The potential of runoff attenuation features as a Natural Flood Management approach

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Abstract
Natural Flood Management (NFM) is receiving much attention in the United Kingdom and across Europe and is now widely seen as a valid solution to help sustainably manage flood risk whilst offering significant multiple benefits. However, there is little empirical evidence demonstrating the effectiveness of NFM interventions in reducing flood hazard at the catchment scale. The Belford Burn catchment (~6km²) in Northern England provides a focus for this article, and utilises observed data collected throughout the NFM project’s monitoring period (2007–2012). This study discusses the introduction of catchment-wide water storage through the implementation of runoff attenuation features (RAFs), in-particular offline storage areas, as a means of mitigating peak flow magnitudes in flood-causing events. A novel experimental monitoring setup is introduced alongside an analytical approach to quantify the impact of individual offline storage areas, which has demonstrated local reductions in peak flow for low magnitude storm events. Finally, a physically based model has been created to demonstrate the impact of a network of offline storage areas to enable assessment of storage thresholds required to mitigate design storm events, thus enabling design of an NFM scheme. The modelling results have shown that peak flow can be reduced by more than 30% at downstream receptors.

KEYWORDS
flood defence measures, hydraulic modelling, hydrology, Natural flood management

1 INTRODUCTION
Following recent large flood events in Europe, concerns have been raised over the reliance on structural measures to manage future flood risk (e.g., Kundzewicz, Pińskwar, & Brakenridge, 2012; Scholz & Yang, 2010). It has been proposed that a more holistic catchment based approach is required, that includes the adoption of both structural and non-structural methods (Pitt, 2008). Natural Flood Management (NFM) is being widely promoted as a non-structural measure for reducing flood risk (European Commission, 2016; Scottish Government, 2019; Wilkinson, Addy, Quinn, & Stutter, 2019). NFM is defined as the alteration, restoration or use of landscape features to reduce flood risk (POST, 2011). It also utilises soft engineering methods, seeks to emulate natural processes and provide multiple benefits including habitat creation, carbon sequestration, and enhanced water quality. Approaches include increased water retention, for example, through the use of tree planting (Stratford et al., 2017); the creation of wetlands and ponds...
(Evrard, Vandaele, Van Wesemael, & Bielders, 2008; Metcalfe, Beven, Hankin, & Lamb, 2017; Nicholson, 2013), the management of the conveyance of the drainage network through large woody debris (LWD), wet woodlands (Environment Agency, 2017), and the restoration of river floodplains (Clilverd, 2016); and the restoration and management of peatlands (Shuttleworth et al., 2019). However, the uptake of these measures by practitioners remains limited (Waylen, Holstead, Colley, & Hopkins, 2018) and one factor controlling uptake is the limited evidence surrounding their effectiveness at the catchment scale. Interestingly, despite the evidence gap, a review of flood protection in England and Wales (EFRA, 2016) committed to catchment measures as part of future flood risk management schemes, the SEPA NFM handbook (SEPA, 2016) gave high-level guidance on the implementation of various NFM projects, the Defra 25 year Environment Plan (HM Government, 2018) called for expanding the use of NFM solutions in targets to reduce flood risk across England and Wales, and the Draft National Flood and Coastal Erosion Risk Management Strategy for England call for the use of NFM techniques to improve the resilience of schemes with respect to future climate change scenarios (Environment Agency, 2019).

There is limited empirical evidence demonstrating the effectiveness of NFM interventions in reducing flood hazard at scales greater than ~10 km² (Dadson et al., 2017; Wilkinson et al., 2019), particularly for measures that promote online and offline temporary storage (Environment Agency, 2017). Wide-ranging reviews of the impacts of rural land use and management practices have concluded that although changes in runoff can be significant at the field/plot scale, evidence of changes being transferred to downstream flood sites is lacking (McIntyre et al., 2013; O’Donnell, Ewen, O’Connell, & Quinn, 2007). This is not to state that impacts are not transferred downstream, but rather highlights a significant gap in understanding that is required for the effective implementation of NFM for flood alleviation.

Hydrological and hydraulic modelling has been used to gain indirect evidence of the impacts specific landscape interventions on downstream flooding (Bulygina, McIntyre, & Wheater, 2011; Metcalfe et al., 2017; O’Donnell, Ewen, & O’Connell, 2011). There has been a focus on land cover and land use management changes, with results from several studies suggesting that such interventions may be more effective at reducing flood risk at the smaller catchment scale (Hooijer, Klijn, Pedrol, & Van Os, 2004; O’Donnell et al., 2011). However, there are known limitations in current capabilities for the reliable prediction of the impacts of land use and management change on catchment scale flooding, for example, in terms of modifying parameters a priori to reflect change, quantifying predictive uncertainty and model validation (Defries & Eshleman, 2004; Ewen, O’Donnell, Burton, & O’Connell, 2006; McIntyre et al., 2013; O’Connell et al., 2007). A fundamental concern for practitioners, as demonstrated by a model inter-comparison study, is there is no consensus on the most appropriate type a model that should be used (Breuer et al., 2009).

This study investigates the potential to manage runoff through the use of runoff attenuation features (RAFs) that provide temporary storage of flood water, and disconnection and lengthening of flow pathways throughout catchment headwaters (Nicholson, Wilkinson, O’Donnell, & Quinn, 2012; Wilkinson, Quinn, & Welton, 2010). A RAF is a man-made landscape intervention that intercepts and attenuates surface flow pathways, principally, for flood management (Quinn et al., 2013; Wilkinson, Quinn, Barber, & Jonczyk, 2014). Attenuation involves the reduction of flow velocities using LWD in channels, riparian woodland on floodplains and creating storage ponds (Nicholson et al., 2012; Quinn et al., 2013). Additional benefits associated with managing flow pathways include the improvement of water quality through sediment deposition (Barber & Quinn, 2012) and ecological enhancement (Allot et al., 2015). The RAF approach, which complements traditional flood risk management options, advocates the use of many features distributed across the landscape, rather than employing a dominant intervention, on the basis that smaller features may be more easily incorporated into the landscape with minimal impact on existing agricultural land use. A central component of this soft engineering approach is to create new storage or attenuation of peak flow that is operating during flood-causing events.

The study examines the effectiveness of offline storage areas in reducing flood peaks in a small catchment (~6 km²) where approximately 40 RAfs, of varying types, have been constructed. The catchment has been instrumented to provide evidence of the functioning of storage features and the drainage network during flood events (Barber & Quinn, 2012; Nicholson et al., 2012; Wilkinson et al., 2010). A mass-balance analysis is introduced, which quantifies the local flow reduction provided by an individual storage feature. A simple model of a network of features is then developed, underpinned by field data, to explore alternate scenarios of interventions at the larger catchment scale. Thereby, this study contributes to the urgent need to quantify the effectiveness of NFM interventions (and to provide best practice).

2 STUDY AREA AND INSTRUMENTATION

The upper Belford Burn catchment (5.7 km²), Northumberland, was selected to trial the use of RAfs for the reduction
of flood hazard in the downstream village of Belford (Figure 1). Elevations within the upper Belford catchment range from 185 m to 55 m, with land use predominately improved grazing in the uplands and rotational arable in the lowlands. The length of the upper Belford Burn is 4.5 km and there are no major tributaries.

Belford has a history of flooding (Wilkinson et al., 2010), but traditional structural flood defences could not be justified on the basis of cost–benefit analysis, which is the primary consideration in determining the funding of schemes in the United Kingdom (Krieger, 2013). There are 30 residential properties located on the floodplain at Belford, which have an associated risk of flooding ranging from a 2-year to a 200-year event. Additionally, several businesses and a caravan park are at risk from flooding (Wilkinson et al., 2010). Recently there have been several damaging floods between 1997 and 2007 (Halcrow, 2007).

2.1 Runoff attenuation features

The primary intervention for flood mitigation investigated herein is the offline storage area (see Chapter 2 of Environment Agency, 2017), although LWD dams, engineered barriers, sediment traps, and overland flow interception ponds have also been constructed within the catchment (Figure 1). Offline storage areas are located on the floodplain in proximity to the river network. Construction involves the creation of a downstream earth bund, constructed using the excavated material, to provide a typical temporary storage of 300–1,000 m$^3$. The offline storage areas become hydraulically active when water levels within the adjacent watercourse reach a given threshold, with flow entering via an armoured inlet channel. The offline storage areas are gravity drained via a pipe inserted into the base of the downstream earth embankment, draining from full, in the absence of inflows, within approximately 8 hr (see schematic in Figure 2). Hence, the offline storage areas are dry for most of the year.

2.2 Instrumentation

Field instrumentation has been installed to measure catchment rainfall, river stage and pond storage at 5-min resolution at locations shown in Figure 1. Pressure transducers were installed immediately upstream of the offline storage area draw-off channels (Figure 2) to measure stream stage, and rating curves were developed to derive flow.
Additionally, pressure transducers were installed within each pond to measure storage depth, with depth–volume relationships developed from topographic surveys. An existing river gauge monitors flow upstream of the village of Belford.

### 2.3 Catchment hydrology

The hydrometric monitoring network was established in 2007, with monitoring continuing until late 2012. Over this period of field experimentation, the average rainfall and runoff for the catchment were 738 mm and 475 mm, respectively. The river response is flashy, with a time to peak of 2 hr, and the Base Flow Index is 0.313 (Boorman, Hollis, & Lilly, 1995), indicating a relatively high groundwater contribution, which can be attributed to the presence of the permeable rock formations (e.g., limestone) within the geology of the catchment (Nicholson, 2013).

### 3 METHODS

#### 3.1 Mass balance analysis

The performance of the offline storage areas, in terms of impact on the adjacent channel flows, was first assessed using a simple mass balance approach. The net change in water storage of an offline storage area is:

\[
\frac{dV}{dt} = Q_{\text{in}}(t) - Q_{\text{out}}(t)
\]

where \(V\) is the pond volume (m\(^3\)), \(Q_{\text{in}}\) is the storage area inflow from the adjacent channel and \(Q_{\text{out}}\) is the outflow to the downstream channel (m\(^3\)/s). The net change in storage \(dV/dt\) is provided at time increments \(t = 300\) s from the monitoring of depths from the offline storage area combined with the volume–depth relationship. Using continuity, the perturbed channel flow immediately downstream of the feature \(Q_{\text{ds}}\):

\[
Q_{\text{ds}}(t) = Q_{\text{us}}(t) - \frac{dS}{dt}
\]

where \(Q_{\text{us}}\) (m\(^3\)/s) is the stream flow measured upstream of the draw off channel. This mass balance approach makes a number of simplifying conditions. Equation (1) assumes that there are no lateral inflows from the adjacent hillslope into the offline storage area, which was justified on the basis that a water depth was not recorded within the feature until the river stage exceeded the draw off channel height, and additionally that there are no infiltration losses from the feature. Equation (2) assumes that the gain or losses of the channel flows in the vicinity of the offline storage area do not have a significant hydraulic impact along the reach.

#### 3.2 Modelling approach (the pond model)

Accurate, direct measurements of the inflows and outflows from the offline storage areas were not possible due to the shallowness of the inflowing depth and the unstable nature of the pond outflow from the drainage pipe. However, to explore hypothetical intervention options, including changes to outflow pipe diameter and draw-off channel height, the ability to calculate these values is necessary.

The sharp crested weir equation was used to simulate the inflow from the river via the draw off channel to the offline storage area, which is an approach that has previously been used to couple one-dimensional and two-dimensional hydraulic models (Liang et al., 2007):

\[
Q_{\text{in}} = \begin{cases} 
0 & \text{if } z_{s1} \leq z_{sw} \\
fr C_d \frac{2}{3} b \left( \frac{z_{s2} - z_{sw}}{z_{s2} - z_{s1}} \right)^{1.5} & \text{if } z_{s1} > z_{sw}
\end{cases}
\]

where \(z_{s1}\) and \(z_{s2}\) are the water levels in the river and on the floodplain, respectively, \(z_{sw}\) is the elevation of the bank crest (mAOD) (Figure 2), \(b\) is the length (m) of the overtopped part of the bank (or the width of the inlet channel), \(C_d\) is the discharge coefficient (=0.8), and \(fr\) is the drowned flow reduction factor, which is determined from the following equation:

\[
fr = \begin{cases} 
1.0 & \text{if } z_{s2} \leq z_{sw} \\
\left[ 1 - \left( \frac{z_{s2} - z_{sw}}{z_{s1} - z_{sw}} \right)^{1.5} \right]^{0.385} & \text{if } z_{s2} > z_{sw}
\end{cases}
\]

Here, there are three possible conditions for flow entering the offline storage area; no flow; free flow from the channel...
to the offline storage area; and drowned flow from the channel to offline storage area (Liang et al., 2007).

The flow into the offline storage area \( Q_{in} \) is converted into a volume \( (m^3) \), by multiplying by the time-step \( (300 \text{ s}) \) and converted into water level \( (z_{s2}) \) using a volume-depth relationship from topographic surveys. The outflow from the feature \( (Q_{out}) \) is calculated assuming hydrostatic flow through a small orifice (Toricelli’s Formula):

\[
Q_{out} = C_d A \sqrt{2gH}
\]

where \( H \) is the depth of water in the pond \( (m) \), \( A \) is the submerged cross-sectional area of the pipe \( (m^2) \) and the coefficient of discharge \( C_d \) can typically range between 0.61 and 0.75 depending on the orifice type (Bevelled, and Borda’s [re-entrant] mouthpiece, respectively; Marriot, et al., 2009). The difference between inflow and outflow is then subtracted from the upstream discharge in the river \( (Q_{us}) \), which has been obtained using a Rating Curve and the observed river level, to produce a simulated downstream discharge in the river \( (Q_{ds}) \):

\[
Q_{ds} = Q_{us} - Q_{in} - Q_{out}
\]

This group of equations is hereafter referred to as the “Pond Model” and is intended as a rapid assessment tool to investigate potential configurations of offline storage areas (and other storage-based RAFs). The equations mimic observed phenomena with physical controls and work well with offline storage areas.

3.3 | Pond network model

Once the methods were in place to simulate a single offline storage area, it was desired to demonstrate the impact of multiple features acting as a network. A Pond Network Model (PNM) was created to approximate the impact of a network of hypothetical features installed in sequence along a river network. The PNM assumes both online and offline RAFs are being approximated by a series of offline storage areas with a specified bypass conveyance rate and a repeating storage discharge function (Figure 3).

Each offline storage area is thus identical, with the physical characteristics broadly based on those used to test the Pond Model; the elevation of the draw-off channel was set to 0.45 m above the river bed, an outlet pipe diameter 0.3 m, storage capacity 550 m\(^3\) (each having a footprint approximately 25 m x 25 m) and draw-off channel width 1 m. In essence, the perturbed flow from the upstream offline storage area provides the upstream boundary condition for the next feature in the sequence, providing a simple cascade. The aim of the scenarios was to establish how increased storage reduces the flood peak at the downstream of the reach.

To validate the PNM, results were compared to the hydraulic model NewChan (Liang, 2008) using a simplified digital elevation model (DEM). The DEM contains a straight 500 m river section with sloping floodplain sections either side forming an open book configuration (Figure 4).

A simple scenario was chosen for this analysis, examining impacts on river discharge. The July 2009 storm event was simulated using observed river discharge as an upstream boundary condition. The DEM was manipulated to enable representation of five, identical, RAFs in the 2D domain Figure 5.
Simulations were performed with and without the inclusion of RAFs. The inlet heights for each RAF was set at 0.5 m above the channel bed and the available storage volume of each RAF was 235 m$^3$ (with a combined storage of approximately 1,200 m$^3$). The results of this experiment, and comparison to the PNM under the same parameters, are provided in Section 4.5.

4 | RESULTS

4.1 | Rainfall-runoff analysis of high flow events

Analyses are presented for a large summer (July 2009) and a large winter (March 2010) event and a smaller event recorded in November 2009. The hyetographs and stream hydrographs recorded at the R3 gauge are shown in Figure 6. The July 2009 event was the result of a one-day storm, with 59 mm and 61 mm of rainfall recorded over the 24 and 48-hr periods preceding the flood peak, respectively. The associated runoff totals for the July event were 29 mm and 36 mm for the 24 and 48-hr periods, respectively. The March 2010 event was the result of a two-day storm, with 59 mm and 79 mm of rainfall recorded over the 24 and 48-hr periods preceding the flood peak, respectively. The associated runoff totals for the March event were 35 mm and 55 mm for the 24 and 48-hour periods, respectively. The July 2009 and March 2010 events are both classified as 1:12.5-year events in terms of 24-hr rainfall totals. The November 2009 event was a 1:2-year event, in terms of the 24-hr rainfall total. It is noted, however, that antecedent conditions during the March 2010 event, led to above expected magnitude of flow at Belford Village. The magnitude of flow associated with the rainfall exceeded that of the 1:100-year design storm undertaken through FEH analysis (Nicholson, 2013).

Flood peaks in excess of a 3.5 mm/hr (5.5 m$^3$/s) threshold have the potential to cause flooding within the village of Belford, although the damage associated with the July and March events was relatively minor (Nicholson et al., 2012). In the case of the March event, the flows exceeded the 3.5 mm/hr flood level threshold by 1 mm/hr for a duration of 4 hr, with the approximate volume of runoff exceeding this threshold value over this period 20,000 m$^3$. For the July event, the duration above the flood threshold was 2.5 hr and with an associated volume 7,000 m$^3$. These values provide some indication of the volume of storage that a catchment wide network of RAFs would need to provide to alleviate flooding in the village. (Although it is noted that some types of RAF such as in-stream barriers aim to attenuate flow and alter the timing of contributions without specifically storing flow; the impacts of which are not considered here.) Nicholson et al. (2012) hypothesised that 20,000 m$^3$ of peak flow storage is required in Belford to raise the standard of protection to 1:100-years.

4.2 | Offline storage area performance based on mass balance analysis

For an offline storage area (RAF-3) located in the upper Belford Burn catchment (Figures 1 and 7, right panel), the observed time-series of pond storage (m$^3$) and the observed stage (m) in the adjacent river channel during the March 2010 event are shown in Figure 8. River flow enters the pond via the draw-off channel when the river stage exceeds 0.36 m (0.5 m$^3$/s) and the maximum storage volume of the pond, derived from a topographic survey, is approximately 400 m$^3$. This maximum storage potential is small in comparison to the event volume exceeding the flood threshold downstream in Belford village (20,000 m$^3$) (Nicholson et al., 2012). Additionally, it is noted that the pond is full at the time of the arrival of the main flood peak.
FIGURE 6  Hyetographs and hydrographs for July 2009, November 2009, and March 2010 storm events recorded at EA Flow Gauge (Figure 1; shown in mm/hr)

FIGURE 7  Left panel; Offline storage area (runoff attenuation feature (RAF)-1) captured during March 2010 storm event. Right panel; Offline storage area (RAF-3) captured during September 2008 storm event
**FIGURE 8** Observed river stage at the R3 gauge and observed runoff attenuation feature (RAF) volume (for RAF-3) (Figure 1)

**FIGURE 9** Measured change in flow upstream ($Q_{us}$) and downstream ($Q_{ds}$) of RAF-3 in Belford during the July 2009, November 2009, and March 2010 storm events
Figure 9 shows the local impact on the river flow immediately downstream of the pond (RAF-3), for the selection of events, derived from continuity using Equation (2). The graphs also show the observed percentage impact during the event (defined as $\frac{dV}{dt}$ as a proportion of the flow in the river). The impact can be used to demonstrate whether the RAF is functioning as designed. When the impact is positive, the RAF is filling from the river channel. The positioning of the impact relative to the flow enables determination of whether the peak of the storm event has been reduced.

For the July 2009 and March 2010 storm events, it can be observed that the RAF has greatest impact on the rising limb of the storm hydrographs rather than the peak (Figure 9). The modest storage capacity of the RAF is depleted prior to the arrival of the flood peak.

The November 2009 event (Figure 9) was relatively small in magnitude in comparison to the July 2009 and March 2010 events. However, it is shown to demonstrate the effect of storm magnitude on a storage-based flood defence. The RAF storage reaches capacity at the time of the peak flow, which is reduced by approximately 12%. The November 2009 event and events of similar magnitude, demonstrate the potential for peak flows to be impacted through the implementation of well-designed storage measures.

4.3 | Pond model

Prior to exploring scenarios of configurations of RAFs for flood alleviation, firstly the ability of the simplified ‘Pond Model’ presented in Section 3.2 to reproduce the observed behaviour of a single was explored. The RAF inflow ($Q_{in}$) is calculated using the observed time-series of upstream river stage with Equations (3) and (4), the depth of water within the RAF is then updated using the calculated inflow and the known storage-depth relationship, and finally the outflow ($Q_{out}$) is calculated from the water depth in the RAF using Equation (5) and the flow downstream of the RAF can be calculated using Equation (6).

In Figure 10, the simulated and observed RAF volumes are shown for the March 2010 event. The simulated and observed time series are in reasonable agreement, although the rate of RAF filling is under-predicted on the second smaller peak of the event. It should be noted that no calibration was required; the coefficients of discharge ($C_d$) were taken from the literature with 0.8 for flow from the river into the RAF and 0.66 for flow through the outflow pipe.

The Pond Model presented above simulates just one RAF in the catchment (e.g., Figure 7, right panel). While there are additional RAFs of different types within the Belford catchment, the key question to be addressed here is how much additional storage is required to reduce downstream flood hazard?

4.4 | Pond networks

The PNM was setup to represent 35 identical ponds in sequence (as described in Section 3.3). Figure 11 shows the discharge at the downstream of the reach for incremental increases in the number of RAFs from 5 to 35 for the two larger storm events (5 RAFs provide a combined storage of approximately 2,500 m$^3$ and 35 RAFs provide...
a combined storage of 19,250 m$^3$). Essentially, each feature delays the onset of flow into the downstream through a reduction in the river levels resulting from the pond storage.

The PNM demonstrates that significant impacts can be achieved for Belford Village if storage of at least 10,000 m$^3$ is created. Peak flow storage of 20,000 m$^3$ has the potential
to reduce flood risk from the observed events by approximately 30%.

4.5 | Hydraulic simulations

The river channel in NewChan was simulated in the virtual experiments (described in Section 3.3) both with and without the presence of RAFs (accounting for channel conveyance over the short reach). The pre- and post-change hydrographs for NewChan were then compared to the PNM output for the same configuration (Figure 12).

The results in Figure 12 show that the experimental setup in the hydraulic model predicts a greater reduction in peak flow than the equivalent setup in the PNM. This is primarily due to the additional attenuation provided in-channel and the more complex hydraulic interactions being represented within the offline storage areas in the 2D domain than is being represented by the PNM.

5 | DISCUSSION

The mass balance approach, based on monitoring data, has demonstrated that a measurable impact can be detected from individual RAFs during storm events. It is noted that RAF-3 functions well (locally) during the smaller storm event (November 2009), reducing the peak flow in the Belford Burn by approximately 12%. During this event, the RAF filled to approximately 75% of its total capacity. The same offline storage area is shown to be full by the time of arrival of the flood peak for the two larger events (July 2009 and March 2010), and hence there is limited impact on peak flows. This can be attributed to the timing in which the draw-off channel becomes hydraulically active. The draw-off channel begins to receive flow at 0.5 m³/s. For the July 2009 event, RAF-3 commenced filling approximately 10-hr prior to the peak flow at Belford.

The Pond Model has been demonstrated to closely mimic reality through a simple representation of the hydraulic interactions between river, floodplain, and outflow pipe. The findings of this study subsequently raised the question that; if each RAF is capable of having a minor impact on river flows, to what extent can a network of RAFs mitigate peak river flows? There is still a need to determine the storage discharge relationships for a range of RAF types, especially the LWD and riparian woodland (highlighted in Figure 1). Additionally, potential limitations on constructing large offline storage areas include regulatory issues relating to the Flood and Water Management Act 2010 (UK), which imposes a capacity beyond which regulation is required (see Environment Agency, 2017), resistance from land owners to sacrifice significant areas of fields (particularly if prime locations impact land owners with a smaller total land availability; see Holstead, Kenyon, Rouillard, Hopkins, & Galan-Diaz, 2017; Spray et al., 2015), structural concerns associated with erosion of draw-off channels, stability of high earth embankments and the requirements the Reservoirs Act 1975 (UK) should a single feature or cascade of features exceed 25,000 m³ of, above ground-level, storage.

It is reiterated that the RAF approach promotes the use of a network of features distributed throughout the catchment, and even large events have the potential to be impacted by such a network. To assess the use of networks, simple experiments were performed using the PNM. The scenarios demonstrated that a combined storage of a network of RAFs has the potential to reduce peak flows by up to 30%, assuming 20,000 m³ of storage distributed between 35 RAFs. Thus, a crucial concept to the RAF approach is the creation of a critical lower storage capacity.

It is interesting to note that for the March storm, the PNM has shown that 8,000 m³ of storage is required before there is a noticeable impact on the flood peak; the addition of storage is therefore more effective in reducing flashy flood events. The PNM has been shown to be a rapid assessment tool for exploring potential impacts of configuration of ponds to achieve targeted reductions in flood risk. For similar, flashy catchments it is a reasonable assumption to estimate between 2,000 m³ and 4,000 m³/km² of catchment area is required to provide the attenuation storage necessary to reduce downstream flood risk to manageable levels (using storage alone). In the case of Belford, these hypothetical storage assessments give some confidence in the actual RAFs installed in the catchment, which have a total storage capacity of 12,000 m³.

Assessment of the outputs from the NewChan and PNM reveals a greater simulated impact on downstream discharge in the NewChan simulation (see Figure 12). This may be due to the explicit representation of topography and momentum losses in the NewChan simulation. The comparison between the virtual experiments using NewChan, and the representation of networks of RAFs using the PNM has demonstrated further evidence to the effectiveness of RAFs. It has also demonstrated the transferability of the approach in the hydraulic domain of the NewChan model.

Belford is a small catchment, and there remain questions as to the size of a catchment in which such approach could be beneficial in reducing downstream flood hazard. With increasing catchment scale consideration is required of the role of the river network, through the processes of geomorphological dispersion, which relates to the timing of contributions from the various sub-catchments due to the variations in travel pathway lengths, and hydrodynamic dispersion, with friction and within-channel storages causing flood waves to attenuate and disperse as they travel downstream (Henderson, 1966; McIntyre & Thorne, 2013; White,
Kumar, Saco, Rhoads, & Yen, 2004). Hence, the knowledge of the impacts of interventions on the local flood peaks will not provide reliable evidence of the sensitivity of the downstream peak to interventions without further investigation and modelling (e.g., O’Donnell et al., 2011).

6 | CONCLUSION

For the management of future flood risk, there is increasing interest in supplementing traditional hard defences with more sustainable approaches that work with natural processes. One such approach is NFM, which involves the alteration, restoration, or use of landscape features to reduce flood risk. The knowledge base with regards to the design and implementation of NFM is increasing (Environment Agency, 2017), but there is a lack of empirical evidence demonstrating the effectiveness in reducing flood hazard. Monitoring the functioning of interventions is possible at the local scale, but understanding how the impacts propagate to downstream flood sites is poorly understood (Blöschl, 2001). There are few studies that have attempted to quantify the impacts of NFM interventions (Dadson et al., 2017; McIntyre & Thorne, 2013).

To contribute to the knowledge base, a field experimentation, monitoring and modelling programme has been implemented in a small rural catchment. The field programme demonstrated that significant catchment-wide water storage opportunities exist in river catchments. The monitoring demonstrated that offline storage areas are most effective at reducing local flood peaks for small flashy events (1 in 2-year events); during long duration events the available storage is depleted before the arrival of the main flood peak. Modelling has demonstrated that a network of offline storage areas distributed along a channel reach may be effective in reducing downstream flooding at the small catchment scale (≈10 km²) for 1 in 12.5 to 1 in 100-year events. However, there remain issues of how effective such approaches are when moving to mesoscale catchments, given the roles of geomorphologic and hydrodynamic dispersion.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the Environment Agency. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from the authors with the permission of the Environment Agency. Time-series data from the modelling study is available from Zenodo at the following url: https://zenodo.org/record/3381927.

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