prior to WELJ installation; B) the site follow-  
825 ing WELJ installation

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828 **Figure 3:** A) Daily precipitation at the Two Lads rain gauge and Rivington meteorological  
 829 station; B) continuous water levels for WLS1 (08/08/2019 - 02/10/2020); C) WLS  
 830 (08/08/2019 - 02/10/2020); and, D) WLS3 (08/08/2019 - 02/10/2020). The dashed vertical  
 831 line marks the installation of the five WELJ (19-30 August 2019).

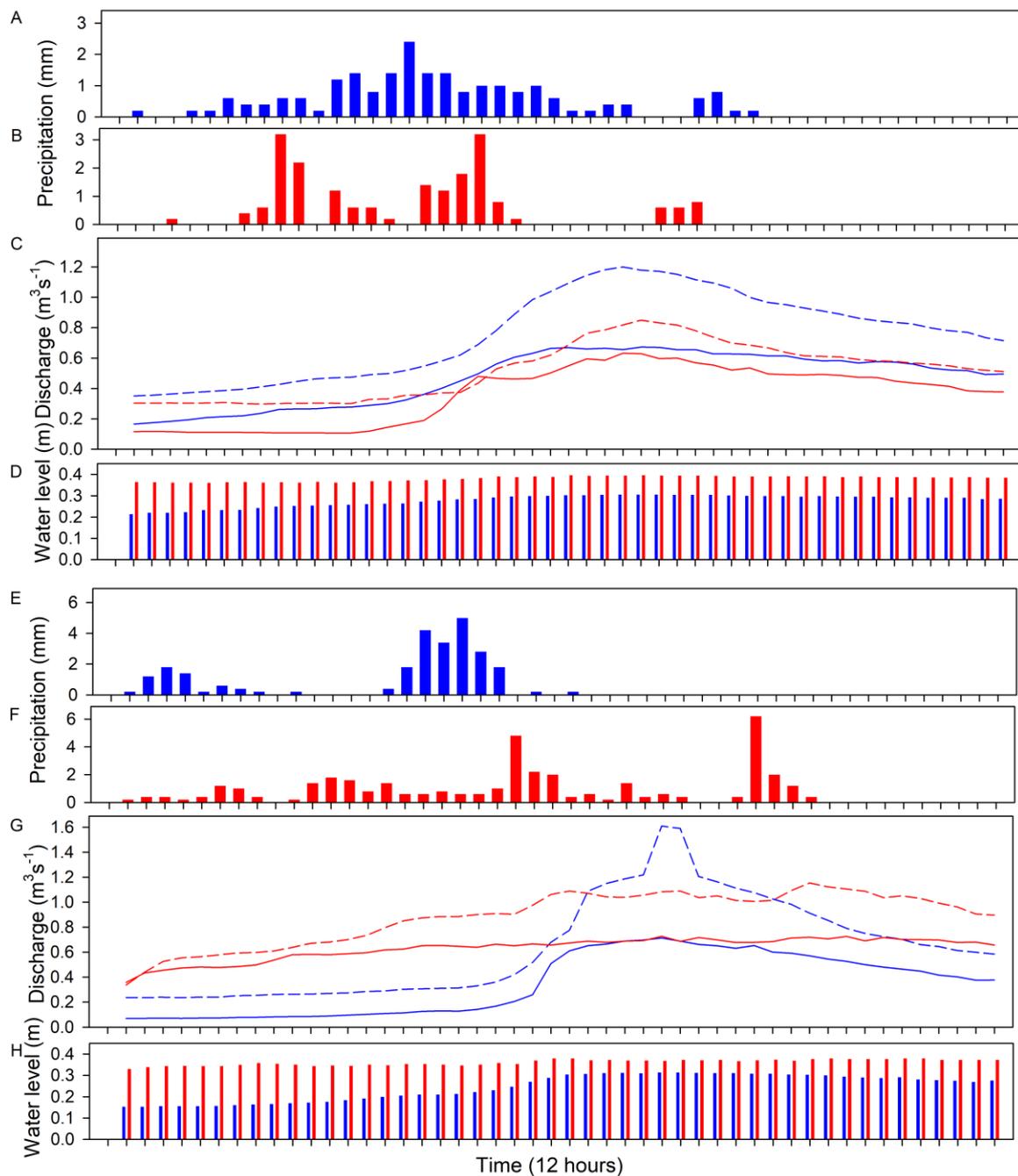
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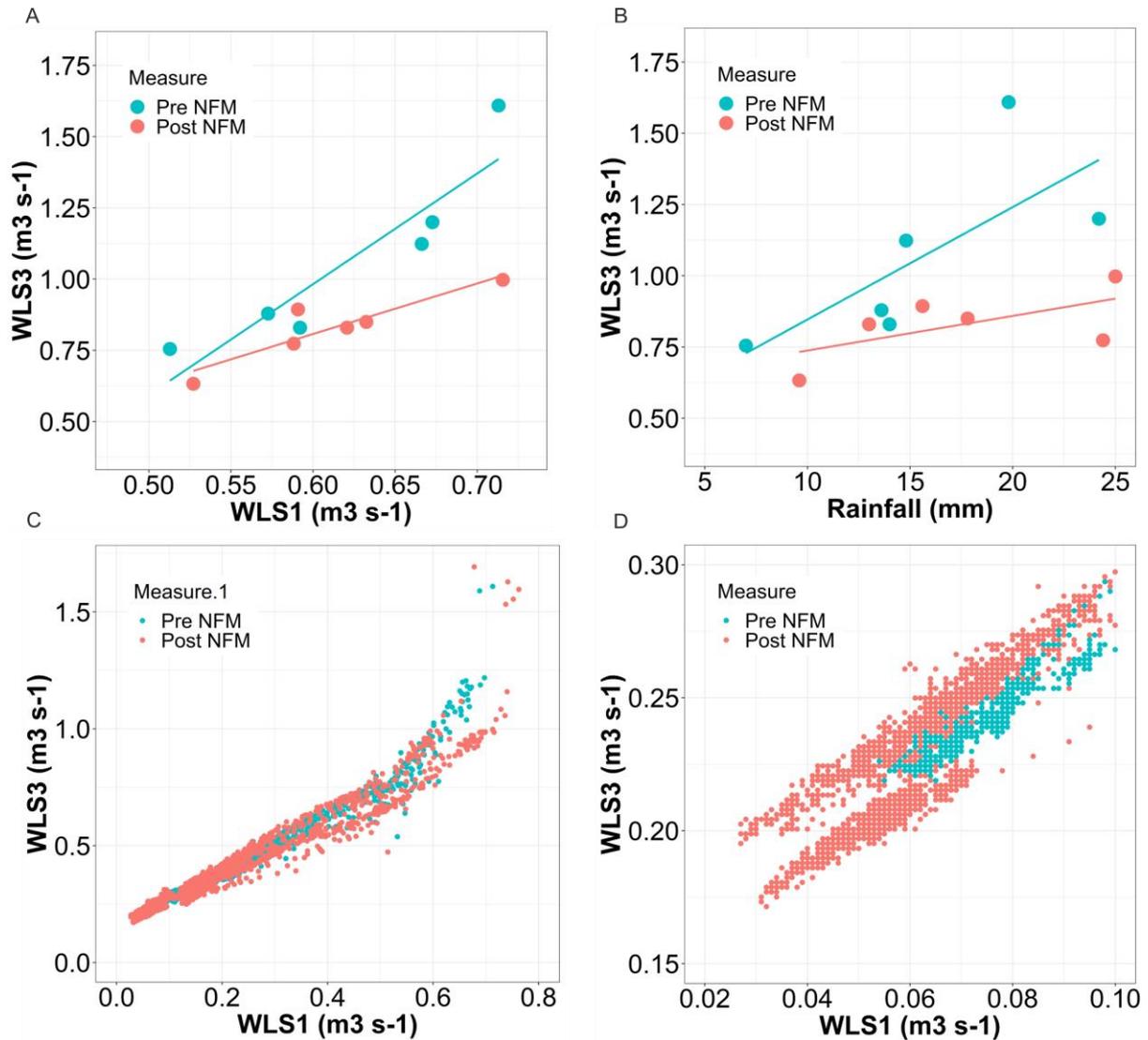
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 838 **Figure 4:** Comparison of similar magnitude pre- and post-WELJ installation 12-hour events,  
 839 A) precipitation (10:00-22:00 16/08/2019, blue), B) precipitation 05:00-17:00 09/10/2019,  
 840 red), C) respective hydrographs at WLS1 (solid) and WLS3<sup>adj</sup> (dashed) for the two events (a-  
 841 b), D) comparative water levels in WELJ002 from WLS2 for each event; E) precipitation  
 842 (05:00-17:00 09/08/2019, blue), F) precipitation 02:00-14:00 02/09/2020, red), G) respective  
 843 hydrographs at WLS1 (solid) and WLS3<sup>adj</sup> (dashed) for the two events, and H) comparative  
 844 water levels in WELJ002 from WLS2 for each event (E-F).

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

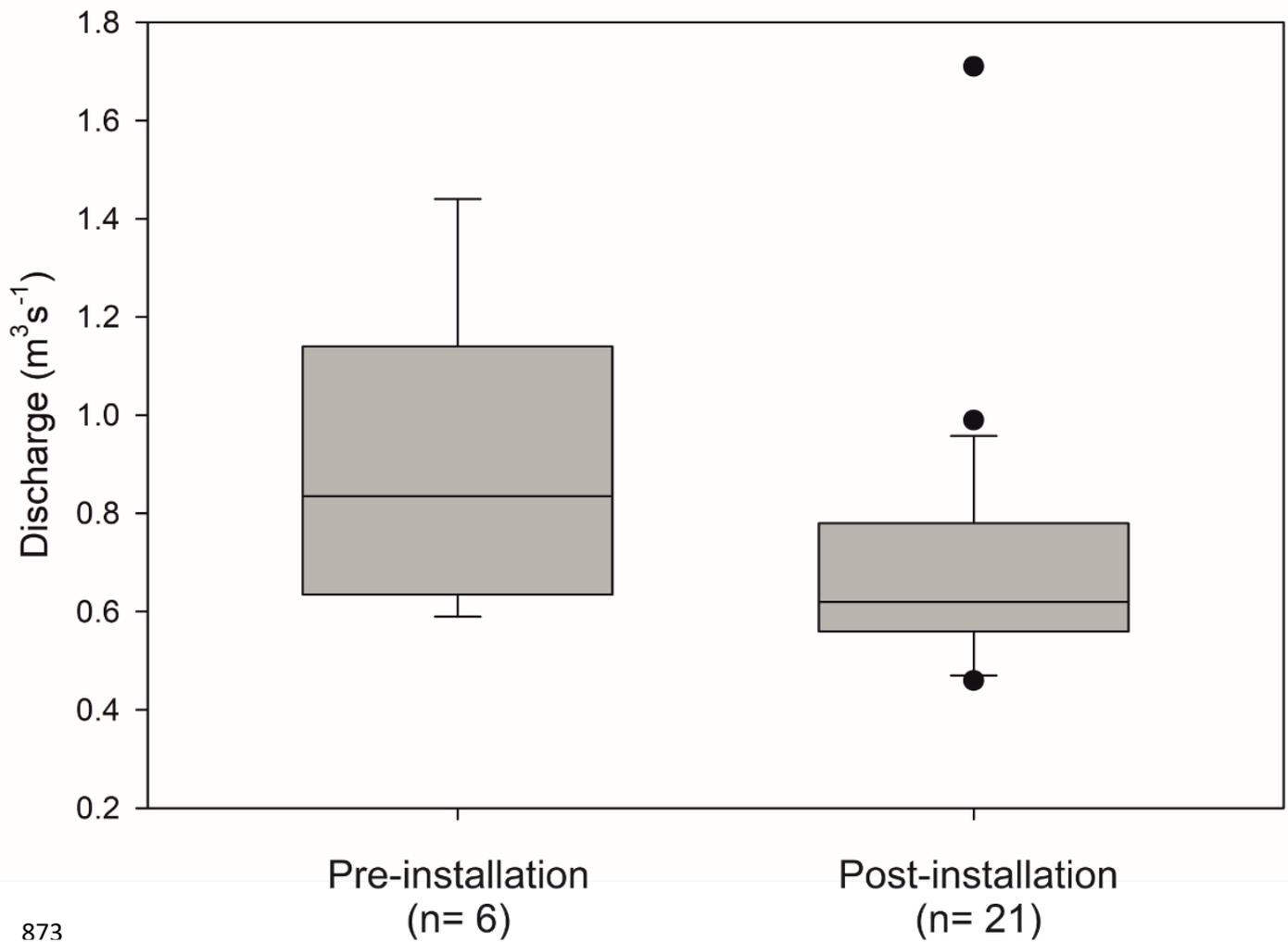
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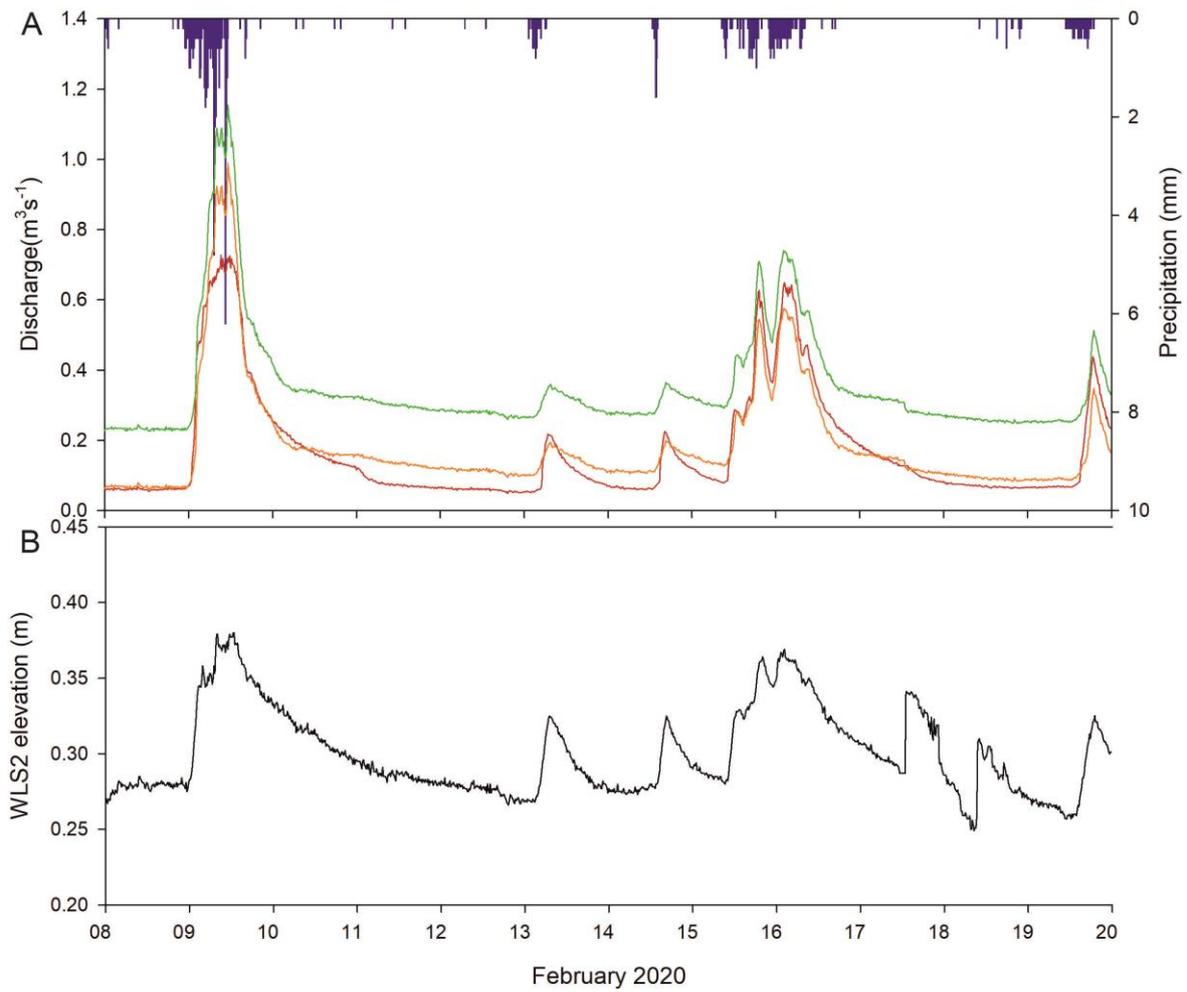
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874 **Figure 6:** WLS3<sup>adj</sup> discharge pre- (08/08/2019-21/08/2019) and post- (22/08/2019-  
875 16/02/2020) installation for events where WLS1  $>0.5 \text{ m}^3 \text{ s}^{-1}$  and events precipitation  $>7.5 \text{ mm}$   
876  $\text{hr}^{-1}$ .

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

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888 **Table 1:** Comparison of differing events pre- and post-WELJ installation, where WLS1  
 889  $>0.5\text{m}^3\text{s}^{-1}$  and events precipitation  $>7.5\text{mm}$ . Storm Ciara and Dennis data highlighted.

Date	Precipitation (mm)	WLS1  ( $\text{m}^3\text{s}^{-1}$ )	WLS2  ( $\text{m}^3\text{s}^{-1}$ )	WLS3 <sup>adj</sup>  ( $\text{m}^3\text{s}^{-1}$ )	Percentage change between WLS1 and WLS3 <sup>adj</sup>
<b>Pre-installation</b>					
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
<b>Post-installation</b>					
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
<b>Storm Ciara</b>	<b>46.2</b>	<b>0.72</b>	<b>1.15</b>	<b>0.99</b>	<b>27</b>
<b>Storm Dennis</b>	<b>11.2</b>	<b>0.65</b>	<b>0.74</b>	<b>0.58</b>	<b>-4.3</b>

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891 **Supplementary Material**

892 Video SM1: An Un-crewed Aerial Vehicle (UAV) fly through the Willowed Engineered Log  
893 Jams (WELJs) at two lads, accessible at: [https://www.youtube.com/watch?v=1gyfPbp4I\\_Y](https://www.youtube.com/watch?v=1gyfPbp4I_Y)

894 Figure SM2: A) Catchment map of the natural flood management measures and location of  
895 the Smithills Community at flood risk, accessible at: [https://themerseyforest.sharefile.com/d-](https://themerseyforest.sharefile.com/d-sfb38c2cbc03543be9b1f82cd0aa76a16)  
896 [sfb38c2cbc03543be9b1f82cd0aa76a16](https://themerseyforest.sharefile.com/d-sfb38c2cbc03543be9b1f82cd0aa76a16), B) An interactive edition of the map in A, accessible  
897 at: [https://www.arcgis.com/apps/MapSeries/index.html?appid=5086d50ee3bc49f1bd25b039c](https://www.arcgis.com/apps/MapSeries/index.html?appid=5086d50ee3bc49f1bd25b039c7129c1a)  
898 [7129c1a](https://www.arcgis.com/apps/MapSeries/index.html?appid=5086d50ee3bc49f1bd25b039c7129c1a) (Under: NFM Asset Map, Smithills area nr, Bolton, N.W. England)

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

902 Video SM4: lateral inflow during high flow events (greater than approximately 0.5 m<sup>3</sup>s<sup>-1</sup>  
903 @WLS1 as in Fig 1A), downloadable at: [https://themerseyforest.sharefile.com/d-](https://themerseyforest.sharefile.com/d-s93dfa13ee83e4355accc23189e364e5e)  
904 [s93dfa13ee83e4355accc23189e364e5e](https://themerseyforest.sharefile.com/d-s93dfa13ee83e4355accc23189e364e5e)

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