Water Security 13 (2021) 100091

Contents lists available at ScienceDirect

Water Security

journal homepage: www.sciencedirect.com/journal/water-security

# How can we plan resilient systems of nature-based mitigation measures in larger catchments for flood risk reduction now and in the future?

Barry Hankin [a,b,*], Trevor Page [a], Gareth McShane [a], Nick Chappell [a], Chris Spray [c], Andrew Black [c], Luke Comins [d]

[a] Lancaster Environment Centre, Lancaster University, LA1 4YQ, UK
[b] JBA Consulting, Mersey Bank House, Barbauld Street, Warrington, WA1 1WA, UK
[c] Geography & Environmental Science, University of Dundee, DUNDEE, DD1 4HN, UK
[d] Tweed Forum, UK

ARTICLE INFO

*Keywords:*
Nature based solution
Natural flood management
Floodplain reconnection
Climate
Resilience

ABSTRACT

There is considerable empirical evidence that using nature-based solutions to restore and enhance hydrological processes such as infiltration, interception, floodplain re-connection and water storage, is effective at small scales for low to medium probability floods. However, the performance of systems of spatially distributed nature-based solutions at larger scales or under the more extreme flooding expected with climate change, has mainly been assessed using modelling. The mechanism by which carefully designed nature-based solutions can provide naturally adaptive pathways to divert higher flood flows into expandable areas of storage in the landscape, has been less formally investigated. This paper reports on new hydrometric data collected from one of eighteen small-scale, accurately monitored micro-catchments in Cumbria, UK, to study the effect in more detail. The micro-catchments have been set up by Lancaster Environment Centre as part of the Q-NFM project attempting to quantify changes in hydrological responses due to a range of natural flood management measures that have been installed by catchment partners. A direct-runoff 2d inundation model was setup and calibrated using accurate flow measurements upstream and downstream of new river restoration project in the Lowther catchment (2.5 km$^2$) for two large storm events (Storms Ciara and Dennis, February 2020). It was used to analyse how the storage on the floodplain can expand with flood magnitude, and can be enhanced with appropriately designed natural flood management. Model evidence was then assessed for the same mechanism in the larger UK catchments of Eddleston Water (70 km$^2$) and Culm (280 km$^2$) using the same whole-catchment direct-runoff modelling approach. For both of these large catchments the same expandable field storage is evident, and we highlight how this latent property of well-designed nature-based solutions can complement traditional strategies and provide significant economic benefits over a thirty-year appraisal period of the order of €0.7 m.

## 1. Introduction

Nature Based Solutions are considered to provide natural resilience to climate change extremes [25], helping to reduce further warming, supporting biodiversity and securing ecosystem services [3,4,8,23]. However, with little empirical evidence specifically for flood risk reduction at larger scales [6], it is difficult to understand the limits of effectiveness of NBS in combination with other traditional risk reduction measures without relying upon broadscale modelling evidence [11,12]. This stems from the difficulty in detecting changes to large catchment responses due to land use management change [9], with environmental variability and uncertainties in modelling hydrological processes as we move from the small scale of $< 10$ km$^2$, where there is stronger supporting evidence for their effectiveness to 100 km$^2$ and 1000 km$^2$ or above [6,16].

That is not to say that more accurate measurements of hydrological processes cannot be used to reduce parameter uncertainties and the uncertainties and in the shift in parameter values that we might use in larger scale models to represent changes in hydrological processes resulting from NBS [11,17]. This approach is being taken in on-going research [24,13,20], and there are now collations of evidence, for example, of the effective parameter shifts in relation to the additional

* Corresponding author at: Lancaster Environment Centre, Lancaster University, LA1 4YQ, UK.
*E-mail address:* barry.hankin@jbaconsulting.com (B. Hankin).

https://doi.org/10.1016/j.wasec.2021.100091
Received 12 August 2020; Received in revised form 8 April 2021; Accepted 21 June 2021
Available online 28 July 2021

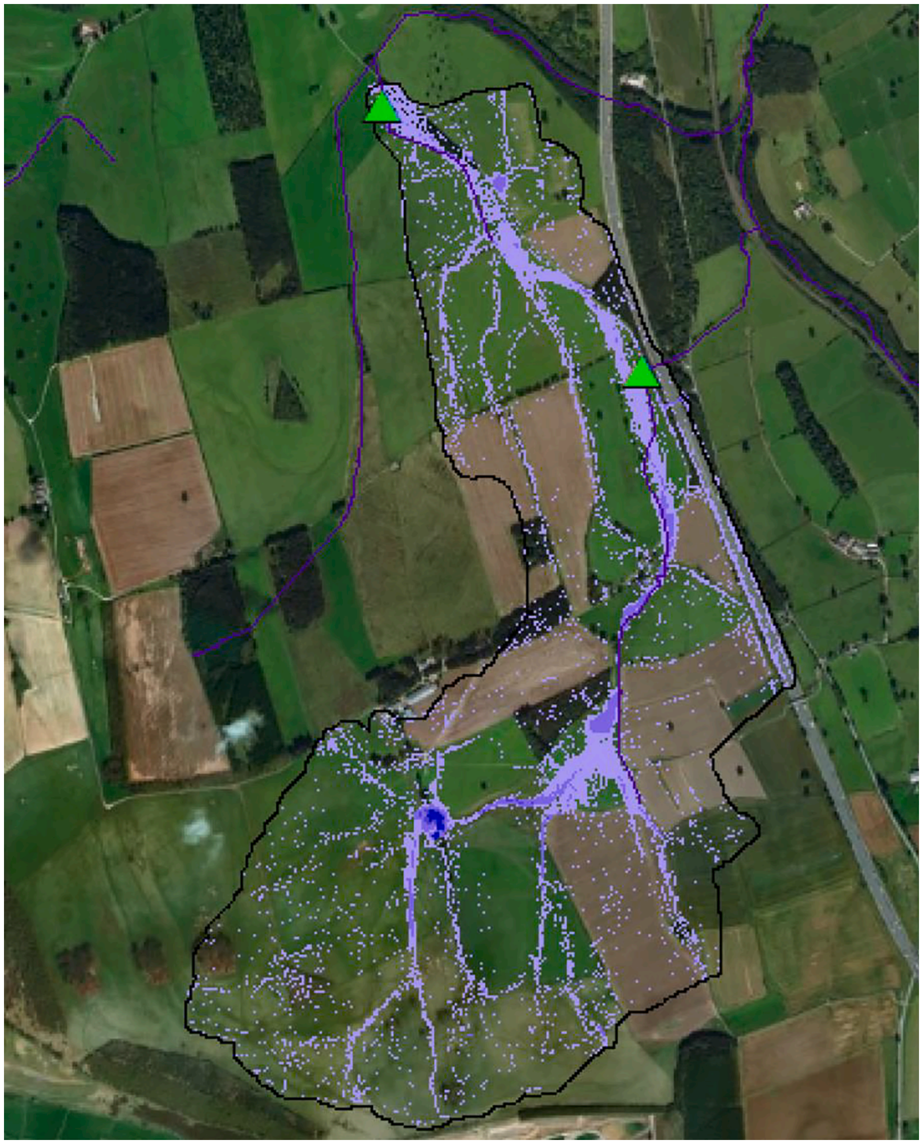

**Fig. 1.** Positions of micro-flumes (green triangles) in relation to watershed with direct rainfall runoff model maximum depth grid used to highlight flow accumulations. The stream has been diverted to the left along the solid arrow shown and no longer flows to the right of the M6 motorway to the east. The dashed arrow points to flow pathways and direction of photo in Fig. 4. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

channel friction (represented by Manning's n effective parameter) incurred through engineered log jams or large woody material [2].

That said, in recent modelling studies it has been noted that certain types of NBS keep working at higher and higher flows, providing landscape storage and additional resilience to climate change [15]. This is unlike embankments or defences, which provide a design standard of protection, which as the loading increases beyond this, it could be argued do not 'keep on working' to reduce risk. If the phenomenon holds true, there are potentially several beneficial impacts on the economics of NBS, notably a reduction (albeit small) across all event magnitudes (or probabilities based on the rarity of the event magnitude) can lead to a significant long term net present value (NPV) which can complement traditional risk reduction strategies.

Natural adaptation pathways develop from using leaky barriers, woody material, bunds and floodplain reconnection techniques in order to connect flows of increasing magnitude to field storage [19], but the fact these areas are often expandable is overlooked. Their integrated impact on attenuating peak flows is complex, and there are strong benefits from whole-system modelling. It can help understand the in-combination effects on the performance of a network of NBS, taking into account dynamic utilisation of storage, synchronisation and also failure [14,21]. For the quantum of NBS that is typically being installed in the UK as pilots, the peak flow reduction is typically small, yet it can be consistent across a wide range of probabilities. This results in relatively small reduction in expected average annual flood damages, but on integrating the damage versus probability curve and extrapolating into the future with a suitable discounting rate, the Net Present Value (NPV) of NBS can be considerable given the assumptions associated with these simulations. Given parameter uncertainty and model equifinality, it is acknowledged that the simulations used for this analysis are one set of many valid ones that will be explored with further work. In addition, pushing more and more water into expandable areas of storage on the floodplain can help with other integrated measures, for example water resources if the areas of new storage are above permeable geology then this can promote additional recharge.

**Fig. 2.** Lowther Estate stream diversion by Eden Rivers Trust: channel delivers water to marsh area to the left beyond the calibrated micro-flume at Back Greenriggs.

**Fig. 3.** Downstream calibrated micro-flume at Bessy Gill.

## 2. Method

### 2.1. Study area

Lowther Estate, working with the Eden Rivers Trust and Natural England, have developed a series of NBS in some of the small tributaries of the Lowther which flows to Eamont Bridge (NY523281) near Penrith Cumbria, and eventually into the Eden (2,300 km$^2$). Fig. 1 shows the location of the stream diversion undertaken in summer 2019. The catchment has an area of 2.5 km$^2$ and an average annual rainfall of approximately 1230 mm with a relatively low base flow index (BFIHOST 0.35–0.55) and variable percentage runoff (27–38) using the Flood Estimation Handbook (IH, 1999).

In addition to the diversion, the stream has been allowed to establish its own pathway along the old floodplain, similar to a stage-zero

**Fig. 4.** Photograph along dashed arrow in Fig. 1, showing ponding on floodplain in wetted-up catchment following diversion, and looking across to the flow pathways that were emergent under wet conditions (Nov 2019).

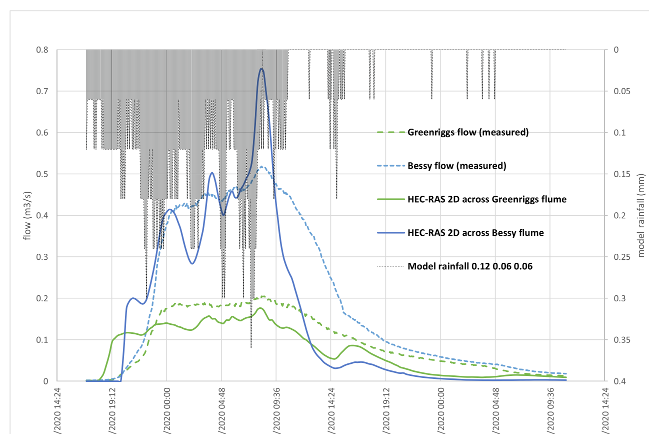


**Fig. 5.** Calibration upstream (NSE = 0.64) and downstream (NSE = 0.68) of the floodplain reconnection for Storm Ciara.

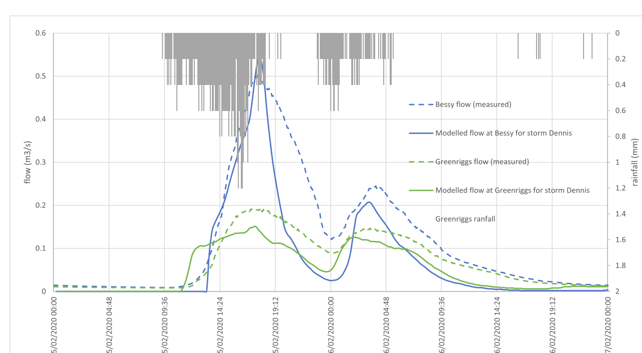


**Fig. 6.** Split record validation upstream and downstream of the floodplain reconnection for storm Dennis using calibration values for storm Ciara.

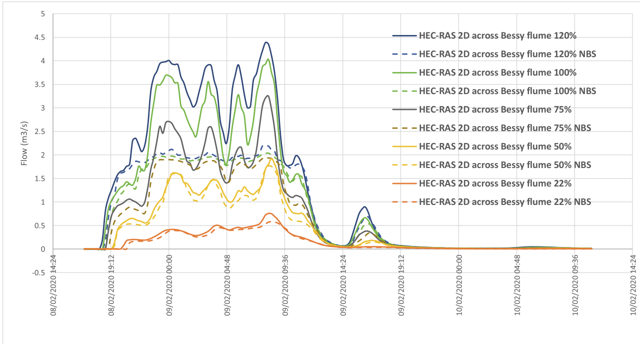


**Fig. 7.** reduction in peak flow with NFM for 5 magnitude flows (0.22,0.5,0.75,1,1.2 times the size of storm Ciara).

**Table 1**
changes to volumes stored on the floodplain with increasing storm magnitude.

| Storm Magnitude (multiplier on Storm Ciara total rainfall) | pre-NBS volume on the floodplain (m3) | post-NBS volume on the floodplain (m3) | Absolute increase in volume on the floodplain | % increase in volume on the floodplain | pre-NBS peak flow (m3/s) | post-NBS peak flow (m3/s) | % reduction in peak flow |
|---|---|---|---|---|---|---|---|
| 0.22 | 4870.0 | 5876.4 | 1006.4 | 21% | 0.75 | 0.58 | 23% |
| 0.5 | 7926.0 | 9835.2 | 1909.2 | 24% | 1.92 | 1.77 | 8% |
| 0.75 | 10116.0 | 12449.2 | 2333.2 | 23% | 3.25 | 1.95 | 40% |
| 1 | 13064.8 | 15608.4 | 2543.6 | 19% | 4.03 | 2.04 | 49% |
| 1.2 | 14556.0 | 17861.6 | 3305.6 | 23% | 4.39 | 2.19 | 50% |

experiment[a], although here the marshland landscape has not been altered. In this unique experiment, the Lancaster Q-NFM project has installed at either end of the diversion accurate Venturi (low obstruction) micro-flumes and telemetered levels and rainfall sensors (shown in Figs. 2 and 3). The flumes were constructed of fibreglass using the original moulds of the Forth River Purification Board and are pre-calibrated to a channel discharge of 430 L/s. Rainfall was measured with an RG3 raingauge connected to an RX3000 telemetry unit (Onset Computer Corporation, Bourne, USA). Level within the flume was measured with a pressure transmitter (MSL-G0250-5A2-AAV-005–000; Impress Sensors & Systems Ltd, UK) also connected to the RX3000. Level monitored every minute was averaged over 5-minute periods and

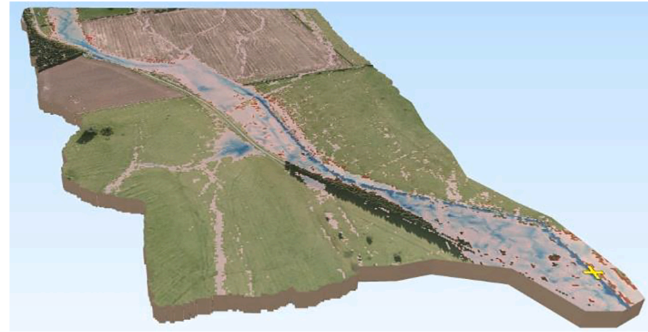

**Fig. 8.** reduction in peak flow with NFM for 5 magnitude flows (0.22,0.5,1,2,3 times the size of storm Ciara).

transmitted to the remote server every 15 min.

Fig. 1 also shows an overlay of the 3.33% Annual Exceedence Probability (AEP) maximum depth grid over the satellite imagery, revealing flow pathways on some of the slopes in the catchment, that were also evident from a site visit during wet weather in November 2019 (Fig. 4). The pixelated nature of the flooding in Fig. 1 also reveals the resolution of the digital terrain model (DTM) being used which is 2 m.

We first demonstrate how re-connection of a channel with this old area of marsh or natural floodplain can be simulated using HEC-RAS 2D[b], using the gauges and estimates of hydrological losses to calibrate the model at the upstream end (Back Greenriggs, Fig. 2) and downstream (Bessy Gill, Fig. 3), the locations of which are shown in Fig. 3.

### 2.2. Calibration and validation

The rainfall recorded at Back Greenriggs station was adjusted for hydrological losses using a simple multiplicative factor (or runoff coefficient) of 0.22 to generate an ‘effective rainfall’ (rainfall generating streamflow rather than being lost to storage and deep seepage into the permeable Yoredale geology), from the recorded rainfall for storms Ciara and Dennis which occurred several days apart in February 2020. These were large events in Cumbria, with 151.8 mm of rainfall in the county in 24 h for storm Ciara and flooding in the town of Appleby which is also in the wider Eden valley. A split record calibration/

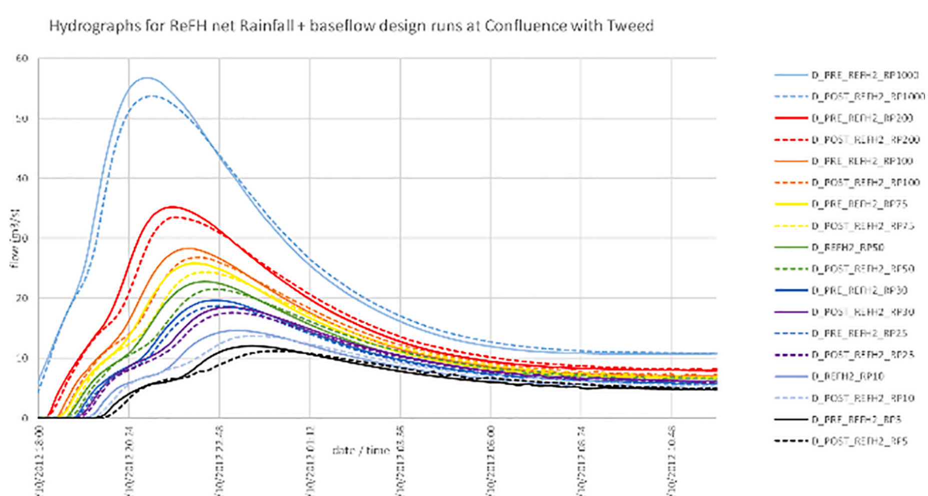


**Fig. 9.** Reduction in design event peak flows and attenuation in Eddleston Water (70 km2) without (solid lines) and with (dashed lines with same colour) NBS.

vali

[a] For example see https://www.jbaconsulting.com/knowledge-hub/one-of-the-first-restoration-schemes-of-its-kind-in-the-uk/

[b] https://www.hec.usace.army.mil/software/hec-ras/download.aspx


**Fig. 10.** As more tree-planting increases the friction over 20 years, the orange areas shows flood waters reaching more areas of temporary high flow storage. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

dation was undertaken, using the calibration of Storm Ciara and Storm Dennis for validation.

The channel, newly connected floodplain and wooded areas were given realistic values of the Manning's roughness (n) based on the typical ranges e.g. [1,5].

The input errors and parameter uncertainties will be investigated by the Q-NFM project, in a further paper where thousands of model simulations are undertaken, so that the uncertainty in the predictions and hypothesis testing made here can be estimated in more detail.

The Manning's n roughness value for the newly connected floodplain / marsh area was initially set at 0.05 (including the ponded area in Fig. 4), with 0.065 for the woodland area at Bessy Gill having a relatively smooth and open terrain with signs of significant flow movement and ponding. These values may change seasonally, and through time it would be expected that roughness will increase given the large number of trees that are also being planted on the Lowther Estate.

This combination of rainfall losses and roughness provided a reasonable manual calibration at the two gauges (Fig. 5) with an NSE performance measure of 0.68 at the more important downstream site, providing confidence that the direct rainfall and losses model is a reasonable simulator of the system between the flow gauges.

It should also be noted that both flow gauges are partially bypassed at very high flows, and for this reason the HEC-RAS 2D mesh is queried directly across the location of the flumes in the RAS-Mapper post-processing interface, as opposed to calibrating against the total flows emerging from the downstream boundary. The calibration parameters (rainfall loss and Manning's n) were then used to simulate Storm Dennis which occurred several days later, under similar conditions (Fig. 6).

There is an under-prediction of the 'bulge' to the main hydrograph at Bessy Gill (downstream), and this has been observed in other recorded hydrographs, and is likely to be due to greater groundwater influence than currently modelled, although the NSE was 0.64 and the peak flows were modelled within 6% at the more important downstream site.

A model cascade has also been setup for this catchment using Dynamic Topmodel feeding predicted runoff into a HEC-RAS 2D model with suitably adjusted internal inflow boundaries (see [13] for modelling framework). Based on Fig. 6, it is likely that the lateral subsurface transmissivity requires better representation to account for the groundwater influence.

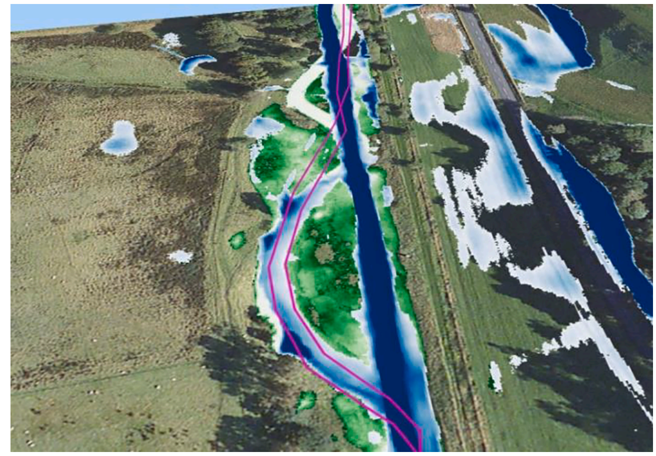

**Fig. 11.** Re-meandering at Cringletie leading to a 6% increase in flood volume stored.

### 2.3. Experimental design

Rather than using the flow diversion to make use of the old channel, the example of NBS *per se*, we take this a step further to look to the future scenario where the trees planted on the re-connected meadows mature, and create greater roughness in the flow pathway. This is the situation that we are modelling in the larger catchments discussed in Section 3.

We then simulate a series of five storms of increasing rainfall and explore how the water stored on the floodplain area increases with rainfall and with NBS measures designed to connect the new channel with the floodplain.

Fig. 7 shows the hydrographs at Bessy Gill with and without NFM for 5 events of different magnitude. These are the calibrated effective rainfall (factor 0.22) and larger and larger factors up to 1.2 times the rainfall recorded at Back Greenriggs for storm Ciara rainfall, these being (0.22, 0.5, 0.75, 1.0 and 1.2). These correspond to a range of increasingly rare probabilities, or storms that are increasingly larger than Storm Ciara. The percentage increase between two *largest* modelled storms (100% rainfall and 120%) is also the expected increase in rainfall intensity between 2020 and 2040 assuming 4 degrees of global heating (Environment Agency [10].

The volumes on the floodplain were also computed using zonal statistics in GIS, and we see how the volume keeps increasing with an expanding area of wet floodplain at higher and higher flows (Table 1). It should be noted that even without assuming any additional floodplain roughness, the volume stored on the floodplain increases with storm magnitude, so the stream diversion at Lowther is already exhibiting resilience. When we consider how that volume increases and provides approximately 20% increased storage if we do assume the floodplain increases in roughness over time.

The increase in storage on the floodplain is visible in Fig. 8 in the fringes of flooding coloured with red (future roughness or NBS scenario) around the blue flooding (current roughness).

Here we see the link again between peak flow reduction and additional peak flow stored on the floodplain that we are trying to re-connect by the simple floodplain re-connection action of roughening up the channel and creating a backwater.

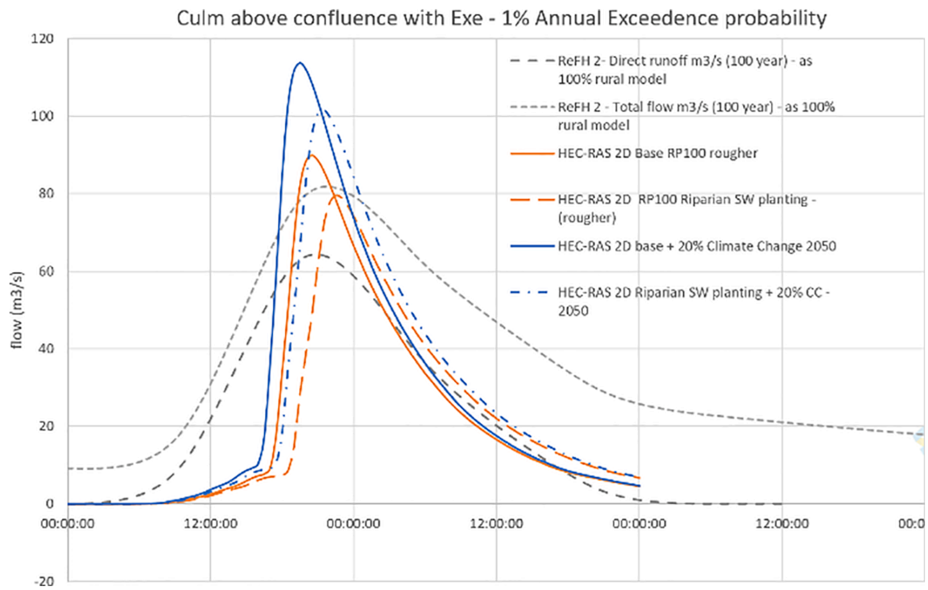


**Fig. 12.** Hydrographs at outflow of whole catchment response before (solid orange) and after NFM (dashed orange) and with climate change before (solid blue) and after NBS (dashed blue) based on extensive increase in riparian roughness. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

## 3. Scaling to larger catchments

Having explored this effect at the detailed micro-scale we now compare with two studies of larger catchments, both being funded by EU *Interreg* funding. These are the 70 km$^2$ Eddleston Water catchment in relation to the *Building with Nature* project[c], and the 280 km$^2$ Culm catchment in relation to the Connecting the Culm project[d], with data and modelled outputs here[e]. Both projects have been worked on by the lead author, and both use a broad scale Direct Rainfall and losses HEC-RAS 2D model approach to investigate the effectiveness of different NFM strategies.

Here a HEC-RAS 2D model was constructed and calibrated[f] against a set of distributed monitoring network, focusing on the downstream flow gauge near Peebles in the Scottish Borders.

**Table 2**
The peak flow reductions and time delays for Eddleston Water calibrated model with and without NBS.

| Design Event | Peak Flow Baseline | Peak Flow (NFM) | % Peak reduction | Time Delay |
|---|---|---|---|---|
| RP1000 | 56.68 | 53.64 | 5.4% | 00:00 |
| RP200 | 35.19 | 33.42 | 5.0% | 00:15 |
| RP100 | 28.29 | 26.76 | 5.4% | 00:15 |
| RP75 | 25.77 | 24.34 | 5.5% | 00:15 |
| RP50 | 22.77 | 21.51 | 5.5% | 00:15 |
| RP30 | 19.67 | 18.51 | 6.3% | 00:15 |
| RP25 | 18.68 | 17.58 | 5.9% | 00:30 |
| RP10 | 14.63 | 13.69 | 6.4% | 00:30 |
| RP5 | 12 | 11.17 | 6.9% | 00:30 |

The DAYMOD (or *Cini calibration*) software was used to set the initial soil moisture for real storm events *before* and *after* NBS installation and the adjusted net rainfall to drive the 2D model as in the Lowther example. The NBS included a range of measures, including the installation of woody barriers extending onto the floodplain, called lateral or *high flow deflectors*[g] designed encourage out-of-bank flow and hold back water in the headwaters.

In total nine different return periods were simulated with and without the distributed NBS measures represented in the mesh either through the use of increased friction, or a change in storage in the DTM.

Fig. 9 shows how there is a small 5% reduction in each of the simulated design events (dashed lines of same colour as solid lines).

looking for a physical explanation of this, a range of plots were made in the upper headwaters, such as Fig. 10, where it is evident that with more rainfall and flows, more areas of the floodplain come into play as storage, especially where re-meandering is concerned (Fig. 11).

Fig. 11 shows the re-meandering work at Cringletie, where the additional floodplain storage before (8700 m$^3$) and after (9216 m$^3$) restoration was estimated using zonal statistics, giving an increase in 6% of the original storage for the same event.

Scaling up to the Culm catchment (280 km$^2$), a similar story plays out

**Table 3**
Damages and damages avoided for nine probability design storms with and without NBS.

| Return Period | Pre-NFM Damages (£k) | Post-NFM Damages (£k) | Difference (£k) |
|---|---|---|---|
| 5 | 2,562 | 2,494 | -68 |
| 10 | 2,644 | 2,567 | -78 |
| 25 | 2,801 | 2,680 | -121 |
| 30 | 2,869 | 2,728 | -140 |
| 50 | 3,040 | 2,855 | -185 |
| 75 | 3,200 | 2,998 | -202 |
| 100 | 3,307 | 3,103 | -204 |
| 200 | 3,622 | 3,383 | -239 |
| 1000 | 4883 | 4,291 | -592 |
| Annual average damage | 937 | 905 | -32 |

c https://tweedforum.org/our-work/projects/the-eddleston-water-project/
d https://blackdownhillsaonb.org.uk/project/connecting-the-culm/
e https://connecting-the-culm.jbahosting.com/Map
f https://tweedforum.org/download/241/all/6502/eddleston-water
g https://tweedforum.org/our-work/projects/the-eddleston-water-project/eddleston-water-project-progress-to-date/

this time when we increase the riparian friction in areas identified in the EA WWNP maps[h]. Fig. 12 shows the reduction in peak flows with and without climate change for a baseline 100 year return period event and the same event with an increase in rainfall intensity of 20% to represent climate change.

Looking in other headwaters, and shading the before and after NFM depth grids, the expanding areas of flooding on fields is visible again in the Culm landscape (Fig. 13).

## 4. Economic analysis

Returning to the Eddleston Water catchment the summary of the peak flow reduction (Fig. 9) before and after NBS is given in Table 2 with an average of about 5% peak flow reduction based on all the measures in the catchment.

The depth grids were exported and used to compute the damages with and without the NBS (Table 3) using vulnerability curves based on the Multi-Coloured-Manual [22], giving a reduction in 3.5% in the average annual damages. This equates to £32 k, which may seem small, but integrated over a 30 year scheme lifetime, and using current acceptable discounting rates over this period, this equates to £0.6 m or €0.7 m. This is a significant contribution to reducing risk in the long term that comes about by the consistent reduction in the hydrograph across all the probabilities modelled.

## 5. Summary and conclusions

Nature Based Solutions could help us plan more resilient flood risk management strategies at large scales and for the larger floods expected with climate change, considering the expandable nature of upstream field storage present in many catchments. It is possible to divert high flows and improve floodplain reconnection to these areas, enhancing natural adaptation pathways to climate change. The modelling reported in this investigation shows that if designed correctly, NBS such as increased riparian roughness or careful use of large woody material, can enhance this connection across a wide range of scales.

Understanding the integrated impact of distributed NBS on a whole catchment response is complex, and benefits from a whole-system modelling approach, where different performance issues, including performance failure can be properly explored [14,18]. The peak flow reduction is often small (5–10%) but can occur across a wide range of probabilities. This consistent, but small reduction also results in relatively small reduction in expected average annual flood damages, but on integrating the damage versus probability curve and extrapolating into the future 30 years, the net present value of NBS can be significant in relation to other benefits such as carbon sequestration and inline with long term government planning for resilience [7].

**Fig. 13.** Additional storage (blue) in the landscape with greater flows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

[h] https://www.gov.uk/government/publications/working-with-natural-processes-to-reduce-flood-risk

We have attempted to demonstrate how accurate small-scale micro-catchment measurements used to calibrate a whole-catchment direct rainfall and losses model can add confidence to the hypothesis that expandable areas of floodplain act as adaptation pathways and deliver a degree of climate change resilience. We have then demonstrated the implications of this at the larger scale for a 70 $km^2$ and a 280 $km^2$ catchment using the same whole-catchment modelling approach. For the larger catchments the same resilient properties and expandable field storage are evident when NBS is designed to connect watercourses with the floodplain, whether through using lateral flow deflectors in-channel, or increasing floodplain friction to increase backwater effects and push more water onto the floodplain.

## CRediT authorship contribution statement

**Barry Hankin:** Conceptualization, Methodology. **Trevor Page:** . **Gareth McShane:** . **Nick Chappell:** . **Chris Spray:** . **Andrew Black:** . **Luke Comins:** .

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

This work has been supported by UKRI-NERC Grant **NE/R004722/1** ('Q-NFM') With kind thanks to Lev Dahl from Eden Rivers Trust, Luke Comins of the Eddleston Water Interreg funded project *Building with Nature*, and Steven Johnson and Tim Youngs of the Interreg 2 *Seas Co-Adapt* project, *Connecting the Culm*.

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