Journal of Flood Risk Management

WILEY

CIWEM Chartered Institution of Water and Environmental Management | Journal of Flood Risk Management

ORIGINAL ARTICLE OPEN ACCESS

Using Storage Ponds in Natural Flood Management Schemes in Practice: The Need for Fine-Tuning and Upscaling

Leo Peskett[1] | Sarah Collins[2] | Andrew Black[3] | Matthew Arran[2] | Alan MacDonald[2] | Andy Young[4]

[1]Heriot-Watt University, Edinburgh, UK | [2]British Geological Survey, Edinburgh, UK | [3]University of Dundee, Dundee, UK | [4]Wallingford Hydrosolutions, Wallingford, UK

Correspondence: Leo Peskett (l.peskett@hw.ac.uk)

Received: 5 September 2024 | **Revised:** 31 March 2025 | **Accepted:** 14 April 2025

Funding: This work was supported by Scottish Government.

Keywords: flood storage ponds | green infrastructure | natural flood management | nature-based solutions

ABSTRACT

There is increasing interest in installing water storage ponds as part of natural flood management (NFM) approaches being implemented globally. Despite decades of experience with constructing flood storage ponds within civil engineering disciplines, there remains little empirical evidence of their effectiveness in NFM. In NFM, 'natural' ponds use green infrastructure, are often smaller but more numerous, and are built and maintained by land managers rather than engineers. Here we investigate six flood storage ponds in the 69 km^2 Eddleston NFM pilot catchment in Scotland, UK, analysing impact on peak stream flows at different scales and pond designs. The ponds generally reduce peak stream flows where they have large available capacity, catchments are small (< 1 km^2), and events are low magnitude (> 20% Annual Exceedance Probability (AEP)). No discernible flow reduction was observed at the largest pond and catchment (64 km^2) for the largest (~21% AEP) event. There was significant variability between ponds, and gains can be made in engineering pond inlet/outlet structures, maintenance, and more widespread installation. The findings suggest that natural storage ponds have most potential to contribute to flood control in small catchments (< 10 km^2) and small flood events (> 25% AEP), when they are carefully designed and maintained, and sufficient in number.

1 | Introduction

Globally, there is increasing interest in nature-based solutions for controlling environmental hazards, including flooding (Seddon 2022; World Bank 2018). This is being driven by a growing concern that 'hard engineered' approaches may be of limited effectiveness especially under future climate change scenarios and the potential cost-effectiveness of NFM (Vineyard et al. 2015). Natural flood management (NFM) is one type of nature-based solution that has been incorporated into policy over the last decade in many countries (Acreman et al. 2021; European Parliament and European Council 2007; Flood and Water Management Act 2010; Scottish Government 2009). NFM seeks to manage flood risks through distributed 'natural' changes to catchments that help to attenuate flood peaks, such as reducing runoff through afforestation, increasing surface water storage through the creation of temporary flood storage structures, and reducing conveyance through re-meandering of river channels and construction of woody debris dams (Environment Agency, 2017).

Measures to increase surface water storage are a key component of many of the NFM schemes that are now in operation globally (Acreman et al. 2021; Kay et al. 2019; Molnar-Tanaka and Surminski 2024). These measures aim to create additional water storage to reduce and delay flood peaks. They also have additional benefits such as sediment retention, biodiversity enhancement, and potentially groundwater recharge (Lucas-Borja et al. 2021). There is a wide range of approaches to creating such storage features, including micro-dams, engineered buffer zones, bunds, leaky barriers, and online/offline storage ponds (Roberts et al. 2023). As a result, the terminology is often confusing—we refer to them in this paper collectively as natural flood storage ponds.

The creation of flood storage ponds in order to regulate river flows is not a new strategy, and has been used widely in many grey infrastructure flood schemes for decades (Arnold 1988; Woods-Ballard et al. 2015). The design of ponds and pond networks, particularly in urban areas, has also been the focus of several modelling studies (e.g., Post et al. 2024; Sahoo and Pekkat 2018) The theory is therefore well understood, although it has not been well tested in practice in NFM schemes, which typically include many more small structures and simpler engineering methods such as avoiding the use of concrete in reinforcing inlet and outlet structures. The key factors controlling the performance of such ponds include: (1) the storage capacity prior to an event, (2) the rate at which they fill, (3) the rate at which they drain, (4) the timing of when they start to fill in relation to nearby watercourses (in the case of offline structures that are not permanently linked to water courses), and (5) their effects on friction and flow pathway length. Storage capacity is the dominant factor, and friction and flow pathway effects are minor (Quinn et al. 2013). Because these structures require available storage prior to storm events, their performance varies temporally and is influenced by both antecedent rainfall and wider catchment properties (e.g., soil types) that will influence the volume and rate of runoff into the structures. Their performance also varies spatially at a catchment scale, with several studies demonstrating how their location can either reduce or increase flood peaks (Birkinshaw and Krivtsov 2022; McCuen 1974; Verstraeten and Poesen 1998).

We focus on online and offline ponds in this study, for which the inlet and outlet structure design are also a key control on performance. In online storage ponds the additional storage is contained in series with the permanent water course, whilst in offline ponds the storage is contained in parallel (Brasil et al. 2021) (Figure 1). Of these storage structures, offline ponds have the best potential to reduce flooding as they target the higher flood flows (Quinn et al. 2022). The height of the inlet, in relation to the adjacent stream controls when the pond starts to fill, and its dimensions control the magnitude of flow into the pond. In traditional flood engineering schemes, such structures are usually designed to target events above a threshold magnitude (Abawallo et al. 2013). Output structures can include pipes and spillways, and the elevation and size of these structures control how quickly ponds drain (Shen et al. 2021). The hydraulic conductivity of pond bed materials also controls the drainage rate and needs to be considered in design.

Empirical evaluations of the performance of ponds typically monitor water levels in ponds and compare these with the analysis of flood peak magnitude and timing at upstream and downstream gauges (Nicholson et al. 2020; Wilkinson et al. 2010). These have found that ponds can help to reduce peak flows, but generally in small catchments and for small events. For example,

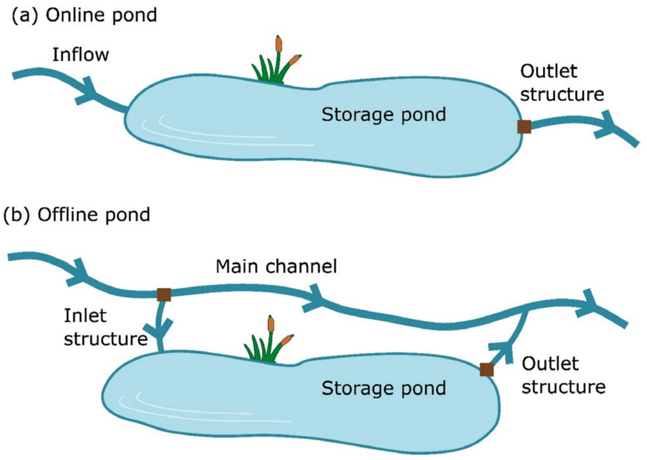

FIGURE 1 | Online (a) versus offline (b) storage ponds.

Lockwood et al. (2022) found a 7% reduction in peak flow for a maximum event AEP of 83%. At catchment scales, the effect of storage ponds has mainly been estimated using modelling studies (Birkinshaw and Krivtsov 2022). It has been suggested that for offline ponds, a density of $> 2000\,m^3\,km^{-2}$ is required to achieve > 10% reduction in flow in events up to 1% AEP (Roberts et al. 2023).

While natural flood storage ponds are now being widely implemented, there is still limited empirical evidence surrounding how they perform under different flows, antecedent conditions, and spatial scales. Most evidence comes from small catchments ($< 50\,km^2$) (Lockwood et al. 2022; Wilkinson et al. 2010). There are still gaps in understanding about how these interventions change over time, which has implications for properly evaluating their maintenance costs and effectiveness compared to alternative approaches. There are also ongoing debates about where to position ponds in catchments, the advantages of many small versus fewer large ponds, and unexpected consequences such as synchronicity of catchment flood peaks (Ayalew et al. 2015).

The research reported here investigated the operation of natural flood storage ponds at different spatial scales within the long-running Eddleston pilot NFM research catchment in Scotland, UK (Spray et al. 2022). We investigated the following questions:

1. What is the impact of natural flood storage ponds on flood peaks?
2. How does this vary with pond design and at different catchment scales?
3. What are the implications for using temporary flood storage ponds as an NFM strategy?

2 | Methods

We investigated the operation of flood storage ponds at two different scales within the $69\,km^2$ Eddleston Water catchment in Scotland, UK (Figure 2). It is the site of a major NFM pilot project and UNESCO ecohydrology test site aiming to

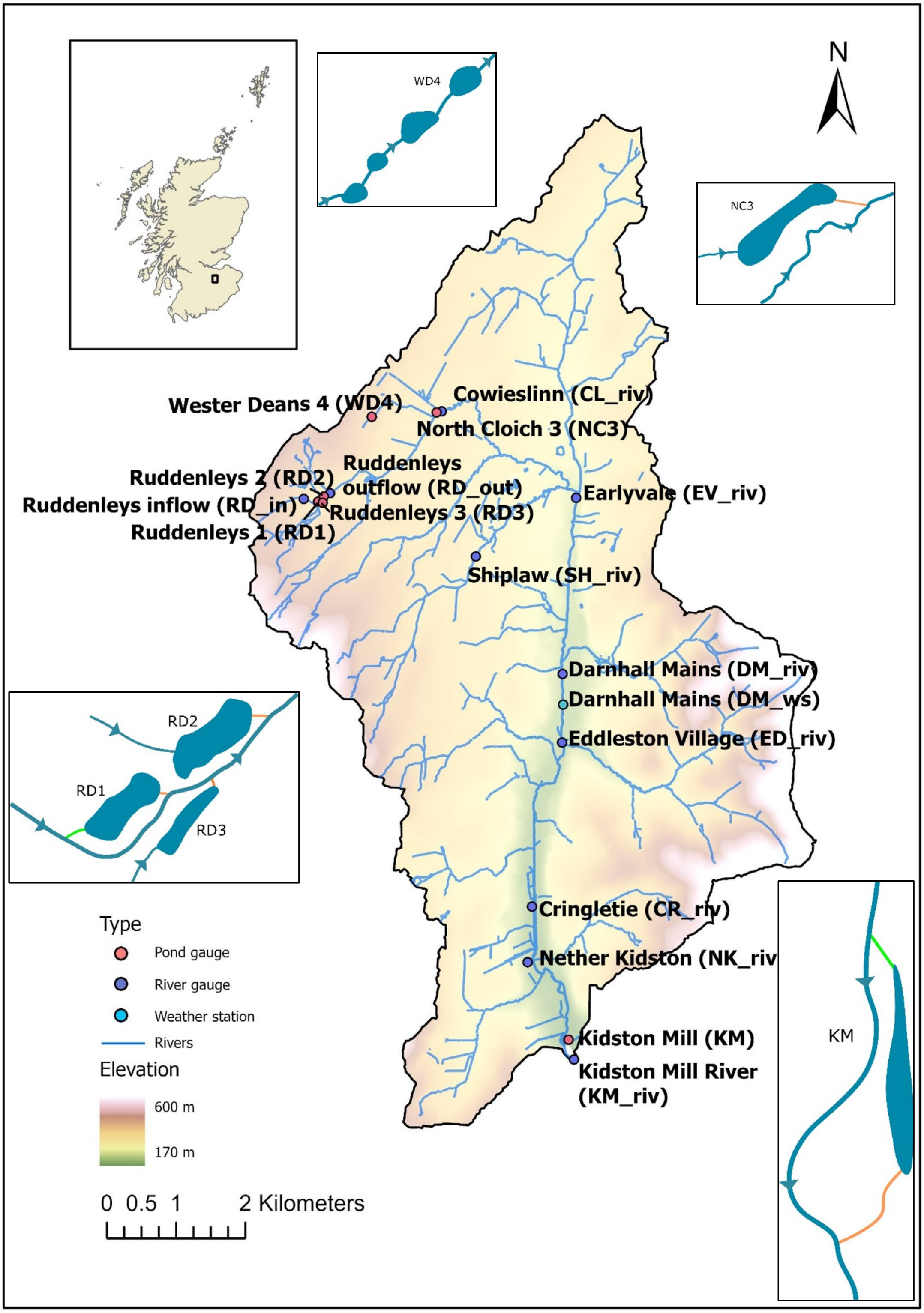

FIGURE 2 | The Eddleston NFM pilot research catchment, including ponds with water level monitoring and associated river level gauges referred to in this paper. Weather station at centre of the catchment and main distributed catchment rain gauges are also shown. Inset schematics for each pond/pond group, all sharing same scale. Green lines show inlets and orange outlets for ponds where applicable.

inform UK and European water policy (under the EU Water Framework Directive and EU Floods Directive) (Tweed Forum 2019; Werritty et al. 2010). The catchment is typical of much of the UK uplands, is one of the longest-running NFM pilot sites in the UK, and has an extensive hydrological monitoring network, making it ideal for investigating natural flood storage ponds. We analyzed available water level data across all the monitored ponds within the catchment, alongside relevant local river discharge and rainfall data, to evaluate the ponds against several performance metrics.

TABLE 1 | Summary of monitored ponds in the Eddleston Water catchment. Acronyms refer to the location name; numbers refer to the number of the pond when in a group.

Summary data	WD4	NC3	RD1	RD2	RD3	KM
Catchment area (km^2)	0.10	0.97	0.42	0.17	0.57	59.35
Max pond depth (m)	0.28	0.74	2.0	0.84	0.61	1.4
Pond area (m^2)	487	998	3300	4178	2651	4119
Max storage (m^3)	139	736	6649	3497	1608	5739
Installation date	2014	2014	2019	2019	2019	2017
Monitoring	03/2015—	09/2015–01/2018	07/2021 —	07/2021 —	07/2021 —	11/2018 —
Pond type	Online	Online	Offline	Online	Online	Offline

2.1 | Site Description

The monitored ponds were in two main areas: one location along the main river stem near the catchment outlet, and multiple locations in the north-western headwaters of the Eddleston river.

2.1.1 | Catchment Description

Elevation ranges between 180 and 600 masl across the catchment. At Eddleston Village, mean annual precipitation (2011–2024) is ~1100 mm, falling mainly as rainfall; monthly mean air temperatures are 3°C–13°C; and actual daily evapotranspiration ranges from 0.2 mm in winter to 2.5 mm in summer (estimated using methods of Granger and Gray (1989) from weather station data at Eddleston Village). Land cover is mainly improved or semi-improved grassland on the lower slopes, rough heathland at higher elevations, and marshy ground in hollows (Medcalf and Williams 2010). Forest cover was historically limited in most of the catchment, but extensive coniferous plantations (primarily Sitka spruce, *Picea sitchensis*) were established in the 1960s and 1970s with up to 90% forest cover in some of the western sub-catchments (see Peskett et al. 2021). Soils in the western sub-catchments include extensive areas of poorly permeable gley soils and peats, but also areas of more freely draining brown soils, whilst the east is dominated by brown soils with some peaty and gley soils on hilltops.

2.1.2 | Main Stem Ponds

Two flood storage ponds and one bund adjacent to an existing pond have been installed along the main Eddleston river, close to the catchment outlet, with catchment areas varying from 50 to 59 km^2 (Figure 2). We focus on the Kidston Mill flood storage pond—one of the oldest ponds installed in 2017 and with the longest monitoring dataset. It is fed by an earth bank spillway from the main Eddleston River and has an upstream catchment area of ~59 km^2 and a catchment dominated by semi-improved and improved grassland (55%), with the remaining areas approximately equally split between forest, wetland, and heathland. The reach upstream of the pond has an average slope of 0.2°. Design drawings for the pond were produced along with 2D hydraulic modeling prior to pond installation to model the effect of the pond on peak flows and lag times, as well as the effect of adding multiple ponds of the same design in series (Spray et al. 2016). It was designed to have 0.66 m freeboard, which is controlled by a single outlet pipe of 180 mm diameter. In addition, it has a natural 10.7 m wide spillway, 0.6 m below the embankment height, which is reinforced with boulders at the sides and gravel and cobbles in its base, which is now mostly vegetated.

2.1.3 | Cowieslinn Ponds

The Cowieslinn catchment is situated in the NW of the wider Eddleston catchment. It has an area of 5.6 km^2 to the stream gauge and is a rural catchment dominated by improved grassland (39%) and plantation forest (38%), primarily underlain by glacial till. Various NFM measures have been installed in the catchment, including 12 storage ponds, transverse hedge strips to intercept runoff, and numerous leaky wooden log jams. The storage ponds are in three main groups that were installed at different times (Table 1). All ponds contain a 150 mm diameter outlet pipe designed to activate when the pond has approximately 0.3 m of freeboard relative to the spillway. None of the ponds has a formally designed spillway, but bank overflow occurs at the lowest topographic point close to the downstream extent of the pond in each case (indicated by orange lines in insets on Figure 2).

1. Wester Deans ponds: Four ponds (Wester Deans 1–4) were excavated in 2014 close to the Cowieslinn Burn running through Wester Deans Farm and fed mainly by field drains from the adjoining fields. The average slope of the river upstream is 4°.
2. North Cloich ponds: Five ponds (North Cloich 1–5) were excavated in 2014, intercepting runoff and resulting flow within ditches established during a previous conifer stage of forest planting (now felled). The average slope of the river upstream is 7°.
3. Ruddenleys ponds (Figure 3): Two 'online' ponds and one 'offline' pond constructed in 2019 in an area of felled plantation forest. The average slope of the river upstream is 5°.

2.2 | Stream and Pond Level Monitoring

Stream water levels have been measured every 15 min (Hobo U20 0–3.5 m or In Situ Rugged Troll 100 0–9 m unvented pressure-based

FIGURE 3 | Ruddenleys ponds: 1 (West); 2 (North) and 3 (East) (left to right). Photos L Peskett © Scottish Government, 2023.

water level recorders) since April 2011 in most sub-catchments. Discharge was calculated at the same time step using rating curves derived from applying the mid-section method (Dingman 2014) to velocity-area gauging at natural rated sections approximately eight times a year under a range of conditions. Stream discharge monitoring has been conducted up- and downstream of the Kidston Mill pond since April 2011. Discharge monitoring has been conducted in the Cowieslinn catchment since October 2014, and upstream and downstream of the Ruddenleys pond site since September 2020 and July 2019 respectively.

Pond water levels have been measured using the same types of water level recorders as used in the streams (Figure 4). The recorders were installed around 1 m from the bank of the ponds and as low as possible to record minimum water levels. Several ponds have been bathymetrically surveyed using GPS, and a survey was conducted for all ponds to measure their inlet and outlet geometry and relationships to the local drainage network.

Rainfall is measured at tipping-bucket rain gauges (TBRs) with a 15-min logging interval around the Eddleston catchment, initially with RIM8020 gauges and incrementally complemented by aerodynamic ARG100 and SBS500 designs (Figure 3). Rainfall data has been collected in or near Cowieslinn catchment at Cloich Forest (since August 2016); Wester Deans Farm (since June 2019); and the nearby Shiplaw catchment (~1 km to the east) since March 2011.

Groundwater levels are not measured directly in the vicinity of the ponds. However, based on other sites in the catchment and observations of the ponds at different times of year, they are expected to be above the level of water in the ponds in winter in Wester Deans and North Cloich and below the level of water in the ponds in Ruddenleys and Kidston.

2.3 | Data Analysis

We analysed pond performance using available water level, stream discharge, and rainfall data. The analysis centred on calculating metrics of pond performance using a sample of events. A similar approach was used in recent papers at other NFM sites (Lockwood et al. 2022).

2.3.1 | Event Selection

We selected events from peaks exceeding a threshold in the nearest downstream flow data. Given the short length of most pond records and our interest in responses to larger events, the threshold was chosen to give an average of ~8 events per year from which to calculate simple metrics of pond response. To reduce problems of noise in the data, LOWESS smoothing with a two-hour span (Cleveland 1981) was applied to the stream level dataset prior to the selection of events.

2.3.2 | Pond Antecedent Conditions, Recession Rates and Impact

The following metrics were produced to analyze the response of each pond, including:

1. Capacity prior to event: Pond capacity at the time the level starts to rise prior to the event peak, relative to maximum recorded storage capacity. The maximum storage capacity was taken as the difference between the 5th and 95th percentiles of pond level multiplied by the pond area. As the bathymetry of some of the ponds is unknown, they were assumed to have vertical sides, giving conservative estimates for all metrics.
2. Recession:
   - Median recession rate for all recession periods during events when the pond is >50% full. Only nighttime recession periods with no rain in the previous six hours or following two hours were taken to account for impacts of rainfall and evaporation (method after Kirchner, 2009). We also calculated event drainage time to 50% capacity for events where this occurred prior to the onset of the next event.
   - Relative pond levels and relative peak timings compared to the nearest stream gauge (to indicate whether and by how much the pond is filling or draining during the peak of the event).
3. Impact: The 'impact' of the ponds was calculated for ponds with a nearby stream gauge as the fraction of stream flow stored by the pond compared to the stream flow at each time step:

$$\text{Impact} = \frac{\frac{dS}{dt}}{\left(\frac{dS}{dt} + Q\right)} \,.\, 100\,\%.$$

with:

$$\frac{dS}{dt} = \frac{Pond\ level\ (t_2) - Pond\ level\ (t_1)}{\Delta t}.A$$

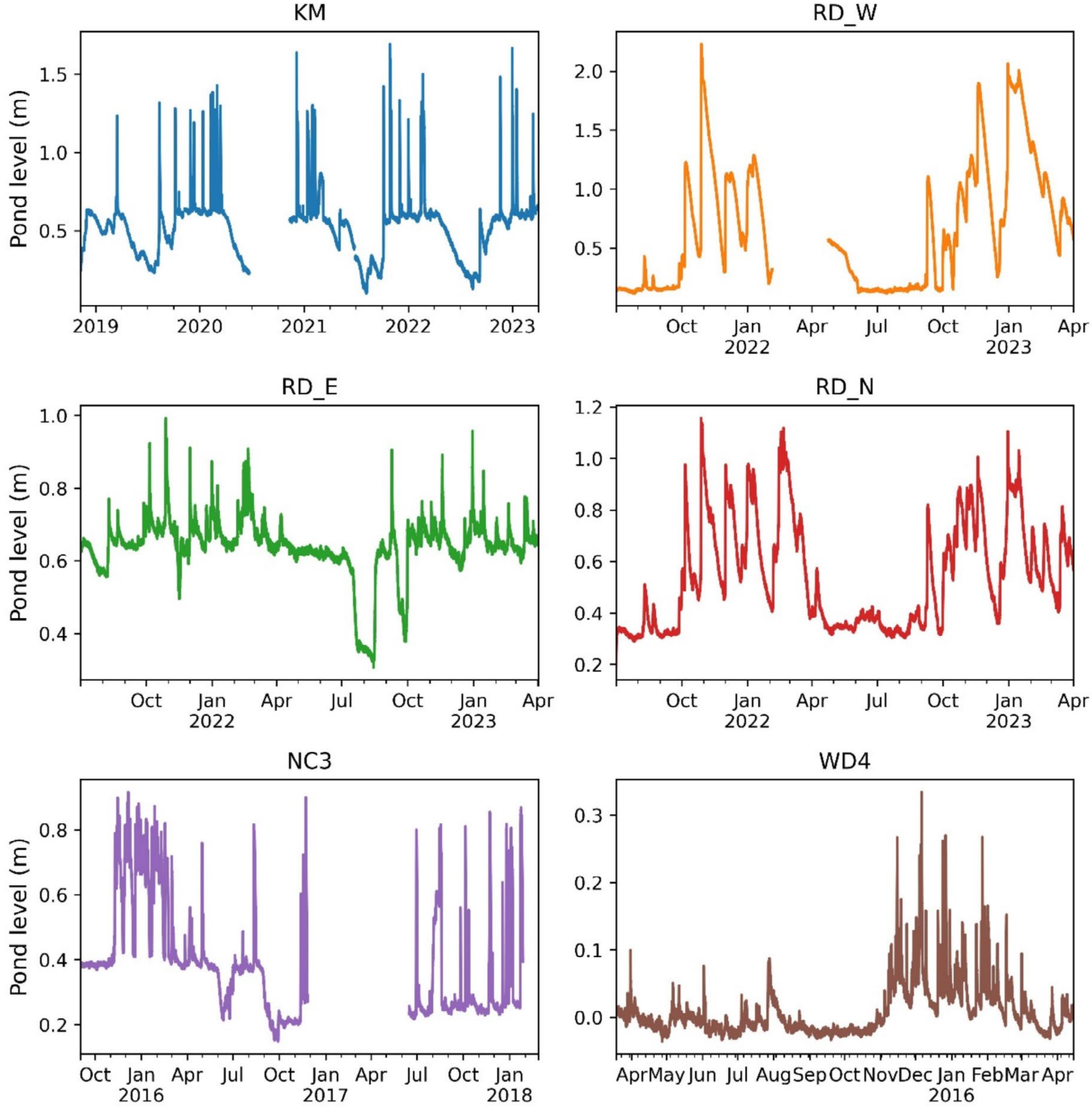

FIGURE 4 | Time series data for water levels in the six ponds discussed in the study. Gaps in data are due to instrument failure.

where S is water stored, t_1 and t_2 are time steps (15 min) (Δt is t_2—t_1), A is the area of the pond in m^2 and Q is downstream river flow in $m^3\ s^{-1}$. This involves the following assumptions (Quinn et al. 2013): the storage/attenuation of flow along the travel paths to and from the pond is not quantified; it has been assumed that the pond is closely coupled to the channel. This is a reasonable assumption for the majority of ponds. Moreover, the local lateral overland flow inflows from the pond are assumed small and are neglected based on knowledge of pond design and observation of inflow channels at the ponds during high flow events. Infiltration losses are also assumed small based on the underlying soil and rock type (clay rich gleyed soils and glacial tills with low hydraulic conductivities—Archer et al. 2013), and also pond construction, which involved destruction of any field drains and puddling of the pond base.

2.3.3 | Upstream–Downstream Lag Time in Peak Stream Flows

Given the phased installation of the ponds and the monitoring network, we used two different methods to investigate the impact of ponds on the lag time of peak stream flows. In the upper Cowieslinn catchment, we compared peak flow timing pre and post-Ruddenleys pond installation at the Cowieslinn stream gauge, with the neighbouring Shiplaw catchment as a control. This assumes that the other smaller ponds are having a negligible impact, a point reinforced by our investigation of the impact in Section 3.3. For the Kidston Mill pond, we compared lag times between the stream gauge upstream and downstream of the pond pre and post pond installation. We also compared this with two other control reaches further upstream, which had fewer natural flood management measures installed in the monitoring period.

2.3.4 | Antecedent Conditions

We assessed the frequency of events with multiple peaks over the whole time series and their potential impact on pond performance. Multi-peaked events were defined as when a peak over the threshold (POT) was preceded by another POT within the calculated 50% drainage time of the pond.

3 | Results

3.1 | Pond Storage Capacity

Ponds are quite variable in available capacity prior to events (31%–78%). NC3 has the lowest capacity prior to events, whilst the RD1 and KM have the greatest. As shown in Table 2, the Ruddenleys ponds (particularly 1 and 2) have considerable capacity relative to the upstream catchment area. However, there is also considerable variability in prior storage capacity between events for RD1, RD2, and NC3, probably linked to their slow drainage rates discussed below (Figure 5).

The calculated pond capacities compared to catchment area suggest that most have limited capacity to store a significant fraction of storm runoff. Three of the ponds store less than 1 mm of runoff, either due to being situated in large catchments or due to the small size of the ponds. The RD1, RD2, and WD4 are an exception: the Ruddenleys ponds are relatively large ponds situated in a small headwater catchment ($< 1\,km^2$), whilst WD4 is a small pond draining a micro-catchment ($0.1\,km^2$).

3.2 | Pond Retention Times

The ponds vary in the rate at which they drain after an event, from a median recession rate of 0.0011 to $0.016\,m^3\,s^{-1}$. When considered as an estimate of time to drain to 50% of their maximum capacity, ponds vary between ~12 and 0.2 days (Figure 6). The rate of recession has an impact on pond performance, particularly during wet periods and frontal rainfall events. RD1 and RD2 in particular are very slow to drain and do not appear to drain significantly between October and April in the years they have been monitored (Figure 4). NC3 drains more quickly than RD2 and RD1, but during the extremely wet winter of 2015/16, several ponds had high levels for weeks.

In dry summer periods, some of the ponds drop to new base levels. For example, RD3 generally drops to a level close to the 50% threshold level quite quickly, but it can drop quite quickly below this in prolonged dry weather. KM also drops to a winter base level, but slowly falls below this level in summer to a relatively stable summer level. WD4 drains quickly, but it also fills quickly.

3.3 | Impact on Stream Flows

The data suggest that the ponds have a variable impact on reducing peak stream flows. Three of the ponds have a small impact (up to ~1% median reduction in stream flow at the peak of the event), whilst the three Ruddenleys ponds have a larger impact (~3%–14% median reduction), although this varies widely between events (Figure 7).

The timing of pond impact on flows (i.e., whether it is near the peak of the event) is also important. Two of the ponds (WD4 and NC3) consistently peak before peak stream flow, so they are having a minimal impact at peak stream flow. For WD4 the peak is substantially sooner (2.25 h), but this is partly a function of the distance of the pond from the stream gauge (~1 km). KM and RD3 have an impact on stream flows approximately 50% of the time, whilst RD1 and RD2 have an impact on all analysed peaks (Figure 8). However, the scale of the impact is limited for KM, which only has an impact $> 0.1\%$ if prior available capacity is high ($> \sim 60\%$) and peak flow is $<\sim 13\,m^3\,s^{-1}$.

This is illustrated in Figure 9a which shows how the pond contributed a small reduction in stream flow during the rising limb, but no discernible reduction at peak stream flow for the largest event recorded at KM (~21% AEP). The maximum impact is 1% for flows of 10–12 m^3/s, which is equivalent to an ~66% AEP (Figure 9b). Hydraulic modeling of KM during the design phase considered events of approximately this magnitude (Spray et al. 2016).

By contrast, Figure 10 shows an example of an event at Ruddenleys ponds, for which the ponds contribute to a relatively large reduction in stream flow at the peak of the event (~18%). This is an event where the ponds were relatively empty before the event began. As highlighted in Figure 5 this is rarely the case for these ponds and tends to occur at the end of long dry periods in summer.

3.4 | Impact on Lag Time

Comparison of pre and post pond installation lag times for the upstream catchment showed no difference pre and post installation of the Ruddenleys ponds ($n = 30$ events pre and 36 events post installation), although there was more variability in lag times post installation (IQR of 75 and 122 min respectively). On the main stem, by contrast, a change in lag times of 0.75 h was observed in the period following the installation of the ponds ($n = 57$ pre and 35 post installation). Lag times also increased in control reaches further upstream on the main stem, but these were only 0.25 h, suggesting that around 0.5 h of difference in lag time could be explained by Kidston Mill pond, assuming no other changes on the reach with the pond. However, there is considerable variability in lag times pre and post installation (IQR of 75 and 83 min respectively) and the difference in medians is not significant.

3.5 | Effect of Antecedent Conditions on Pond Performance

Analysis of catchment antecedent conditions in terms of 7-day pre-event rainfall suggests that pond responsiveness to antecedent rainfall varies between ponds. All ponds showed a slight trend of reducing capacity with increasing antecedent wetness, as would be expected. We found no evidence that offline ponds are filling significantly from other inlets (e.g., runoff from local

TABLE 2 | Summary of results from analysis of pond data. Values are medians, number of events (n) in parentheses.

Question	Indicator	KM	RD1	RD2	RD3	NC3	WD4
1. What is available pond storage capacity prior to events?	% available storage prior to event	65 (26)	77 (10)	52 (15)	37 (15)	31 (19)	78 (13)
	Depth of storage cf. catchment area (mm)	0.06	10	9.0	0.99	0.23	6.4
2. Is the pond remaining full during peak streamflow in the nearest stream gauge?	Lag time pond vs. river (hrs) (+ve = pond level peaking before event peak)	−0.12 (26)	−19 (10)	−2.0 (15)	−0.24 (15)	1.5 (19)	2.3 (13)
3. How are ponds draining following an event?	Event drainage rate ($m^3 s^{-1}$)	0.016 (21)	0.0017 (5)	0.0028 (10)	0.0020 (11)	0.0011 (14)	na (0)
	Estimated drainage time to 50% capacity from drainage rate (days)	1.9 (21)	11.8 (5)	5.0 (10)	4.0 (11)	3.4 (14)	na (0)
	Time to reach 50% capacity (days)	1.9 (18)	8.9 (2)	6.8 (3)	na (0)	1.9 (7)	0.19 (13)
4. What is the magnitude and timing of pond impact on stream flow?	Max dS/dt vs. stream flow (%)	1.4 (26)	30 (10)	32 (15)	22 (15)	9.0 (19)	3.2 (13)
	dS/dt at peak stream flow vs. peak stream flow (%)	0.011 (26)	14 (10)	2.1 (15)	0.33 (15)	−0.22 (19)	−0.30 (13)
	Lag between max dS/dt and river peak (h). (+ve = pond peak dS/dt before river)	2.5 (26)	1.4 (10)	0.75 (15)	1.5 (15)	5.3 (19)	5.5 (13)
5. How have downstream lag times changed pre/post installation of ponds?	Change in lag time pre/post installation (h). (−ve = decrease)	0.75 (92)	0 (66)	0 (66)	0 (66)	0 (66)	0 (66)

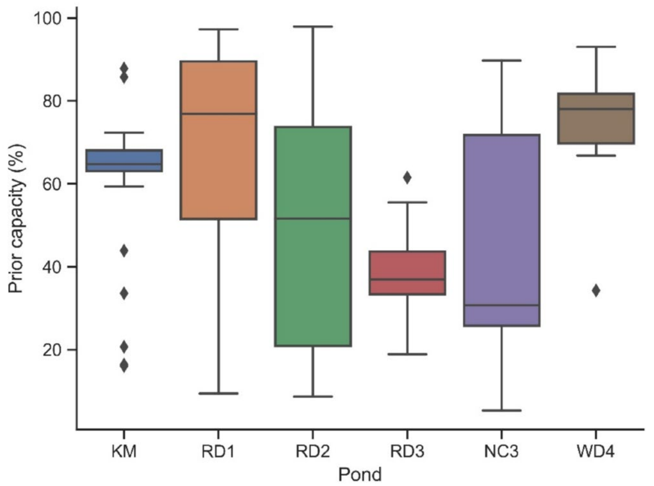

FIGURE 5 | Available capacity (%) in the pond prior to high flow event.

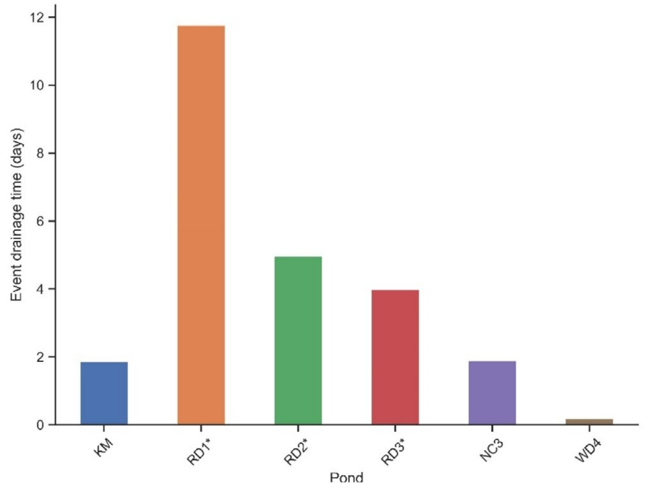

FIGURE 6 | Time taken after high flow events to drain to 50% capacity. Where $n<5$, drainage time is estimated from drainage rate after high flow event (indicated by *).

agricultural fields or groundwater) as is the case in some studies (e.g., Lockwood et al. 2022). In general, ponds with longer retention times (e.g., RD1 and RD2) were more sensitive, whilst those that drain more quickly were less sensitive (e.g., KM). However, even KM appears to have been affected by multiple peaked events over the monitoring period. Figure 11 illustrates this for the whole monitoring period—had the pond been installed back in 2011, the pond would not have had a chance to empty to its 50% level prior to the next event in around 17% of peak flows.

4 | Discussion

4.1 | Impact of Ponds on Flood Peak Magnitude and Lag Times

The results indicate high variability in pond response across the Eddleston catchment. The maximum observed impact on peak flows was an 18% reduction. Whilst this is a considerable reduction, it was for a relatively large pond in a small catchment (0.42 km^2), a 21% AEP event, and following a dry period in which the pond was empty. The impact of the Kidston Pond—a larger pond in a larger catchment (59 km^2) – was unobservable for the same event. Its maximum impact was a 1% reduction in peak flows for a 66% AEP event. These results are difficult to compare with other studies given differences in catchment areas and pond design, but are of a similar order of magnitude to Lockwood et al. (2022) who observed up to 7% reductions for a 32% AEP event in an ~6 km^2 catchment, and Nicholson et al. (2020) who observed a 12% reduction for a 66% AEP event in an ~6 km^2 catchment. However, all of these studies suggest that such ponds are likely to have negligible impacts on much lower AEP events (e.g., < 2%) often associated with significant flooding.

Whilst there is significant variability in how ponds respond in Eddleston, the analysis also shows some more generalisable findings. Firstly, it illustrates the importance of total pond storage capacity across catchments like Eddleston. The overall installed capacity is small (~18,400 m^3 for the monitored ponds) compared to the size of the catchment and the runoff generated (median daily runoff ~60,000 m^3 at Kidston Mill (Peskett 2020)), implying the need for many more ponds in such a catchment. This corresponds with other studies that have suggested a need for vast increases in the cumulative volume of natural storage features across catchments in order to impact large flood events (Follett et al. 2024). Saying this, the Ruddenleys ponds demonstrate the scale of impact that is possible in much smaller catchments (< 1 km^2), so their potential for very localised flood mitigation. The benefits of NFM for small catchments and the management of localised flood events have been demonstrated in various studies (Dadson et al. 2017; Wilkinson et al. 2019) and our results support these findings, but also highlight the importance of specifying clearly what size of catchment and event schemes are targeting.

Secondly, storage capacity is intrinsically linked to the retention time of ponds (Beven et al. 2022). This was found to be highly variable across the different ponds. Many of the ponds have retention times greater than a day, meaning that they are likely to struggle during prolonged wet periods such as frontal rainfall events. The data show that the long retention times for the most effective ponds (Kidston Mill and Ruddenleys 1) in Eddleston significantly reduce their impact in double-peaked events. A similar issue has been observed in other catchments—Lockwood et al. (2022), for example, found that the two upstream ponds monitored in their system were > 66% full and one of the downstream ponds takes up to seven days to drain. Some catchments have tried to address this challenge by designing ponds to drain in < 24 h and/or having adjustable outlets that shorten the retention times to a few hours (e.g., Belford) (Wilkinson et al. 2010). Recent literature on retention times in NFM suggests that ~10 h is the optimal time for ponds to drain to accommodate sequences of events in a UK context (Follett et al. 2024; Wren 2022). There is, of course, no perfect retention time, as this is governed by both the nature of the weather event and antecedent conditions. Recently, real-time control optimisation techniques have been used in retention basins worldwide (Gomes Júnior et al. 2024, 2022; Oh and Bartos 2023), which would be extremely useful in networks of natural storage ponds. These are more common in grey infrastructure networks and are highly technical solutions that may not be deemed suitable for NFM projects. However, they have been explored in natural flood management contexts (Roberts et al. 2023; Leon et al. 2018) and in low-cost water management contexts (Rohrer and Armitage 2017), suggesting that these approaches have potential in certain contexts, especially with rapid developments in technology and management approaches.

Whilst the monitoring of ponds in Eddleston has been conducted for a relatively long period compared to many UK NFM projects, it also demonstrates some of the challenges. Key among these is the need to adapt monitoring strategies as new measures are implemented and to be opportunistic in terms of resourcing monitoring programmes, which are often underfunded in catchment restoration projects and require voluntary cooperation from land managers (Spray et al. 2022). This has led to some gaps in data and challenges in directly comparing pond response through a Before-After-Control-Intervention (BACI) approach (Spray et al. 2022). However, the network has captured data for a range of catchment conditions including some relatively high flow events, so we are confident that it gives useful insight into the performance of natural flood storage ponds in these contexts.

An uncertainty in the research relates to wider changes in the catchment over the monitoring period. This includes significant deforestation and afforestation in the upper catchment (Cowieslinn) since 2018, which could potentially have an impact on the catchment water balance (Peskett et al. 2021) and mask the impacts of ponds. However, while this may have changed the inputs to ponds and potentially reduced the number of observed high flow events, it is unlikely to have significantly changed the input/output response of the ponds themselves, which has been the focus of the study. Another uncertainty surrounds pond geometry and volume, which have not been accurately quantified for all ponds through detailed bathymetric surveys. However, our estimates assume ponds are vertically sided tanks, so provide conservative estimates.

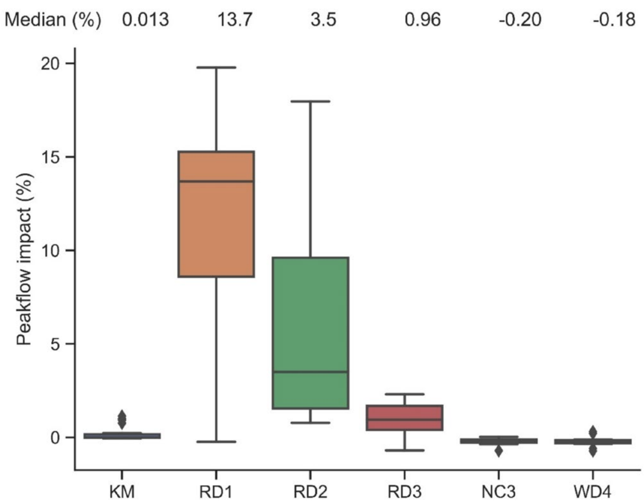

FIGURE 7 | Impact of pond at peak stream flow, comparing rate of change of storage in the pond to flow at the nearest downstream gauge.

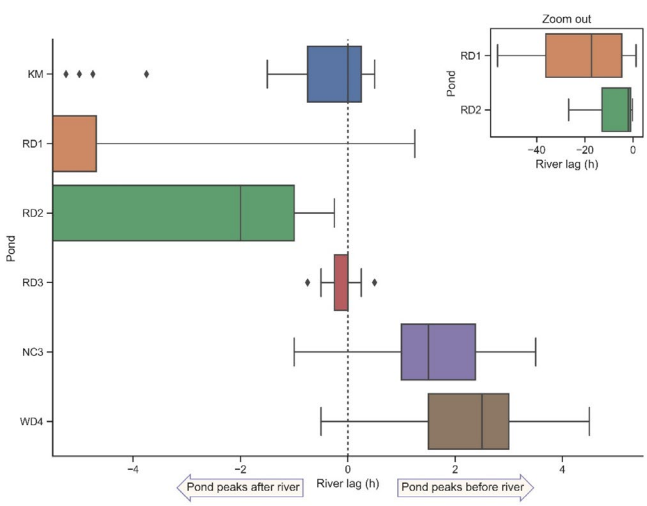

FIGURE 8 | Lag between the highest water level in the river at the nearest downstream gauge and in the pond. Positive values indicate that the pond is filling during the rising limb and full at peak; negative values indicate the pond is still filling during the peak.

4.2 | Implications for Natural Flood Management

The study raises several implications for natural flood storage pond design. The results support other studies suggesting that offline ponds may be more effective interventions than online ponds as they can target particular magnitude events more easily (Quinn et al. 2022). They also suggest the need for considerably more storage to be installed in meso-scale catchments similar to Eddleston, which raises questions in how to navigate different stakeholder preferences surrounding what is acceptable in terms of the number and size of ponds, and the optimal water level that is maintained between events, which may differ between engineers, farmers, and ecologists (Mobley and Culver 2014). Whilst we have not considered pond location in detail in this study, the analysis demonstrates a more general point surrounding how available pond storage capacity relative to catchment area affects performance. RD1 has the potential for significant impact on stream flows because of its large storage capacity compared to the 0.5 km^2 catchment it is situated in (storing ~9 mm of runoff). KM is larger but is situated in a larger catchment (storing < 1 mm of runoff) and begins to fill at a modest flow threshold, so alone is unlikely to have an impact on large events. The findings from this study have, however, helped to corroborate predictions from hydraulic models of the KM on small-medium events and give some confidence in the estimates of additional impact from ongoing pond installation on the main river stem.

Our results demonstrate the importance of optimal pond design for NFM flood storage ponds. In particular, for offline ponds, the elevation of inlet structures relative to the inlet stream bed is a key design criterion and should be designed to target specific magnitudes of event (Lockwood et al. 2022; Nicholson et al. 2020). This is well illustrated by the data from KM, which was designed to target the 66% AEP event using a hydraulic model, and our analysis suggests it is having the greatest impact at this magnitude. The outlet structures are equally important in controlling pond retention times, and there are differences between the performance of the ponds in Eddleston that have been formally designed and those that use more standardised approaches to outlet design. Both inlet and outlet structures require regular maintenance to reduce

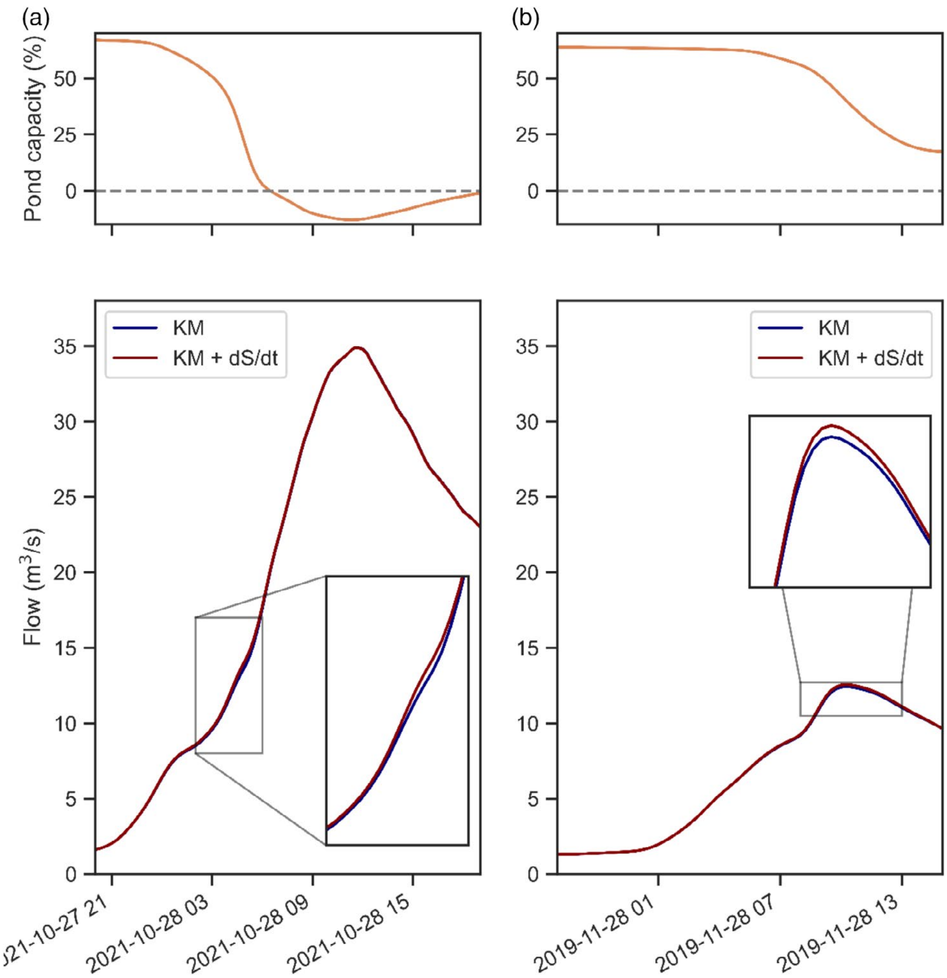

FIGURE 9 | Available pond capacity prior to the event (%) and impact on streamflow at Kidston Mill pond for (a) the largest event on record (~21% AEP) and (b) the event where the pond had the largest impact (~66% AEP). Note that capacity below 0% is because the maximum pond level is taken as the 95th percentile level, rather than the maximum recorded level.

problems of erosion, scour, siltation, and blockage (Wren 2022). Despite relatively stable channel structures in the vegetated upland peat and Brown Earth soil environment of Eddleston, there are signs of erosion and scour affecting pond inlet geometry and gradual siltation of some ponds affecting their capacity. It is not clear in many NFM schemes that these costs and requirements are factored into the development process despite many decades of experience in the design of retention ponds (Verstraeten and Poesen 1998). Detailed design guidance that has been produced in recent years should help with the development and maintenance of future ponds (Woods-Ballard et al. 2015).

The results demonstrate the value of hydrological/hydraulic modelling for the design of ponds or at least the benefit of some local pre-installation data on stream flows. In many catchments, there is likely to be a lack of local stream level monitoring data, which could create significant design challenges (Hankin et al. 2017). In addition, it may be useful to design ponds so that they are adjustable once installed in order to target specific magnitude events or to respond to different types of event (e.g., frontal rainfall events where there are wet antecedent conditions) (Lockwood et al. 2022). Designing in active and reactive management of adjustable pond outlet structures and pond networks, which, as noted in Section 4.1, has shown potential in more grey infrastructure settings, would help optimise their performance and should be considered in future NFM implementation where this is possible. However, this raises further issues surrounding the need for long-term monitoring so that ponds can be adjusted in relation to their known performance (Roberts et al. 2023), higher economic costs as the design and maintenance requirements increase (Mulligan et al. 2023), and the need for long-term landowner support and clear agreement about responsibilities for maintenance (Spray et al. 2022).

Another issue highlighted by this research relates to how NFM deals with both short- and long-term variability in catchments. These include key spatial uncertainties about where to locate ponds and their potential effects on the relative delay of flood peaks in tributaries (Hankin et al. 2017; Pattison et al. 2014) but also their response to different weather events and antecedent wetness conditions. As illustrated in Section 3.5, multi-peaked events have been relatively common in Eddleston over the 14-year monitoring period. Given the relatively long retention times in many of the ponds, these could significantly reduce the effectiveness of flood storage ponds on downstream flood risk. Longer-term increases in peak rainfall intensity and wetter winters that are predicted to arise from climate change suggest that these factors need to be considered in pond design (Hanlon et al. 2021).

The study raises some questions about the 'naturalness' of pond installation for flood management in rural areas or whether it is more akin to catchment engineering (Hewett et al. 2020). It is clear from the above discussion that flood storage ponds need considerable design input prior to their installation, as well as ongoing adjustment and maintenance. This in turn requires baseline data and potentially external expertise and resourcing issues. Eddleston is in many respects typical of other NFM catchments in the UK in that it has been developed with limited funding and significant, often voluntary, input from local land managers. Pond design and placement has had to flex depending on resource constraints and land manager preferences, with many of the ponds having no budget for design or modelling, and many sold to landowners on the basis that they were getting water features rather than temporary storage structures. This is likely to be true in many catchments and highlights the need for effective support in terms of guidance and finance if these approaches are to be incorporated into effective flood management strategies.

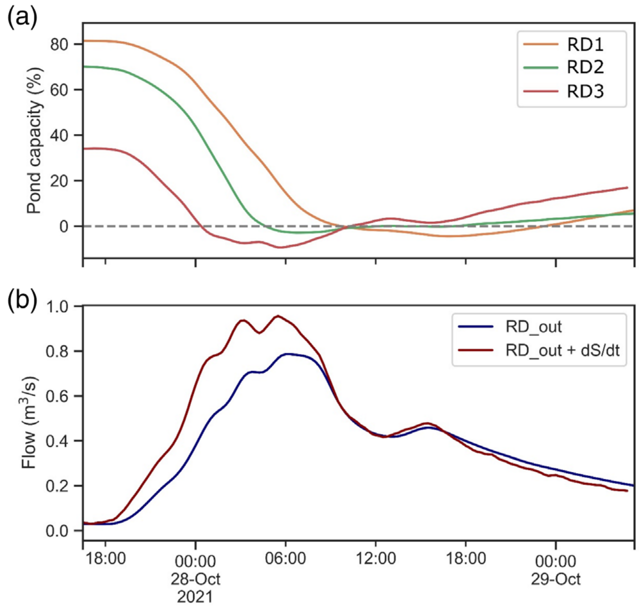

FIGURE 10 | Example event (21% AEP) at Ruddenleys ponds, showing (a) how available pond capacity changes during the event for each of the ponds, and (b) the impact this has on reducing stream flows. Note that available capacity below 0% is because the maximum pond level is taken as the 95th percentile level, rather than the maximum recorded level.

This discussion has not covered the wider benefits of natural flood storage ponds, for example in terms of their pollution management, agricultural production, biodiversity, or recreational value. Such benefits can be significant (Ibrahim and Amir-Faryar 2018; Krivtsov et al. 2020; Staccione et al. 2021) and could help justify the financing of NFM, for example through new biodiversity markets (Green Finance Institute 2024). However, the potential negative impacts of significant increases in storage also need to be considered, such as changes in sediment supply or maintenance of adequate low flows to support local biodiversity. This highlights the need to evaluate the potential of flood storage ponds holistically within broader multifunctional catchment management planning (Fahy et al. in review).

5 | Conclusions

Our analysis of the operation of natural flood storage ponds in the Eddleston catchment provides important insights on the impact

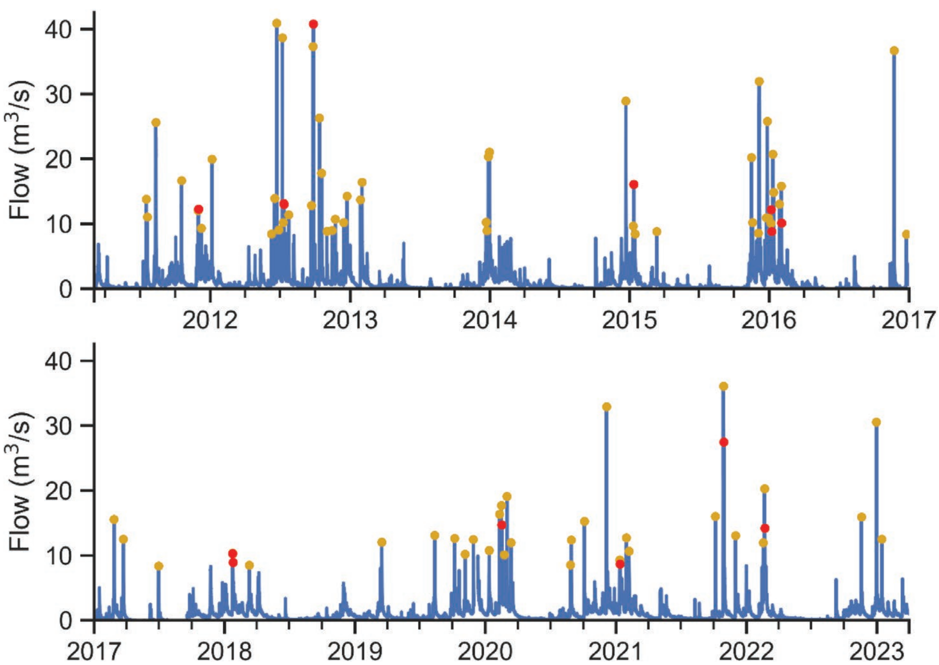

FIGURE 11 | Flow at Kidston Mill. Yellow dots show peaks. Red dots show peaks that are preceded by another (yellow) peak within the last 1.9 days (the estimated time it takes for this pond to return to 50% full).

of these approaches in other UK and international contexts. The ponds generally have a low impact on peak stream flows for larger storm events and in larger sub-catchments, suggesting the need for much greater installed capacity across the catchment. However, pond response is also highly variable, due particularly to differences in their capacities, and the design of inlet and outlet structures that influence their capacity prior to storm events. These findings point to the need for both more ponds, and more design and maintenance of ponds within NFM schemes in order to deliver benefits from a flood management perspective. This raises practical challenges and is perhaps the most important insight from the study. Every pond has involved negotiation with landowners and a degree of opportunism, which has undoubtedly affected their design, operation and maintenance. The data therefore highlight the potential benefits in a 'typical' implementation setting, particularly relevant in the UK uplands, but likely to arise in many meso-scale catchments worldwide. These practicalities, along with attention to pond engineering, need to be factored into future support for such measures in NFM schemes.

Acknowledgements

We would like to thank the Tweed Forum for supporting this study as part of the Eddleston Water Project. The project is a partnership initiative led by Tweed Forum, with the Scottish Government, SEPA and University of Dundee, and is funded by the Scottish Government and the Scottish Environmental Protection Agency. Other key partners include British Geological Survey, NatureScot, Scottish Borders Council, the Forestry Commission, National Farmers' Union of Scotland, the Tweed Foundation, Scottish Forestry, Forest Carbon and the Woodland Trust. We would also like to thank the Tweed Forum and various local land managers who installed the ponds that were the focus of this study and who helped provide access to monitoring sites. For the purpose of open access, the author has applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising from this submission. Sarah Collins and Alan MacDonald publish with the permission of the Executive Director of the British Geological Survey (UKRI).

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

References

Abawallo, S. S., L. Brandimarte, and M. Maglionico. 2013. "Analysis of the Performance Response of Offline Detention Basins to Inlet Structure Design." *Irrigation and Drainage* 62, no. 4: 449–457. https://doi.org/10.1002/ird.1752.

Acreman, M., A. Smith, L. Charters, et al. 2021. "Evidence for the Effectiveness of Nature-Based Solutions to Water Issues in Africa." *Environmental Research Letters* 16, no. 6: 063007. https://doi.org/10.1088/1748-9326/ac0210.

Archer, N. A. L., M. Bonell, N. Coles, A. M. MacDonald, C. A. Auton, and R. Stevenson. 2013. "Soil Characteristics and Landcover Relationships on Soil Hydraulic Conductivity at a Hillslope Scale: A View Towards Local Flood Management." *Journal of Hydrology* 497: 208–222. https://doi.org/10.1016/j.jhydrol.2013.05.043.

Arnold, J. L. 1988. *The Evolution of the 1936 Flood Control Act*. Office of History, U.S. Army Corps of Engineers.

Ayalew, T. B., W. F. Krajewski, and R. Mantilla. 2015. "Insights Into Expected Changes in Regulated Flood Frequencies due to the Spatial Configuration of Flood Retention Ponds." *Journal of Hydrologic Engineering* 20, no. 10: 04015010. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001173.

Beven, K., E. Follett, B. Hankin, D. Mindham, T. Page, and N. Chappell. 2022. "*The importance of retention times in Natural Flood Management interventions* (IAHS2022-453). IAHS2022. Copernicus Meetings." https://meetingorganizer.copernicus.org/IAHS2022/IAHS2022-453.html.

Birkinshaw, S. J., and V. Krivtsov. 2022. "Evaluating the Effect of the Location and Design of Retention Ponds on Flooding in a Peri-Urban River Catchment." *Landscape* 11, no. 8: 1368. https://doi.org/10.3390/land11081368.

Brasil, J., M. Macedo, C. Lago, et al. 2021. "Nature-Based Solutions and Real-Time Control: Challenges and Opportunities." *Watermark* 13, no. 5: 651. https://doi.org/10.3390/w13050651.

Cleveland, W. S. 1981. "LOWESS: A Program for Smoothing Scatterplots by Robust Locally Weighted Regression." *American Statistician* 35, no. 1: 54–54. https://doi.org/10.2307/2683591.

Dadson, S. J., J. W. Hall, A. Murgatroyd, et al. 2017. "A Restatement of the Natural Science Evidence Concerning Catchment-Based 'Natural' Flood Management in the UK." *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* 473, no. 2199: 20160706. https://doi.org/10.1098/rspa.2016.0706.

Dingman, S. L. 2014. *Physical Hydrology*. 3rd ed. Waveland Press.

European Parliament and European Council. 2007. DIRECTIVE 2007/60/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the Assessment and Management of Floods. European Parliament and European Council.

Fahy, J., J. Dodd, C. Spray, and O. Beat. in review. "The Potential Contribution of Flood Management Ponds to Pondscape Biodiversity: Evidence From Dragonflies." *Ecological Solutions and Evidence*.

Flood and Water Management Act. 2010. http://www.legislation.gov.uk/ukpga/2010/29/contents.

Follett, E., K. Beven, B. Hankin, D. Mindham, and N. Chappell. 2024. "The Importance of Retention Times in Natural Flood Management Interventions." *Proceedings of IAHS* 385: 197–201. https://doi.org/10.5194/piahs-385-197-2024.

Forum, T. 2019. "The Eddleston Water Project Information Leaflet. Tweed Forum." https://tweedforum.org/our-work/projects/the-eddleston-water-project/.

Gomes Júnior, M. N., M. H. Giacomoni, A. F. Taha, and E. M. Mendiondo. 2022. "Flood Risk Mitigation and Valve Control in Stormwater Systems: State-Space Modeling, Control Algorithms, and Case Studies." *Journal of Water Resources Planning and Management* 148, no. 12: 04022067.

Gomes Júnior, M. N., A. F. Taha, L. M. Rápalo, E. M. Mendiondo, and M. H. Giacomoni. 2024. "Real-Time Regulation of Detention Ponds via Feedback Control: Balancing Flood Mitigation and Water Quality." *Journal of Hydrology* 643: 131866.

Granger, R. J., and D. M. Gray. 1989. "Evaporation From Natural Nonsaturated Surfaces." *Journal of Hydrology* 111, no. 1–4: 21–29. https://doi.org/10.1016/0022-1694(89)90249-7.

Green Finance Institute. 2024. *Financing Natural Flood Management*. Green Finance Institute.

Hankin, B., P. Metcalfe, D. Johnson, et al. 2017. "Strategies for Testing the Impact of Natural Flood Risk Management Measures." In *Flood Risk Management*, edited by T. Hromadka and P. Rao, 1–39. IntechOpen. https://www.intechopen.com/books/flood-risk-management/strategies-for-testing-the-impact-of-natural-flood-risk-management-measures.

Hanlon, H. M., D. Bernie, G. Carigi, and J. A. Lowe. 2021. "Future Changes to High Impact Weather in the UK." *Climatic Change* 166, no. 3: 50. https://doi.org/10.1007/s10584-021-03100-5.

Hewett, C. J. M., M. E. Wilkinson, J. Jonczyk, and P. F. Quinn. 2020. "Catchment Systems Engineering: An Holistic Approach to Catchment Management." *WIREs Water* 7, no. 3: e1417. https://doi.org/10.1002/wat2.1417.

Ibrahim, Y. A., and B. Amir-Faryar. 2018. "Strategic Insights on the Role of Farm Ponds as Nonconventional Stormwater Management Facilities." *Journal of Hydrologic Engineering* 23: 04018023. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001666.

Kay, A. L., G. H. Old, V. A. Bell, H. N. Davies, and E. J. Trill. 2019. "An Assessment of the Potential for Natural Flood Management to Offset Climate Change Impacts." *Environmental Research Letters* 14, no. 4: 044017. https://doi.org/10.1088/1748-9326/aafdbe.

Krivtsov, V., S. Birkinshaw, S. Arthur, et al. 2020. "Flood Resilience, Amenity and Biodiversity Benefits of an Historic Urban Pond." *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences* 378, no. 2168: 20190389. https://doi.org/10.1098/rsta.2019.0389.

Leon, A. S., Y. Tang, D. Chen, A. Yolcu, C. Glennie, and S. C. Pennings. 2018. "Dynamic Management of Water Storage for Flood Control in a Wetland System: A Case Study in Texas." *Watermark* 10, no. 3: 325. https://doi.org/10.3390/w10030325.

Lockwood, T., J. Freer, K. Michaelides, R. E. Brazier, and G. Coxon. 2022. "Assessing the Efficacy of Offline Water Storage Ponds for Natural Flood Management." *Hydrological Processes* 36, no. 6: e14618. https://doi.org/10.1002/hyp.14618.

Lucas-Borja, M. E., G. Piton, Y. Yu, C. Castillo, and D. Antonio Zema. 2021. "Check Dams Worldwide: Objectives, Functions, Effectiveness and Undesired Effects." *Catena* 204: 105390. https://doi.org/10.1016/j.catena.2021.105390.

McCuen, R. H. 1974. "A Regional Approach to Urban Storm Water Detention." *Geophysical Research Letters* 1, no. 7: 321–322. https://doi.org/10.1029/GL001i007p00321.

Medcalf, J., and H. Williams. 2010. *Scottish Borders Council and Tweed Forum Consortium Tweed Aerial Survey Phase 2: Aerial Photography Interpretation Land Cover Classification & Habitat Mapping.* Final Report. Scottish Borders Council and Tweed Forum. www.scotborders.gov.uk.

Mobley, J. T., and T. B. Culver. 2014. "Design of Outlet Control Structures for Ecological Detention Ponds." *Journal of Water Resources Planning and Management* 140: 250–257. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000266.

Molnar-Tanaka, K., and S. Surminski. 2024. "Nature-Based Solutions for Flood Management in Asia and the Pacific." https://www.oecd-ilibrary.org/development/nature-based-solutions-for-flood-management-in-asia-and-the-pacific_f4c7bcbe-en.

Mulligan, M., A. van Soesbergen, C. Douglas, and S. Burke. 2023. "Natural Flood Management in the Thames Basin: Building Evidence for What Will and Will Not Work." In *Greening Water Risks: Natural Assurance Schemes*, edited by E. López-Gunn, P. van der Keur, N. Van Cauwenbergh, P. Le Coent, and R. Giordano, 223–246. Springer International Publishing. https://doi.org/10.1007/978-3-031-25308-9_12.

Nicholson, A. R., G. M. O'Donnell, M. E. Wilkinson, and P. F. Quinn. 2020. "The Potential of Runoff Attenuation Features as a Natural Flood Management Approach." *Journal of Flood Risk Management* 13, no. S1: e12565. https://doi.org/10.1111/jfr3.12565.

Oh, J., and M. Bartos. 2023. "Model Predictive Control of Stormwater Basins Coupled With Real-Time Data Assimilation Enhances Flood and Pollution Control Under Uncertainty." *Water Research* 235: 119825.

Pattison, I., S. N. Lane, R. J. Hardy, and S. M. Reaney. 2014. "The Role of Tributary Relative Timing and Sequencing in Controlling Large Floods." *Water Resources Research* 50, no. 7: 5444–5458. https://doi.org/10.1002/2013WR014067.

Peskett, L. 2020. *Catchment Subsurface Water Storage, Mixing and Flowpaths: Implications for Land Cover Change as a Natural Flood Management Strategy*. University of Edinburgh.

Peskett, L. M., K. V. Heal, A. M. MacDonald, A. R. Black, and J. J. McDonnell. 2021. "Tracers Reveal Limited Influence of Plantation Forests on Surface Runoff in a UK Natural Flood Management Catchment." *Journal of Hydrology: Regional Studies* 36: 100834. https://doi.org/10.1016/j.ejrh.2021.100834.

Post, R., F. Quintero, and W. F. Krajewski. 2024. "On the Optimized Management of Activated Distributed Storage Systems: A Novel Approach to Flood Mitigation." *Water* 16: 1476. https://doi.org/10.3390/w16111476.

Quinn, P., G. O'Donnell, A. Nicholson, et al. 2013. *Potential Use of Runoff Attenuation Features in Small Rural Catchments for Flood Mitigation*, 35. Newcastle University. https://research.ncl.ac.uk/proactive/belford/newcastlenfmrafreport/reportpdf/June%20NFM%20RAF%20Report.pdf.

Quinn, P. F., C. J. M. Hewett, M. E. Wilkinson, and R. Adams. 2022. "The Role of Runoff Attenuation Features (RAFs) in Natural Flood Management." *Watermark* 14, no. 23: 23. https://doi.org/10.3390/w14233807.

Roberts, M. T., J. Geris, P. D. Hallett, and M. E. Wilkinson. 2023. "Mitigating Floods and Attenuating Surface Runoff With Temporary Storage Areas in Headwaters." *WIREs Water* 10, no. 3: e1634. https://doi.org/10.1002/wat2.1634.

Rohrer, A. R., and N. P. Armitage. 2017. "Improving the Viability of Stormwater Harvesting Through Rudimentary Real Time Control." *Watermark* 9, no. 6: 371. https://doi.org/10.3390/w9060371.

Sahoo, S. N., and S. Pekkat. 2018. "Detention Ponds for Managing Flood Risk due to Increased Imperviousness: Case Study in an Urbanizing Catchment of India." *Natural Hazards Review* 19: 05017008. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000271.

Scottish Government. 2009. Flood Risk Management (Scotland) Act 2009 (asp 6) (p. 68). Scottish Government.

Seddon, N. 2022. "Harnessing the Potential of Nature-Based Solutions for Mitigating and Adapting to Climate Change." *Science* 376, no. 6600: 1410–1416. https://doi.org/10.1126/science.abn9668.

Shen, T., R. Wang, P. Jiao, and Y. Wang. 2021. "Evaluation of Drainage Water Detention Efficiency of off-Line Ditch-Pond Systems and Its Influencing Factors." *Watermark* 13, no. 21: 3029. https://doi.org/10.3390/w13213029.

Spray, C., A. Black, D. Bradley, et al. 2022. "Strategic Design and Delivery of Integrated Catchment Restoration Monitoring: Emerging Lessons From a 12-Year Study in the UK." *Watermark* 14, no. 15: 2305. https://doi.org/10.3390/w14152305.

Spray, C. J., A. Baillie, H. Chalmers, et al. 2016. *Eddleston Water: Project Report*, 58. University of Dundee. http://tweedforum-org.stackstaging.com/wp-content/uploads/2018/08/Eddleston_Report_Jan_2017.pdf.

Staccione, A., D. Broccoli, P. Mazzoli, S. Bagli, and J. Mysiak. 2021. "Natural Water Retention Ponds for Water Management in Agriculture: A Potential Scenario in Northern Italy." *Journal of Environmental Management* 292: 112849. https://doi.org/10.1016/j.jenvman.2021.112849.

Verstraeten, G., and J. Poesen. 1998. "Flooding of Properties and Sedimentation in Retention Ponds in Central Belgium." *IAHS Publication* 249: 187–194.

Vineyard, D., W. W. Ingwersen, T. R. Hawkins, X. Xue, B. Demeke, and W. Shuster. 2015. "Comparing Green and Grey Infrastructure Using Life Cycle Cost and Environmental Impact: A Rain Garden Case Study in Cincinnati, OH." *JAWRA Journal of the American Water Resources Association* 51, no. 5: 1342–1360. https://doi.org/10.1111/1752-1688.12320.

Werritty, A., T. Ball, C. Spray, M. Bonell, J. Rouillard, and N. A. L. Archer. 2010. *Restoration Strategy: Eddleston Water Scoping Study*, 86. University of Dundee.

Wilkinson, M. E., S. Addy, P. F. Quinn, and M. Stutter. 2019. "Natural Flood Management: Small-Scale Progress and Larger-Scale Challenges." *Scottish Geographical Journal* 135, no. 1–2: 23–32. https://doi.org/10.1080/14702541.2019.1610571.

Wilkinson, M. E., P. F. Quinn, and P. Welton. 2010. "Runoff Management During the September 2008 Floods in the Belford Catchment, Northumberland." *Journal of Flood Risk Management* 3, no. 4: 285–295. https://doi.org/10.1111/j.1753-318X.2010.01078.x.

Woods-Ballard, B., S. Wilson, H. Udale-Clarke, et al. 2015. *The SUDS Manual Version 5*. 5th ed. CIRIA. http://www.scotsnet.org.uk/documents/nrdg/ciria-report-c753-the-suds-manual-v6.pdf.

World Bank. 2018. *Nature-Based Solutions for Disaster Risk Management*, 24. World Bank. http://documents.worldbank.org/curated/en/253401551126252092/pdf/134847-NBS-for-DRM-booklet.pdf.

Wren, E. 2022. *The Natural Flood Management Manual*. CIRIA.