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Natural flood management, lag time and catchment scale: Results from an empirical nested catchment study

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Abstract

Natural flood management (NFM) techniques attract much interest in flood risk management science, not least because their effectiveness remains subject to considerable uncertainty, particularly at larger catchment and event scales. This derives from a paucity of empirical studies which can offer either longitudinal or comparison data sets in which changes can be observed. The Eddleston catchment study, with 13 stream gauges operated continuously over 9 years, is based on both longitudinal and comparison data sets. Two years of baseline monitoring have been followed by 7 years of further monitoring after a range of NFM interventions across the 69 km^2 catchment. This study has examined changes in lag as an index of hydrological response which avoids dependence on potentially significant uncertainties in flow data. Headwater catchments up to 26 km^2 showed significant delays in lag of 2.6–7.3 hr in catchments provided with leaky wood structures, on-line ponds and riparian planting, while larger catchments downstream and those treated with riparian planting alone did not. Two control catchments failed to show any such changes. The findings provide important evidence of the catchment scale at which NFM can be effective and suggest that effects may increase with event magnitude.

KEYWORDS

catchment scale, Eddleston, empirical analysis, lag, natural flood management

1 | INTRODUCTION

Natural flood management (NFM) aims to take advantage of and work with natural processes to reduce flood risk, whilst delivering wider improvements in environmental quality and societal benefits in river catchments. A review by Lane (2017) classifies NFM interventions as those aimed at: (a) reducing the rate of rapid runoff generation on hillslopes, for example, through land management such as tree planting to enhance infiltration (Carrick et al., 2018); (b) storage of water during high river flows, for example, through creating temporary holding ponds (Nicholson, O'Donnell, Wilkinson, & Quinn, 2020); and (c) slowing flow by reducing the ease of connection between runoff sources and zones of potential flood inundation, for example, through constructing leaky wood structures in rivers (Addy & Wilkinson, 2016).

In Scotland, interest in NFM was initially stimulated by the opportunities for a whole-catchment management approach arising from the EU Water Framework Directive (Rouillard, Ball, Heal, & Reeves, 2015; Werritty, 2006) and practically realised in the Flood Risk Management (Scotland) Act 2009 (Spray, Ball, & Rouillard, 2009). Duties relating to NFM provide some of the most interesting and innovative sections of the Act (Ball, Hendry, Werritty, & Spray, 2010): it imposes a requirement to "assess the possible contribution of alteration and so forth of natural features and characteristics" in terms of their potential to assist flood risk management. This presents a significant challenge for researchers, recognised in the recommendation of a Scottish Parliamentary Committee that "the government establish further pilot studies to assess the contribution that NFM measures can make at the catchment scale" (Spray et al., 2009).

International interest in NFM and other nature-based approaches (NBAs) has increased markedly over the past decade, driven by concerns about the impacts of climate change on increasing flood risks, potential NFM "co-benefits" such as enhanced biodiversity, pollution prevention and drought resilience, and the potential to lower the costs of flood risk management (Seddon et al., 2020; World Bank, 2018). These issues represent major challenges for countries around the world, and were recognised in the IUCN (2016) resolution defining Nature-based Solutions. Meanwhile, questions of spatial scale were identified in four of the 23 unsolved problems in hydrology, which also flagged measurements and data as obstacles to future progress (Blöschl et al., 2019).

Despite almost 20 years since the first policy moves towards NFM in the United Kingdom (Department for Environment, Food and Rural Affairs, 2004), there is still much uncertainty surrounding the effectiveness of NFM interventions, particularly in larger catchments and larger flood peaks. Limits to the extent of NFM effectiveness remain somewhat unclear; a recent statement of a now well-established position is provided by Dadson et al. (2017, p. 19) that "the larger the catchment and the larger the flood, the smaller is the scope for slowing the flood or storing the floodwater to reduce the flood hazard." Catchment heterogeneity, and the effect that this has on hydrological processes, is a general cause of uncertainty. There are also practical challenges specific to NFM, for example, in how to represent structures such as debris dams in quantitative analyses (Metcalfe, Beven, Hankin, & Lamb, 2017b). At larger catchment scales, another challenge is detecting change from multiple dispersed interventions amongst background environmental noise (Hankin, Metcalfe, Beven, & Chappell, 2019; Pattison & Lane, 2012). This is compounded by a lack of long-term monitoring—it is estimated that <6% of NFM projects in the United Kingdom have intensive hydrological monitoring (Hankin et al., 2017). Long-term monitoring is of particular value given the impact on the effectiveness of NFM over periods of years and decades of the growth in green infrastructure, the processes of erosion and deposition, and the presence or lack of maintenance.

The question of the effectiveness of NFM has been investigated using both modelling and empirical approaches. Modelling studies are much more common: there are now over 40 quantitative studies on NFM effectiveness in the United Kingdom, but over 75% of these are based on modelling and the majority of these are <50 km^2 in area (Kay, Old, Bell, Davies, & Trill, 2019). Modelling approaches often use unverified hydraulic models (using the morphology of the channels in which measures may be applied), which have the benefit that there are no costs or delays in establishing monitoring and can help directly to address questions of scaling. However, uncalibrated models lack validation with real-world data, so provide little evidence for impacts in practice. Modelling studies of NFM or other catchment-based flood management projects that are verified with monitoring data are much rarer (e.g., Wheater et al., 2008). A key constraint is the level of resources required to implement and maintain monitoring systems over long timescales at high spatial and temporal resolution. This situation is changing, with recent investments in combined modelling and empirical NFM studies, although these projects still have relatively newly established NFM interventions and short time series of monitoring data (LANDWISE, 2017; Protect-NFM, 2017; Q-NFM, 2017).

Kay et al. (2019) estimate that fewer than 25% of NFM projects give evidence of effectiveness based on observational data. These studies have typically used hydrograph analysis to investigate impacts of NFM measures, for example, through analysis of effects on peak flows, or other metrics of stream response (e.g., lag time) before and after NFM interventions, but often baseline monitoring periods are short and must be expected to lack extreme events. These projects have the advantage that they do not rely on modelling assumptions about catchment processes, although with obvious trade-offs such as the ability to generalise results for other catchments, attribution of change given measurement uncertainties and understanding impacts for the largest storm events. Given the resource requirements for implementing interventions and monitoring, empirical studies tend to be focused on smaller catchments (<20 km^2). The three empirical UK studies in catchments

>20 km^2 have found variable results relating to the effectiveness of NFM interventions (Kay et al., 2019). The River Irthing (335 km^2) study on the effects of tree planting found little evidence of change in peak flow after 20 years. The Exmoor Mires peatland restoration project (15.6–47.9 km^2) found a 33% reduction in storm flow leaving restored sites. The Pickering Beck (68 km^2) study investigating the combined effects of tree planting and storage pond creation found a 15–20% reduction in flood peak, but this finding is based mainly on analysis of one event.

These issues of scale and empirical evidence constitute two of the major ongoing challenges for NFM. This paper aims to respond to this challenge through an investigation of NFM effects on flood peak lag time (defined in Section 2.3.1 as the time delay between rainfall centroid and peak discharge) in a 69 km^2 catchment that has been subject to a range of NFM interventions coupled with 9 years of monitoring to date. The focus on lag times avoids uncertainties in obtaining accurate data for extreme high flows, which can be subject to extreme calibration uncertainties (Herschy, 1999). Lag time is strongly linked to peak discharge (Bondelid, McCuen, & Jackson, 1982; Loukas & Quick, 1996) via the underlying principle of "slowing the flow" that has been a driver of much of the interest in NFM—metrics of lag time have been used to demonstrate the effects of NFM interventions in a number of studies (Dixon, Sear, Odoni, Sykes, & Lane, 2016; Robinson, 1998; Shuttleworth et al., 2019). Such an analysis also provides a basis for thinking about the potential effects of NFM on synchronicity, which is likely to become a consideration particularly as NFM implementation is scaled up (Pattison, Lane, Hardy, & Reaney, 2014).

The analysis focuses on the Eddleston Water catchment in Scotland where extensive NFM interventions have been implemented since 2013 (Tweed Forum, 2019). An extensive monitoring network that includes 10 principal stream gauges and associated rain gauges has been in place since 2011, which enable disaggregated analysis of effects on lag times between catchments and across scales using a before-after-control-impact (BACI) design. This is also complemented by comparative analysis with control catchments, in which few changes have occurred during the monitoring period. The dataset provides a unique research platform in terms of the density of empirical observations that are available and insights into the scale of catchment at which effects can be detected. The two questions this paper seeks to address are:

1. What is the effect of NFM interventions on flood peak lag times?
2. Do effects on lag times vary according to catchment scale, event magnitude and type of intervention?

2 | METHODOLOGY

2.1 | Site description

The research was conducted in the 69 km^2 Eddleston Water catchment, a tributary of the River Tweed in the Scottish Borders, United Kingdom. The Eddleston Water flows due south and is fed by a number of small streams draining from the west, north and east from distinctly different sub-catchments (Figure 1a). The catchment is host to the Scottish Government's long-term study on the effectiveness of NFM measures to reduce flood risk to downstream communities and improve habitats for wildlife. The project is a partnership initiative led by Tweed Forum (a local non-governmental organisation), with Scottish Government, Scottish Environment Protection Agency (SEPA), University of Dundee, British Geological Survey and Scottish Borders Council. A scoping study provided ideas for potential NFM interventions, and developed a comprehensive monitoring strategy, including a detailed surface hydrological monitoring network combined with hydro-morphological, meteorological, ecological and groundwater measurement systems, providing a comprehensive baseline (Werritty et al., 2010).

2.1.1 | Physical catchment characteristics

The catchment is typical of many mid-altitude catchments in northern and western parts of the United Kingdom. The climate is temperate with a strong maritime influence, delivering mean annual precipitation of 900 mm and monthly mean temperatures of 3–13°C. Topography is varied, with elevations ranging from 180 to 600 m (Figure 1b) and median slope gradients ranging from 2° to 15° across the various gauged catchments. The underlying geology in the east includes Silurian bedrock of impermeable well-cemented, poorly sorted sandstone greywackes (Auton, 2011). However, extensive glaciation during the last glacial maximum has affected the surface geology and soil types (Figure 1a), with significant glacial till deposits in the west, and thick sand and gravel deposits in the centre of the catchment (Aitken, Lovell, Shaw, & Thomas, 1984; Auton, 2011; Ó Dochartaigh et al., 2012, 2018; Peskett et al., 2020; Sissons, 1958). Soils on steeper hillsides are typically freely-draining brown soils but towards the base of the hillslopes and in the west soils comprise sequences of

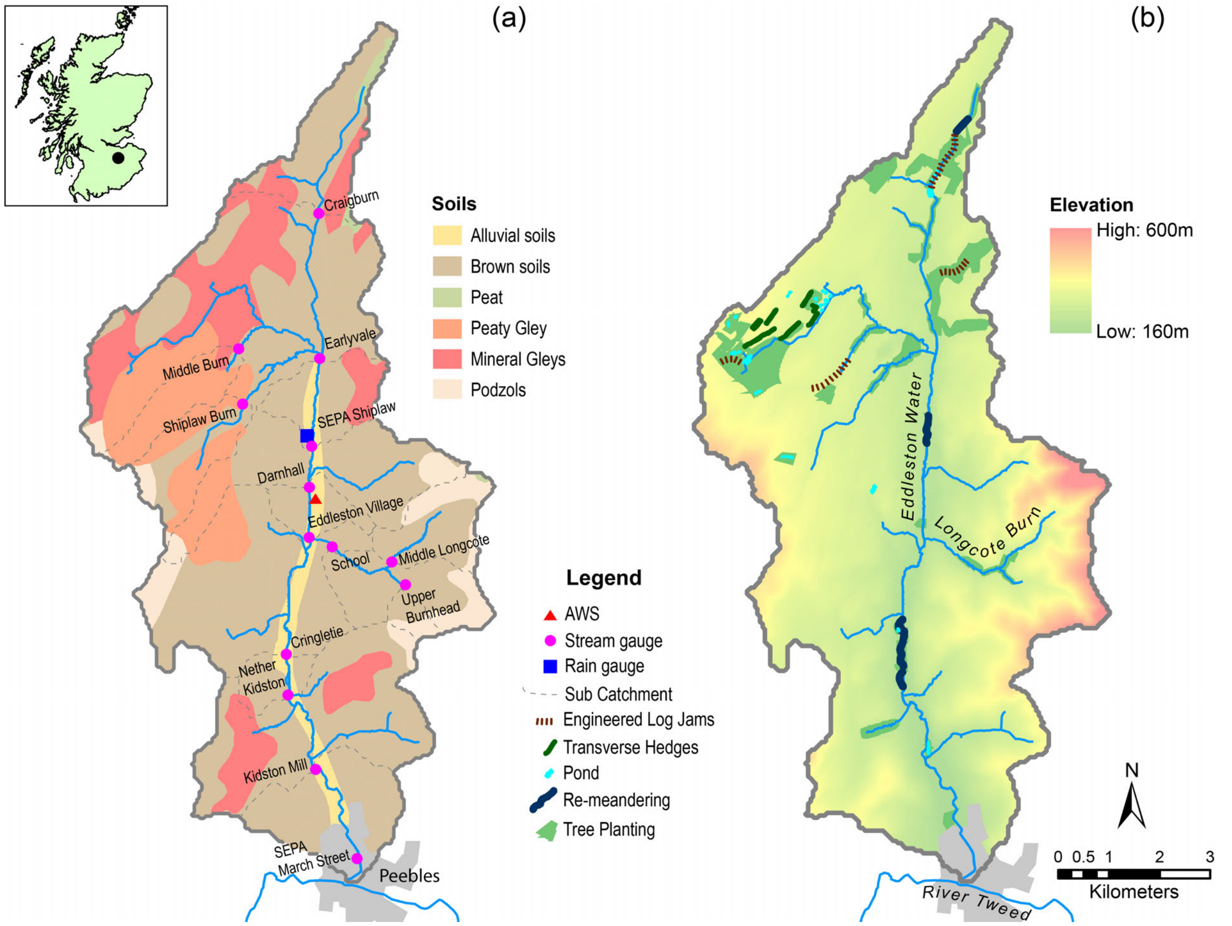

FIGURE 1 (a) Eddleston Water location, principal soil classes, river network, and monitoring sites used in the analysis. The weather station at the centre of the catchment near Eddleston Village is located at 55.717°N–3.208°W. (b) Topography and natural flood management (NFM) interventions

gleyed clays and peats, or alluvial deposits closer to the river (Soil Survey of Scotland Staff, 1970). Upstream of Peebles (Figure 1) the catchment is entirely rural and agriculture is dominated by sheep grazing on improved and semi-improved grassland (Ncube, Spray, & Geddes, 2018), with plantation forestry above 300 m OD in much of the western catchment, covering up to 70% of some smaller catchments. The catchment has undergone extensive human-induced changes over the last 500 years including deforestation, land drainage, river straightening and afforestation (Harrison, 2012).

2.1.2 | Hydrological characteristics

Long-term average monthly flows at the lower-catchment Kidston Mill gauge (64.38 km^2) vary from 0.48 m^3s^{-1} in May to 2.44 m^3s^{-1} in December. Using the Piggott, Moin, and Southam (2005) method with observed daily flow data, Base Flow Index varies across the catchment from 0.251 in the north-western Shiplaw Burn tributary to 0.544 in the eastern Middle Longcote tributary. Most peak flows are caused by either frontal rainfall or localised convective rainfall falling onto a wet catchment, with snowmelt not contributing to any of the four largest events on record since 2011, although contributing to some smaller events. Figure 2 shows the sequence of flows and rainfall intensities for the entire period of record; snowmelt is included in the rainfall data.

2.1.3 | NFM interventions

Since 2012 Tweed Forum and partners have worked with 20 farmers to deliver a range of NFM measures, including:

- 207 ha woodland planting with over 330,000 native trees (predominantly birch, with oak, alder, willow, and smaller numbers of minor species such as aspen, hazel and bird cherry),

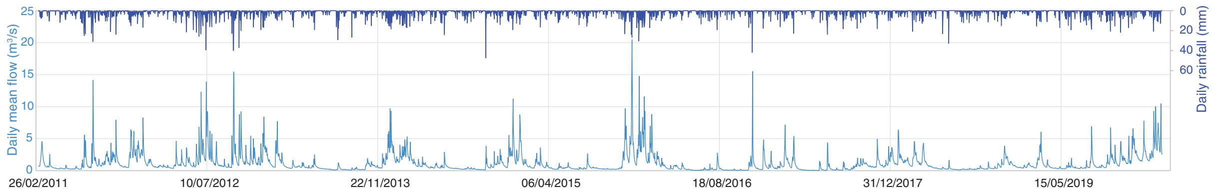

FIGURE 2 Continuous daily flow and precipitation data for the entire period of record: Eddleston Water at Kidston Mill

- 116 large high-flow log structures on upper tributary streams,
- 31 flow attenuation ponds located from headwaters to lower floodplain
- 2.9 km of previously-straightened river channel re-meandered, with adjacent flood banks removed.

The principal NFM interventions are located on the catchment map (Figure 1b), with details of the chronology and locations summarised in Table 1. The bulk of NFM measures were introduced between 2013 and 2015 and most of these interventions have been implemented in the northern Craigburn, Middle Burn and Earlyvale catchments, while on the middle and lower course of the Eddleston Water, channel re-meandering and off-line ponds have incrementally been introduced as opportunities have allowed. Not all of the NFM features have been surveyed with respect to storage potential, but Barnes (2018) surveyed all the leaky wood structures on the Middle Burn, finding an average of 48 m^3 storage for each, while an estimate of not more than 0.6 m vertical range has been used to estimate storage associated with each pond. These figures have been used to obtain the storage volume and equivalent catchment-averaged depth of storage values shown in Table 1.

The catchments of the Shiplaw Burn and the Longcote Burn (Middle Longcote and Upper Burnhead gauges) have undergone much more minor changes during the monitoring period (5 small ponds and 2 ha of wet woodland constructed in the Shiplaw catchment; 7.5 ha riparian planting in the Longcote catchment; all located in the upper reaches of these watercourses), and are used as control catchments. The Eddleston Water represents one of the most intensively managed NFM sites in the United Kingdom and possibly Europe.

2.2 | Monitoring network

A hydrological monitoring network was established in 2011, based around 10 main stream gauging sites established to monitor the NFM project at multiple scales (Figure 1a). SEPA have operated two uncalibrated water level gauges in the catchment since 2001 (Shiplaw) and 2005 (March Street), plus a rain gauge at the former site since 1990, which is located centrally within the catchment and is no more than 8 km from the furthest extremity of the watershed. Since 2011, eight stream gauging stations have been operating along a distance of 15 km of the main stem of the Eddleston Water, making it one of the most intensively gauged watercourses in Scotland at least.

Water level is measured using pressure recorders, with unvented units being compensated by reference to common atmospheric pressure recording. At most gauges, flows have been measured across a wide range of conditions in order to establish flow calibrations ("ratings") and derive continuous time series of river flow: nine sites have gaugings above the 1%ile flow including six with gaugings above the 0.1%ile value. Additional sites have subsequently been added to provide further hydrological detail in selected tributary catchments. Ratings for the SEPA sites were produced by using flow measurements from adjacent gauges and a scaling correction based on ratio of catchment areas. All continuous measurements are taken at 15-min intervals.

A weather station with ARG100 rain gauge was also installed centrally within the catchment in 2011, along with three additional RIMCO RIM8020 rain gauges. Rainfall is recorded at 0.2 mm resolution at all sites. Only the SEPA Shiplaw rainfall record (from a SBS500 rain gauge) has been used for analysis in this study owing to its central location and completeness of record, thereby avoiding some of the risks to analysis arising from gap-filling methods (Ruman et al., 2020).

2.3 | Data analysis

2.3.1 | Lag time estimation

Lag time is adopted as the central focus of this study in order to provide a robust metric with which to assess the effects of NFM interventions. Peaks in stream flow necessarily lag precipitation inputs due to the time taken for runoff to reach the stream network and be routed along it. The lag time is influenced by antecedent conditions, event rainfall, catchment characteristics (e.g., land cover,

TABLE 1 Chronology and location of natural flood management interventions (gauge sites listed in downstream direction; tributary sites indented in left column)

Gauge/ catchment	Upstream area (km^2)	Records from	Riparian and wetland planting (ha)			Length of main stem re-meandering (m)			Number of ponds			Flow restrictors (number)			Volume of storage in ponds and leaky wood structures (m^3)	Equivalent depth across catchment (mm)
			By 1.1.13	By 1.1.15	By 1.1.17	By 1.1.13	By 1.1.15	By 1.1.17	By 1.1.13	By 1.1.15	By 1.1.17	By 1.1.13	By 1.1.15	By 1.1.17		
Craigburn	4.34	2011		2.9	3.4		300	300			3		34	44	9,589	2.21
Middle Burn	2.30	2011		2	2								35	35	1,680	0.76
Shiplaw Burn	3.14	2011			4.9						4				1,095	0.34
Earlyvale	25.64	2011	17.7	41.2	99.6		300	300		8	15		79	109	31,523	1.23
SEPA Shiplaw	28.57	2001	17.7	42.2	101		700	700		8	15		79	109	35,833	1.25
Darnhall Mains	35.16	2011	17.7	42.2	101		700	700		8	15		79	109	42,965	1.22
Eddleston Village	36.69	2011	18.7	60.9	119		700	700	1	9	16		79	109	42,965	1.17
Longcote Middle	2.75	2011													0	0.00
Upper Burnhead	0.50	2011													0	0.00
School	6.89	2011	7.5	7.5	7.5										0	0.00
Nether Kidston	54.84	2011	26.2	65	130		2,100	2,780	1	10	17		79	109	45,252	0.83
Kidston Mill	64.27	2011	26.2	65	130		2,100	2,780	1	10	18		79	109	49,114	0.76
SEPA March Street	68.96	2005	26.2	67	130		2,100	2,780	1	10	18		79	109	49,114	0.71

Note: Cumulative extent of measures increases incrementally downstream from top to bottom of the table.

soils and storage), and channel geomorphology (McCuen, 2005). Most hydrological studies require the estimation of catchment response time parameters, and they constitute inputs to many hydrological modelling frameworks.

Many of the empirical methods used to estimate lag time are an extension of graphical techniques that have been used since at least the 1930s (e.g., Snyder, 1938) to estimate the time between the centroid of effective rainfall and the centroid of, or peak, runoff (Fang, Cleveland, Garcia, Thompson, & Malla, 2005). However, there are numerous variations, both in defining the time base in the hyetograph (e.g., using peak rainfall or the centroid of event rainfall) and the response time in the hydrograph (e.g., measuring lag to peak discharge or lag to the centroid of runoff) (Gericke & Smithers, 2014; McCuen, 2009). These are variously referred to as "time of concentration," "lag time" and "time to peak," with different definitions used in different studies (Gericke & Smithers, 2014). All of these approaches pose conceptual challenges, such as how to identify independent runoff peaks, how best to define individual precipitation events that contribute to streamflow, calculate effective rainfall, or separate the hydrograph. In some studies, alternative approaches have been used which avoid some of these challenges, such as using autocorrelation (Talei & Chua, 2012) or using the time between peak rainfall intensity and the hydrograph peak (McCuen, 2009; Shuttleworth et al., 2019; Viessman & Lewis, 2002).

In order to take a simple approach free of the model assumptions normally involved in hydrograph separation, this study uses observed rainfall rather than effective rainfall, following the precedents set by Deasy, Titman, and Quinton (2014) and Shuttleworth et al. (2019). Peak flow events were first selected from the 9-year common period March 21, 2011 to March 5, 2020, based on flow thresholds for each gauging site that were initially set to yield the largest 100 peaks, or an average of 11 peaks per year where there were missing records. The large number of peaks was chosen in order to avoid undue dependence of results on a small number of events. The use of a common period and a compact catchment helps avoid discrepancies in results attributable to sampling issues. The resulting peaks may be locally significant, but only rarely include events capable of causing flooding. Only the largest event in any 24-hr window was extracted, as a means of ensuring event independence and in the interests of obtaining meaningful lag times. The methods were applied to all gauge records from the entire study, including the control catchments, collectively spanning a range of catchment areas from 0.59 to 69.3 km^2.

Lag time was calculated as the delay between the centroid of event rainfall and the runoff peak. Event rainfall profiles were separated from each other by the occurrence of a 1-hr minimum inter-event time (MIT) and the requirement that a river flow peak must occur within 8 hr of the preceding rainfall centroid (allowing for travel time to the catchment outlet). This is similar to "event rules" in other empirical studies investigating rainfall-runoff response (Hale & McDonnell, 2016). A range of longer MIT values up to 8 hr, and alternative lag calculation methods focusing on the time of highest rainfall intensity were trialled, but produced samples of lag values with much greater *SD*s in both baseline and experimental (post-measures) periods, and were accordingly rejected.

Snowmelt is known to have wholly or partially contributed to some of the recorded peaks. Exclusion on the basis of water temperature readings from the water level gauges was considered, as a means of providing a more homogeneous data set for analysis. However, doing so led only to a reduction in sample sizes without any change in median lag times. Accordingly, all events were retained irrespective of water temperatures.

2.3.2 | Event dataset

A total of 1,222 lag times were obtained from the 13 gauging stations listed in Table 1. There were 76 events in which at least 7 of the 10 primary gauging stations yielded a lag time for analysis.

2.3.3 | Statistical analysis of lag times

For each catchment and for pre- and post-intervention periods defined as before and after August 1, 2013 (May 1, 2013 for the School and Middle Longcote gauges), median lag time was calculated from all available peaks. Medians were chosen as being insensitive to outliers, distribution-independent and easy to communicate. The Mann–Whitney *U* test of difference was used to assess the significance of differences between baseline and experimental samples. A 5% significance level was used on a one-tailed basis in each case.

3 | RESULTS

Changes in lag relate to the dual contexts of catchment scale and event magnitude, so the results are reported in relation to both aspects together. Figure 3 shows the results of assessing median lag for the baseline and post-

FIGURE 3 Median lag time for events in the baseline and experimental periods at different flow sampling thresholds (shown as a fraction of the median annual flood QMED). Median at each threshold in the different periods calculated as the median lag time for all events above the threshold, up to the point where the sample size in either period is <5. Open circles show lag for the largest individual events above this point. LQ/UQ: lower/upper quartiles. Sites are arranged upstream to downstream, with catchment area shown in each plot title. Sites are located on Figure 1. Details of natural flood management (NFM) interventions are in Table 1

TABLE 2 Comparison of median lag times before and after commencement of natural flood management (NFM) interventions (August 2013 except where shown) and results of tests of difference in samples of lag times between periods using varying sample sizes

	Catchment area (km^2)	Median lag (hr) at highest sampling threshold (~QMED)		δ median lag (hr)	*p*-statistic for significance of differences between samples of *n* observations		
		Pre-intervention	Post-intervention		$n \geq 5$	$n \geq 10$	$n \geq 20$
NFM catchments							
Middle Burn	2.21	3.0	10.3	7.3	.011*	.043*	.002*
Craigburn	4.34	4.0	7.3	3.3	.069	.008*	.024*
Earlyvale	25.64	3.3	5.9	2.6	.061	.046*	.020*
SEPA Shiplaw	28.57	3.3	4.5	1.2	.072	.081	.016*
Darnhall	35.16	3.6	5.5	1.9	.206	.129	.264
Village	36.69	4.0	4.5	0.5	.464	.171	.011*
Middle Longcote[a]	2.75	4.0	3.1	−0.9	.298	.429	.326
School[a]	6.89	2.5	3.0	0.5	.268	N/A	N/A
Nether Kidston	54.84	5.3	6.3	1	.058	.326	.192
Kidston Mill	64.38	6.5	8.7	2.2	.181	.397	.268
SEPA March Street	69.3	8.9	7.7	−1.2	.206	.409	.330
Control catchments							
Shiplaw Burn	3.18	3.5	3.0	−0.5	.456	.484	.476
Upper Burnhead	0.59	1.0	1.9	0.9	.232	.281	.409

[a]Interventions in place by May 2013.
*Significant at $p < .05$.

intervention periods for all experimental, as well as control catchments. Changes in lag are attributed to the introduction of NFM measures as indicated in Table 1.

Three sites in the upper Eddleston catchment demonstrated significant increases ($p < .05$) in lag time post-intervention: Middle Burn, Craigburn and Earlyvale (Table 2). Median lag values in baseline and experimental periods tended to be similar at the lowest threshold values, but diverged with increasing event magnitude (Figure 3). This effect can be seen for the three sites listed above, plus Darnhall, SEPA Shiplaw and Eddleston Village (difference at the latter is significant when using a sample size of 20+). At the highest sampling thresholds available from the data (equivalent to approximately QMED—the median annual flood), median lag times increased by 7.3, 3.3 and 2.6 hr at Middle Burn, Craigburn and Earlyvale, respectively. These sites also showed continuing long lag times for the very largest individual events observed post-measures (open circles in Figure 3), although it is not possible to test for the significance of these differences given the small sample size at these event magnitudes. As a check for evidence of the leaky wood structures maintaining their effectiveness over time, the final 3 years of record (2017–20) were compared with the 2 years of baseline, and confirmed the initial findings reported above. In the Longcote catchment, following riparian fencing and planting, no significant changes were observed.

Two control catchments were analysed, the Shiplaw Burn and Upper Burnhead, and both showed no significant change in lag times. At 3.18 and 0.59 km^2, these control catchments are smaller than or similar in size to the Craigburn and Middle Burn catchments. Also, examining the largest individual events in the plots for these control catchments (Figure 3), there is no evidence of any change in the range of lag values.

Median lag values based on the highest sampling threshold values available across all catchments (statistically significant or not) are compared in Figure 4 and in Table 2. This allows the differences in median lag post-interventions to be seen in the context of increasing catchment area, and also allows comparison of results between experimental and control catchments. Neither median lag nor the difference between periods changed smoothly with catchment area, but the figure indicates a general pattern of baseline median lag values being 4 hr or less in catchments up to ~36 km^2 and increasing at greater catchment scales. The largest increases in lag were for NFM experimental catchments subject to leaky structure and pond construction

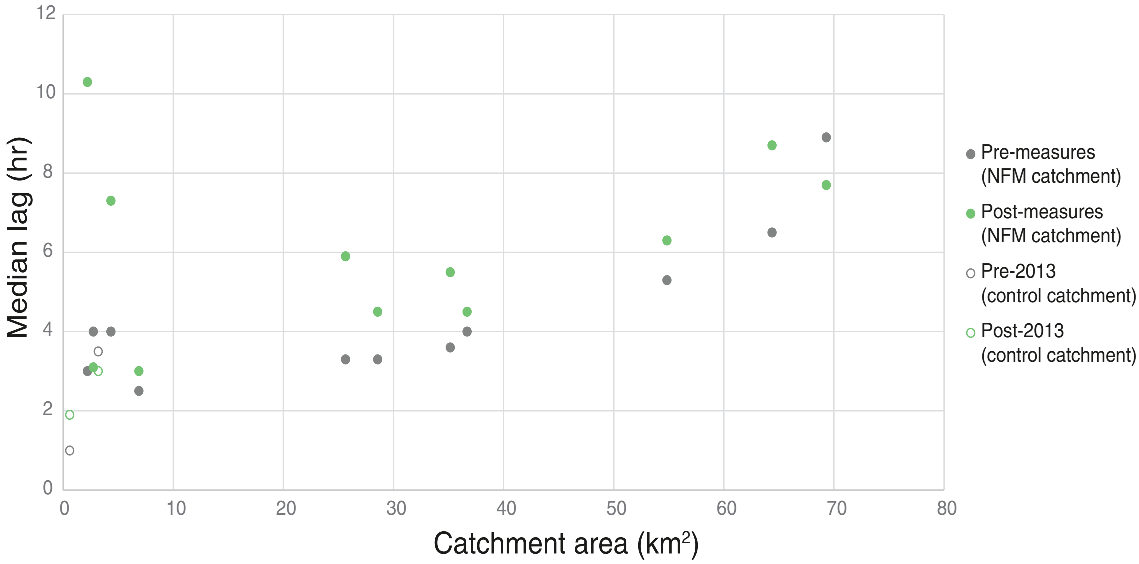

FIGURE 4 Median lag as a function of catchment area for experimental and control catchments, for peaks occurring before and after the commencement of natural flood management (NFM) implementation in summer 2013. Median lag values are those calculated at the highest sampling thresholds shown in Figure 3

and below 26 km^2 in area, and were significant at the $p < .05$ level. None of the sites in the lower Eddleston catchment showed any significant change, nor either of the smaller catchments subject to riparian planting and fencing. The records for SEPA Shiplaw (28.57 km^2) and Eddleston Village (36.69 km^2) did show a small but significant increase in lag of 0.5–1.2 hr using one of the three sample sizes.

4 | DISCUSSION

4.1 | Effect of NFM interventions on flood peak lag times

4.1.1 | Catchment scale

The greatest increases in lag time, of up to 7.3 hr, were found in the smallest catchments subject to NFM interventions (involving leaky barriers, ponds and riparian planting and fencing), with significant differences extending downstream within the nested monitoring network to a gauging site with catchment area of 25.64 km^2 ($p < .05$). Increased lag times were also observed in larger catchments (up to 64.38 km^2), but were not statistically significant. The relatively large catchment size in which significant results were found may well relate to the number and size of NFM features installed within the northern parts of the Eddleston project area.

Sources of empirical evidence for the impacts on NFM on lag times elsewhere is limited and the results are generally difficult to compare due to differences in catchment size, catchment type, climatic conditions, the types and scale of interventions and use of different methods. However, two important points stand out from the other studies which have been reviewed. Firstly, all of them find evidence for increases in lag time; and secondly, empirical evidence addressing changes in flood response in catchments of >20 km^2 remains very scarce. For example, Shuttleworth et al. (2019), found lag time increases of up to 30 min relative to a control for peatland revegetation and ditch blocking in three catchments ranging from 0.4 to 0.7 ha. Kitts (2010) reported a 35 min increase in flood peak travel time between two gauges in a 12.5 km^2 catchment where channel re-meandering had been carried out and debris dams constructed. Wenzel, Reinhardt-Imjela, Schulte, and Bölscher (2014) found a significant deceleration in flood wave propagation over a 282 m reach of channel with large woody debris in a 1 km^2 catchment, causing a ~3 min delay in the flood peak. Wilkinson, Quinn, and Welton (2010) found that the travel time of flood peaks after the construction of a single holding pond increased from 20 to 35 min over a 1.35 km stretch of river in a 6.0 km^2 catchment. In this context, the empirical findings from the Eddleston Water represent an important contribution to debates about the catchment scale at which NFM might be effective (Dadson et al., 2017), given the length of records obtained, the total scale of catchment studied, the nested monitoring network and the observed increases in lag.

The effects of NFM on lag times at scales >26 km^2 in the Eddleston catchment require further investigation.

Tributary relative timing might be important at such scales (Pattison et al., 2014) and it is possible that the runoff timing in the lower part of the catchment is dominated by the responses in the lower tributaries which to date have not received NFM treatments. Additional monitoring and modelling of the lower main stem and tributaries might help to determine the significance of the increase in lag times that is observed at most of the gauges in the lower catchment. As runoff peaks from the Eddleston Water are typically coincident with peaks arriving from the adjoining River Tweed, further delay to the Eddleston peaks and a concomitant flattening of the hydrograph should be expected to benefit reductions in flood risk in Peebles.

4.1.2 | Event scale

At most sites lag times decreased or remained the same with increasing event discharge thresholds during the baseline period. This pattern is common in river systems due to friction effects (arising from bed, banks and any woody debris) reducing as the flow increases (Kitts, 2010; Lee & Ferguson, 2002). During the experimental period, lag times at the three most upstream sites (Earlyvale, Craigburn and Middle Burn) were similar to those in the baseline period in peaks marginally exceeding the sampling threshold. However, lag increased with the magnitude of the sampling threshold (flood magnitude), up to about QMED, in each case showing an increase of at least 2.6 hr compared to the baseline. It is noticeable that post-measures, the highest peaks in the Middle Burn record are all associated with prolonged rainfall of at least 15 hr—a long duration for a catchment of less than 3 km^2.

The increase in lag times with increasing flow for the smaller catchments suggests that the NFM measures have increasingly large impacts on lag times as the scale of event increases, rather than becoming overwhelmed at higher flows. This pattern may be indicative of the design of the NFM measures. The leaky wood structures, for example, are very “leaky” at lower flows, but begin to attenuate flows close to bankfull discharge and then push water on to the floodplain in these catchments (Barnes, 2018). This interpretation supports insights from recent modelling work arguing that NFM measures gain effectiveness with increasing flow due to their ability to make use of “expandable field storage” (Hankin et al., 2020; Kay et al., 2019). This raises the possibility of NFM effectiveness at higher event magnitudes, contrary to the Dadson et al. (2017) review, though it is not possible by this analysis to predict the maximum extent of this effectiveness.

Relationships between event magnitude and lag time are less clear at larger catchment scales. Presumably this is because the impacts of the interventions in the headwater catchments are dominated by other environmental effects, such as tributary inputs and a smaller relative proportion of catchment area/channel length subject to NFM interventions at these scales.

4.2 | Comparing results between NFM intervention types

The most marked increases in lag times occurred in the Middle Burn catchment, in which the main NFM measures are a series of 35 leaky barriers as well as ~2 ha of riparian and wetland tree planting. The Craigburn catchment contains a similar number of leaky barriers (44) and a similar area of tree planting (3.4 ha), but also three offline holding ponds and 300 m of channel re-meandering. Despite a larger number and range of interventions, the increase in median lag time at Craigburn was less marked than in Middle Burn. These differences are assumed to be explained by differences in catchment properties, such as catchment area, geology, soil characteristics, hillslope and channel gradients, surface cover, land management practices and others. There are also likely to be differences in the design and placement of leaky structures between the catchments. It has also been shown that the capacity of holding ponds needs to be considerable in order to have a marked impact on peak flows (Nicholson, Wilkinson, O'Donnell, & Quinn, 2012). The nuances of these impacts require further comparative investigation of the catchments. Meanwhile, the potential role of geology and slope angles are worth emphasis, since the Middle Burn is located in the part of the catchment which generates the flashiest response, being dominated by glacial clays and associated peaty gley soils, and having a mean drainage path slope of 86.7 m/km compared with 48.2 m/km in the Craigburn catchment where brown soils dominate.

It has been suggested that riparian tree planting can lead to significant increases in lag times, due to the effects of floodplain tree cover and riparian vegetation and woody debris attenuating flows through the floodplain, and hence reducing the conveyance capacity of the floodplain. Various studies have modelled these effects through modifying the model roughness of the floodplain. Thomas and Nisbet (2007), for example, showed that a 50 ha area of floodplain woodland (a relatively dense willow stand) in an 84 km^2 catchment during a 1% recurrence interval flood could slow flood wave travel time by 30 min. To date, there is no evidence of any significant increase in lag time in the 6.89 km^2 School catchment, in which 7.5 ha of riparian and wetland tree planting has been implemented since 2013. Given that this is a relatively large proportion of the catchment area compared to the Thomas and Nisbet (2007) results reported above, the lack of significant effect may be due to local factors such as the relative immaturity of the trees. Research indicates that the hydraulic impacts of floodplain vegetation are strongly controlled by planting density, stem diameter, height, structure and phenological phase (Kiss, Nagy, Fehérváry, & Vaszkó, 2019; Uotani, Kanda, & Michioku, 2014).

4.3 | Comparison of approaches

The rich monitoring data set has allowed for longitudinal and paired catchment approaches to be applied. By comparing median lag values pre- and post-2013 in both experimental and control catchments, significant increases in lag are found between periods in catchments where measures have been applied, up to a catchment area of 25.64 km^2, but not in the control catchments and not in catchments which have been subject to riparian planting and fencing alone. While the comparison of lag times along the main stem of the Eddleston Water reveals some inconsistencies, the use of the BACI approach has allowed a robust comparison of the effects of different types of catchment intervention. Substantial variation is found in all samples of lag times, as indicated by the inter-quartile ranges in Figure 3, but nonetheless, the methods have been applied consistently in all catchments, allowing identification of sites where significant change has occurred. Lag does vary between events, depending particularly on rainfall profiles and antecedent conditions, but the lengths of record available for analysis represent a strength of this study.

4.4 | Implications for NFM policy and practice

The policy and practice communities require evidence of the effectiveness of NFM measures, and it was to that end that the Eddleston project was initiated. Key requirements include knowing the effectiveness of different types of NFM measure; where to locate NFM measures within a catchment; demonstrating the spatial and temporal scales over which they operate; and being able to show which can provide immediate benefits for flood risk (and indeed other complementary ecosystem services). Other issues such as detailed design, sustainability and landowners' acceptance should not be overlooked (Waylen, Holstead, Colley & Hopkins, 2017), but the emerging results from Eddleston already have implications both for policy and practice in Scotland and beyond.

The construction of ponds and flow restrictors have been demonstrated to deliver substantial attenuation of hydrographs, as shown by the delays to lag time observed in the headwater catchments. The increase in lag has been most dramatic in the flashiest of the catchments treated, and so a particular recommendation is that sites expected to produce flashy runoff response should be prioritised. SEPA's catchment maps which show opportunity areas for runoff reduction (SEPA, n.d.) provide relevant information for targeting of these measures. In addition, these measures provide immediate benefits and are relatively low-cost compared to downstream grey infrastructure flood defences (Quinn et al., 2013), thus increasing their attractiveness.

Transformation of flood hydrographs through the use of such NFM measures will also lead to reductions in flood peaks as well as increasing lag times. Such alterations in hydrological response provide more time for the preparation of and response to flood warnings, as well as leading to a reduction in the risk or severity of flooding—in the immediate catchment of the measures or downstream.

The empirical evidence for an increase in lag time due to riparian and wetland tree planting is currently unclear in the Eddleston catchment, perhaps as a result of the relative immaturity of the trees, or other complicating factors. As Kay et al. (2019) note, as much as a 25 year delay might be expected in achieving an empirical understanding of the effects of such NFM afforestation interventions. This suggests that while such interventions could be complementary to the installation of debris dams and holding ponds (Metcalfe, Beven, Hankin, & Lamb, 2017a; Odoni & Lane, 2010), as part of a "catchment systems engineering" approach (Hewett, Wilkinson, Jonczyk, & Quinn, 2020) their impacts, and the associated return on investment may remain much less clear until NFM schemes have been in operation for multiple decades (Bogena, White, Bour, Li, & Jensen, 2018). By contrast, Dittrich et al. (2018) showed through modelling that widespread afforestation of the Eddleston catchment as a single management strategy could deliver significant cost benefits for flood risk reduction and especially other complementary ecosystem services.

The scale and size of catchment over which NFM might be effective has raised questions around its real-life utility when developing policies for catchment scale flood risk reduction. Here we show for the first time that the impacts of installation of leaky wood structures in isolation or in combination with online ponds and riparian planting can be detected at scales greater than the 20 km^2 limit previously identified in reviews such as by Dadson et al. (2017). The implication of this result is that NFM should be considered, in isolation or in combination with other forms of flood risk management, in catchments where NFM may previously have been considered inappropriate. The scale of change observed in hydrological lag should be considered in the context of the number and scale of interventions shown in Table 1.

Considering the catchment scales at which NFM may be effective raises the potentially challenging issue of synchronisation of runoff peaks. It may be that local flood risk management needs will normally require to be addressed on a case by case basis rather than recommending some general target for application everywhere. However, this research at least demonstrates the scale of catchments in which significant results can be seen, and raises the possibility of NFM effectiveness increasing with event magnitude beyond the QMED level.

4.5 | Opportunities for further learning

The length and spatial density of monitoring in the Eddleston catchment have provided a strong foundation on which to base the empirical analysis reported in this paper. More than 130 station-years of 15-min water level data have now been collected in the catchment to date, in fulfilment of a strategic commitment to establish and operate a long-term intensive study to gather real-world evidence of what NFM can achieve. In 2020, six further water level gauges were added to the monitoring network to better understand the role of tributary inflows along the main stem (to which two additional gauges have been added); the rain gauge network is being extended in order to provide greater robustness in rainfall monitoring; additional instrumentation is being added at pond locations; and a 0.5 km^2 headwater catchment has been instrumented within the flashy northwest of the catchment. However, the accurate measurement of river flow, snowfall and snow melt remain ongoing challenges.

The baseline data set includes one exceptional cloudburst event which was assessed as having an annual exceedance probability of less than 1%, and which will provide an excellent reference for comparison as NFM measures in the catchment increase in number and maturity. New NFM measures continue to be planned and built as opportunities arise. The catchment therefore represents an important hydrological asset which warrants ongoing support to track the changing effects of NFM interventions in isolation and downstream in combination, across a fine gradation of scales. Equally, the catchment provides a living laboratory in which lessons can be learned and shared as regards practical aspects of NFM installation, maintenance and the benefits which are accrued. The data will also allow future testing of predictive tools, and allow lessons to be learned from comparison of results. Land management activities such as commercial forest harvesting and the establishment of infiltration strips are also being implemented in the catchment, and will provide further opportunities for research, in isolation and as part of catchment-scale studies.

5 | CONCLUSIONS

Significant increases in hydrological lag were found in catchments up to 25.64 km^2 in area which had been treated with leaky wood structures, on-line ponds and riparian planting and fencing. Lag values increased by between 2.6 and 7.3 hr when comparing peaks equal to or exceeding thresholds set at around QMED, while at lower thresholds the increases in lag were much less. This extends the catchment scale at which NFM techniques can be demonstrated to be effective, and may be related to the intensity and size of NFM interventions catchment-wide.

In catchments with only riparian fencing and planting, no significant increases in lag were found. With distance down the main stem of the Eddleston Water, no statistically significant changes were found other than with isolated results at catchment areas of 28.57 and 36.69 km^2. The quantified delays in lag are evidence of successful slowing of runoff response as a catchment management strategy, represent increased opportunities for flood warning and community response, and imply reductions in flood risk downstream. For sites with existing structural flood defences, the results reported here point to the potential to maintain or enhance intended standards of protection, with flexibility lying in the ability to deploy future NFM measures incrementally as future opportunities arise, and as changing flood risks are re-assessed.

The results obtained represent the realisation of more than 10 years of planning, coordination, fieldwork and analysis, built on a strategic ambition to obtain robust empirical evidence to provide detailed insights into how flood response actually changes after the implementation of NFM measures. The BACI design has been critical to delivering the ability to compare changes in lag over time and between adjacent catchments. With more than 9 years of record at 13 sites in a nested monitoring network of 69 km^2, the Eddleston Water dataset is unique at least in the United Kingdom in terms of the duration and density of flow monitoring, providing a rich resource to support further study of NFM effects.

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CONFLICT OF INTEREST

The authors declare no conflict of interest in relation to this work.

DATA AVAILABILITY STATEMENT

The 15-minute streamflow data that support the findings of this study are available from the corresponding author upon reasonable request. Rainfall time series from the Shiplaw rainfall site are available from SEPA upon reasonable request.

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