ENVIRONMENTAL RESEARCH
LETTERS

Supplementary Information

Nature-based Solutions for effective flood mitigation: potential design criteria

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S1. Introduction

Features that deliver Nature-based Solutions (NbS) for flood mitigation for include: (i) planted woodlands, (ii) earth bunds on hillslopes or stone/wooden structures in peatland drains, (iii) woody structures in headwater channels, often called 'leaky dams', (iv) aerated pastures, and (v) storage bunds on floodplains (Burgess-Gamble *et al.*, 2018). Some of these features may benefit flood reductions downstream by changing more than one hydrological process. For example, planting of a stand of trees within a grassland may: (i) lead to drier soils at the start of storms through enhanced transpiration, (ii) slow any overland flow through enhanced surface roughness, (iii) reduce the amount of rainwater reaching the ground through enhanced wet-canopy evaporation ('interception loss') and/or (iv) reduce overland flow through enhanced soil permeability.

S2. Methods

The hydrological process shifts resulting from NbS interventions to reduce flood peaks in the managed grasslands and woodlands of Cumbria (UK) were: (i) enhanced wet-canopy evaporation, (ii) enhanced hillslope (surface) storage, (iii) enhanced in-channel storage, (iv) enhanced soil infiltration, and (v) enhanced floodplain storage. Continuous monitoring of individual NbS interventions was undertaken in parallel to continuous stream discharge monitoring installed on the small watercourses associated with the introduced NbS features. Most of these discharge monitoring stations used fibreglass trapezoidal flumes capable of measuring up to 430 L/s. The resultant flume-catchments or 'micro-basins' were approximately 1 km^2 in area (see Mindham *et al.*, 2023). The locations of these gauged micro-basins in the United Kingdom are shown in Figure S1, with most being located in the Cumbrian mountains (right hand, inset figure). The locations of micro-basins that have monitored surface storage features, namely on hillslope surfaces, in perennial channels, and on floodplains (NbS interventions (ii), (iii) and (iv) are shown with blue shaded circles. Those with monitoring of wet-canopy evaporation (NbS i) are shown with green shaded circles, while those shown with orange shaded circles have overland flow monitoring for the NbS of enhanced soil infiltration. Micro-basins used as a reference basin or 'control' without added NbS features are shown with yellow shaded circles.

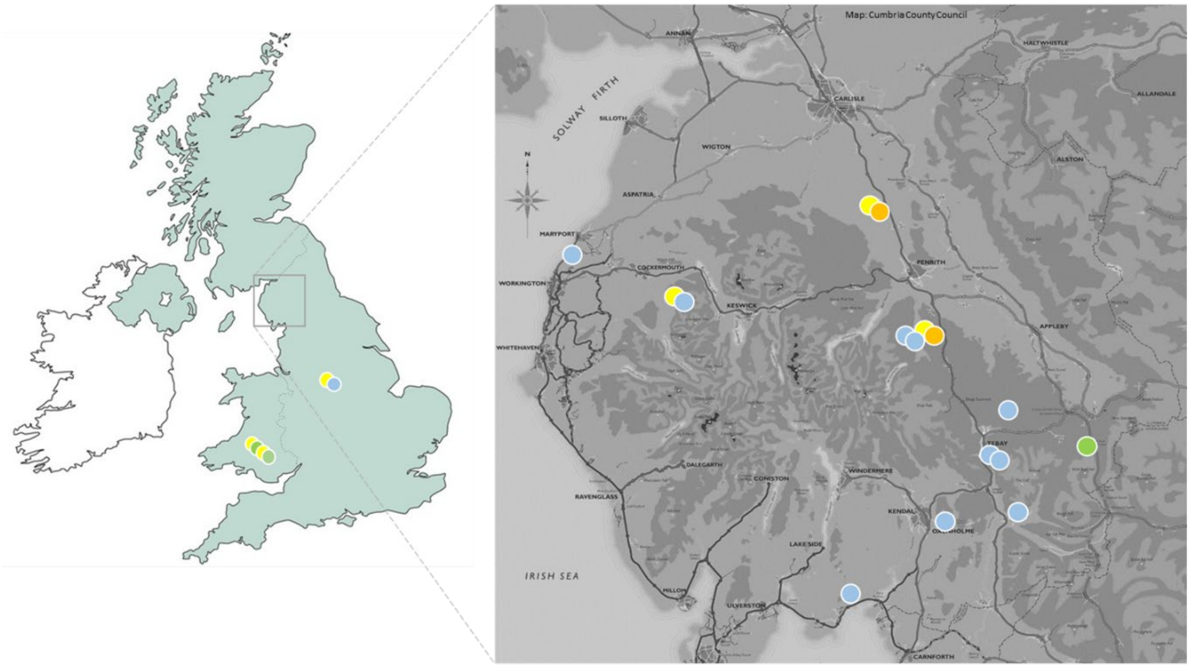

Figure S1. Location of the Q-NFM network of gauged micro-basins in the United Kingdom, with the inset figure showing the Cumbrian mountains where most are centred. Those micro-basins with monitored surface storage features, namely on hillslope surfaces, in perennial channels, and on floodplains (NbS interventions (ii), (iii) and (iv) are shown with blue shaded circles. Those with monitoring of wet-canopy evaporation (NbS i) are shown with green shaded circles, while those shown with orange shaded circles have overland flow monitoring for the NbS of enhanced soil infiltration. Micro-basins used as a reference basin or 'control' without added NbS features are shown with yellow shaded circles.

S3. Results and discussion

S3.1 Potential design criterion 1: Are the interventions designed to work primarily in events that locally flood properties?

If the NbS features fill during such small events, there is the risk that they offer no additional capacity for storage if the storm develops further to produce overbank flows that flood properties. Installing features that too quickly engage with channel flows (or overland flows) during typical rainstorms (that do not lead to property flooding) with the objective of showing funders (or local citizens) they can intercept water, may be counterproductive. To gain maximum storage around the peak of river hydrographs associated with downstream flooding means that the feature should not engage at all except during such lower probability events (see e.g., Kingsbury-Smith *et al*., 2023). A good example of such an in-channel feature can be found in the 5.7 km^2 Belford Burn NbS catchment in Northumberland (UK), where it does not engage with channel flow until bank-full is reached. At that point, larger discharges are diverted onto the floodplain behind a wooden structure (see Plate 1 in Nicholson *et al*., 2012).

With surface storage features on hillslopes (i.e., upslope of the first-order channel network: e.g., Figure 6 in Beven *et al*., 2022), ensuring that they are sufficiently leaky with basal openings capable of easily passing overland flows during rainstorms not associated with downstream flooding is equally important. Sizing such openings is difficult given that the inflow hydrograph of the storage feature cannot be determined with accuracy. Hence, there is value of installing openings that may be modified to give a different fixed size after the first event producing downstream flooding. An example of such openings in hillslope bunds that may be modified following visual or measured effects during major flood events are found at the Birds Park NbS site of Cumbria (Figure S2), a site utilised in Beven *et al.* (2022).

Figure S2. One of the adjustable wooden sluices through the Enhanced Hillslope Storage (EHS) features at the Birds Park NbS trial site, near Kendal town, Cumbria (UK**).**

S3.2 Potential design criterion 2: Are the features designed to have sufficient empty capacity (<u>freeboard</u>) just before peak discharge of events that flood properties?

Empty capacity or ‘freeboard’ is needed above the typical storage immediately before flood peaks, to retain inflows during extreme events. When the degraded peatland on Tebay Fells (Cumbria, UK) was restored by partial gully infilling with peat and protective root mat, wooden-plank structures were added into these restored gullies for storage of flood-water (www.cumbriawildlifetrust.org.uk/tebay-common-peatland-restoration). Figure S3 shows that Peat Dam 1 in the Tebay NbS system may hold a greater volume than Peat Dam 5 some 35 metres upstream. However, because it is already largely full of water at the start of the event (likely due to a more impermeable floor), is not able to change its storage as much as its theoretical capacity would suggest, and so is not significantly more effective than the smaller Dam 5.

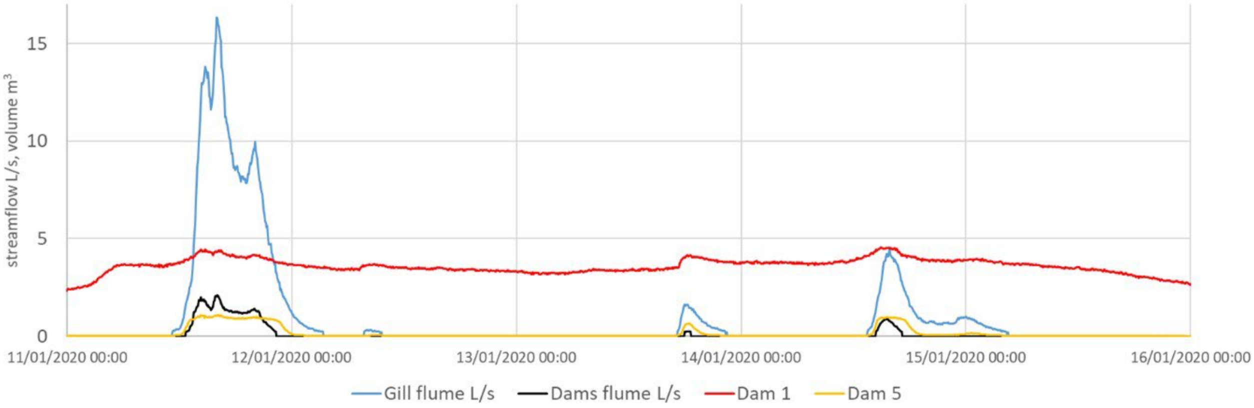

Figure S3. Volume of Enhanced Hillslope Storage (EHS) at Dam 1 (red line) and Dam 5 (yellow line) over the period 11-16 Jan 2020 within peatland at Tebay NbS trial site in Cumbria (UK). The ephemeral channel discharge immediately downslope of Dam 1 at the Dams flume (black line), as is the discharge 520 m downslope in the first-order channel (blue line).

S3.3 Potential design criterion 3: What floodwater retention times should NbS storage features have?

With the previous example (Figure S3), the larger Peat Dam 1 was not as effective as it might be, because it held onto a significant proportion of water for many days following the storm event. The rainfall-streamflow system at the Tebay site has a response time of some 0.81 to 1.76 hours for flood hydrographs with peaks > 0.30 mm/15min (Mindham *et al.*, 2023; Chappell *et al.*, 2024). So the temporary storage features designed to mitigate such peaks should have a retention time longer than this to be effective, but certainly not a factor of 10 larger than this (see Metcalfe *et al.*, 2018). Retaining water many times longer than the retention time of the upstream catchment area means that the feature may still be largely full of water when the next storm arrives, and so considerably less effective. A spreadsheet-based design tool is available to estimate the retention times of in-channel NbS features (www.jbatrust.org/about-the-jba-trust/how-we-help/publications-resources/rivers-and-coasts/nfm-leaky-barrier-retention-times/)

S3.4 Potential design criterion 4: What intensity of intervention per unit upstream area is required to reduce flood risk in a flood-vulnerable community?

With traditional flood storage basins, such as the Garstang Flood Storage Basin in Lancashire (UK), the filling and emptying of the temporary storage may be activated and deactivated with motors. In contrast, constructed NbS-based storage features tend to fill and empty without human intervention. Thus, NbS storage features have a greater risk that their opportunity for capturing floodwater is limited by their capacity being greatly diminished by the presence of pre-event water (see Figure S3). Consequently, designing an NbS feature (or series of NbS features) to deliver up to 10,000 m^3/km^2 for a 2% AEP event (or lower intensity for smaller, more frequent events) may not guarantee that empty storage is available close to the peak of flood hydrographs (see potential design criterion 3).

To deliver 10,000 m^3/km^2 of total flood storage or 1,000 m^3/km^2 of additional storage ± 2 hours of a flood peak is clearly easier to achieve for an upstream catchment area of 1 km^2 (Mindham *et al.*, 2023) compared to one of 2,000 km^2 (Hankin *et al.*, 2017). Note that "upstream catchment area" means the catchment upstream of the properties at risk, not the extreme headwaters (i.e., lower-order basins towards the head of perennial channels) of the catchments that generate the floodwaters. Half of all flooding in England is associated with small upstream catchment areas less than perhaps 10 km^2; this is so called 'surface water flooding' (Environment Agency, 2009). So, by focusing interventions on small upstream catchment areas with substantial flood risk (see Connelly *et al*., 2023), NbS could deliver benefits nationwide if applied intensively within these small upstream catchment areas. By applying NbS to many such communities affected by small upstream catchment areas within a larger catchment, ultimately the benefits will be gained for the communities affected by overbank flows from the main river – see e.g., Hankin *et al*. (2017, 2021) and Beven *et al*. (2022).

S3.5 Potential design criterion 5: How does flood mitigation effectiveness and any negative aspects of interventions change over time?

NbS features that are vegetation-covered diversion channels are ready to deliver flood mitigation benefits as soon as constructed, and are less likely to deteriorate in flood mitigation effectiveness over time. NbS diversion channels are often called 'swales' in the UK (Burgess-Gamble *et al*., 2018). Low earth bunds (sometimes enhanced with excavated hollows) on floodplains or hillslopes are comparable in their nature of delivery. With earth bunds using only natural materials, consideration does however, need to be given to the 'natural' storage feature outlets, to ensure that they do not collapse and so reduce drainage rates following floods (see discussion of potential design criterion 3). Earth bunds on hillslopes where the soil is tilled could act as sediment traps. While this is a positive NbS benefit for water quality, flood storage would reduce over time or require potentially costly excavation of the accumulated sediment to maintain flood mitigation benefits (Ockenden *et al*., 2012; Robotham *et al*., 2021).

Leaky dams constructed from assemblages of branches look more like 'woody dams' or 'debris dams' formed naturally within streams in wooded areas. The mobility of the woody material is seen as a natural dynamic process. The storage effectiveness of such naturalistic leaky dams during floods is therefore, more spatially and temporally variable (e.g., Wohl, 2016).

A further NbS intervention that will certainly change over time is Enhanced Wet-canopy Evaporation (EWE) resulting from tree planting and growth. The research of Page *et al.*, (2020) explains how even leafless deciduous trees within extreme storms in the Cumbrian Mountains are able reduce potential streamflow locally within the catchment system through EWE. Measured effects of EWE have however, primarily been demonstrated for mature woodland canopies. Thus for tree planting to be an effective NbS intervention through EWE, a wait of maybe +30 years (Brantley *et al*., 2019) is needed for the development of the large branch surface area associated with mature trees (i.e., development of an enhanced evaporating surface).

S3.6 Potential design criterion 6: Is it important to measure the flood mitigation effectiveness of features once built?

When flood storage interventions have been constructed on the surface of hillslopes, in channels or on floodplains, the stated measure is often the cumulative storage that could be obtained if all of the features are *completely full of water* (Bevan, 2022). Where measurements of actual storage held behind individual features have taken place, the volumes temporarily held may be considerably less than the hypothetical maximum storage. This would mean that the flood mitigation benefits may be grossly exaggerated by quoting only the hypothetical maximum storage. This is not always the case – see the example of the Grange bund in the previous section. However, with the in-channel log dams in the Tebay example, actual volume measured during flood events (Follett *et al.*, 2024) is considerably less than the reported hypothetical maximum storage (nfm-theriverstrust.hub.arcgis.com). This is therefore a strong argument for measuring actual storage during the flood events of interest (see also Black *et al.*, 2021). This equally applies to knowing whether the hypothetical maximum storage is not delivered because some features are already full just prior to the flood peak; this was shown earlier with the Tebay Peat Dam 1 example (Figure S3).

Where the NbS intervention is a change to soils to enhance infiltration, the direct comparisons may be less robust. For example, if changes to the soil infiltration capacity following an NbS intervention is measured (see e.g., Wallace *et al.*, 2021 in Cumbria), the significance of these for the river hydrograph are not known, without measurements of the time-series of soil moisture content. If the topsoil is already saturated during a flood event of interest, changes to the soil infiltration capacity may have little effect. Similarly, if the soil profile is already highly permeable and near-surface saturation never observed, changing the soil infiltration capacity will have little effect. Directly measuring the overland flow (using 'Gerlach troughs') generated as a result of soil interventions is a more robust measure of change (see e.g., Wallace *et al.*, 2021). However, this approach often suffers from the fact that the spatial variability of the overland flow is rarely measured by replicating the plots across even a micro-catchment with measured streamflow.

S3.7 Potential design criterion 7: How many properties at risk of flooding would benefit from intensive NbS in the upstream catchment (investment targeting)? i.e., is the NbS design value for money?

To be effective, most of this NbS intervention may need to be located close to the Properties-at-Risk ('P@R'). If the introduced storage only affects the headwaters of a catchment, floodwaters entering channels elsewhere will not have been affected by these headwater features. Furthermore, with large catchments the time for a floodwave to route from headwater- to downstream-channels becomes critically important (see e.g., Leedal *et al.*, 2008 modelling of the 2,287 km^2 Eden catchment in Cumbria). Thus when designing large catchment NbS schemes, channel routing times need to be measured and modelled, as does the potential for inadvertently synchronising downstream flood peaks by slowing only fast-responding, river sub-catchments.

S3.8 Proposed design criteria summarised with a single infographic

The potential design criteria for flood mitigation effectiveness of NbS features to be built might be summarised as an infographic (Figure S4). Detailed explanation of the scoring of these two example NbS schemes is given in the key.

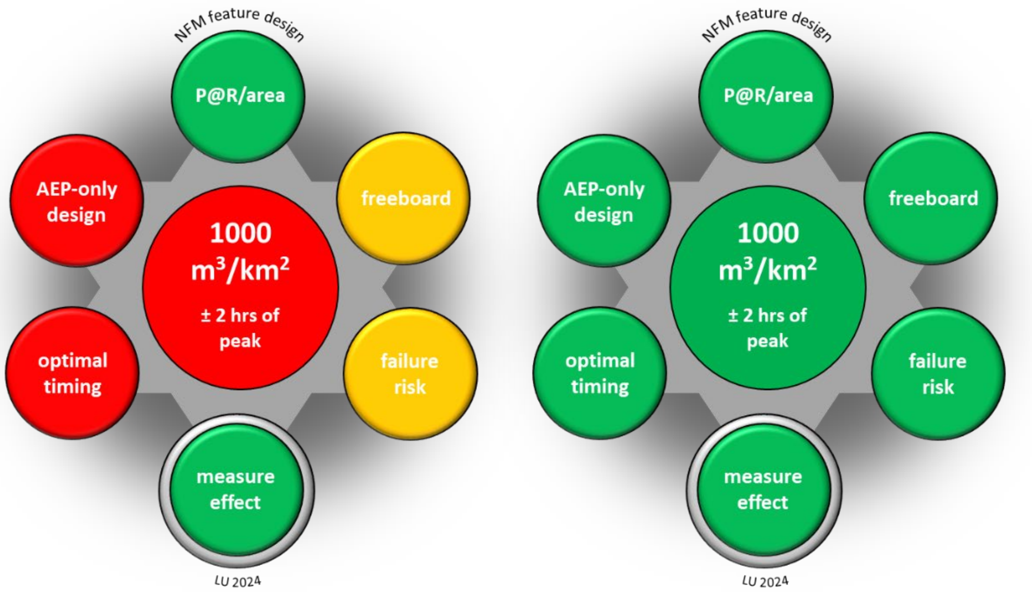

Figure S4. Examples of the new NbS infographic used to summarise Key Performance Indicators (KPIs) for built NbS schemes at (left) Tebay (log dam aspects only), and (right) Grange. For each scheme, where there is evidence that an NbS KPI has been met the 'traffic light' is green. It is then red for failed delivery, and orange for partial delivery. The KPI of "P@R/area", both NbS pilots benefit >5 properties in their 5 km^2 contributory areas. For "Freeboard", the Tebay log dams are largely full in events that do not flood the community, while the Grange bund is empty immediately prior to events that previously flooded the community. For "failure risk" the Grange earth bund is observed stable against erosion, while a few of the Tebay log dams have been dislodged in floods. For "measure effect", continuous monitoring is ongoing at both sites. For "optimal timing", the Grange bund holds floodwater for several hours beyond the peak then drains, while most of the Tebay log dams do not hold water for hours beyond the peak. For "AEP-only design" the Grange bund focuses effect on the twice a year events previously generating floods, while the Tebay log dams fill mostly in small rainstorms. For the most critical delivery of "1000 m^3/km^2 additional storage ±2 hrs of flood peaks", the Grange bund was measured to deliver 1,322 m^3/km^2 in a 1-in-1 year event, while the Tebay log dams only achieved 71 m^3/km^2 in a 1-in-1 year event. Other studies have demonstrated similarly small volumes of total or additional peak-period storage with 'leaky dams' (e.g., Mulligan *et al.*, 2023).

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