Nature-based solutions (Nbs) for flood mitigation: Recent UK case studies

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Abstract. Implementing Nature-based solutions (Nbs) can potentially reduce the flood risk in catchments and improve water and soil quality and biodiversity. Understanding the hydrological functioning of the Nbs interventions is important in determining their effectiveness in reducing flood risks. This study reports the findings from two UK projects namely the Littlestock Brook Natural Flood Management (NFM) pilot and LANDWISE (Land Management in Lowland Catchments for Integrated Flood Risk Reduction). The Littlestock Brook NFM study showed that the Nbs interventions successfully attenuated all storm event discharge peaks during the monitoring period (up to 55% reductions) and that over 40% of the total storage volume remained available throughout all events. The LANDWISE project demonstrated that whilst increased organic matter improves soil structure and porosity, innovative arable management practices (e.g., controlled traffic and min till) can also improve soil structure and porosity, increasing soil hydraulic conductivity and therefore NFM potential.

1 Introduction

In recent decades, there has been an increased interest in integrated catchment management to govern water resources where catchment decisions are made collaboratively using a systems-thinking approach. There has also been an increased recognition of the concept of Nature-based solutions (Nbs) which enhance biodiversity and human well-being through healthy ecosystems (1). Nbs particularly for flood risk reduction are actions to enhance natural features/functioning of the environment to store and/or slow runoff and floodwaters. Such solutions are cheaper and more sustainable than hard-engineering approaches while simultaneously benefiting soil and water quality, and biodiversity. In the UK, some of the common Natural Flood Management (NFM) measures, a form of Nbs, are leaky woody dams, online and offline storage ponds, afforestation and soil/land management (Fig. 1). Soil physical and hydraulic properties play crucial roles in controlling the extent to which soils can absorb, store and diffuse water. Therefore, land use and management have the potential to improve soil properties, increase infiltration and soil water storage.

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Across the UK, NFM has been implemented relatively widely as a multi-purpose catchment management strategy, particularly since a £15 million investment from the government to fund 60 pilot projects (2). These pilot projects aimed to gather evidence to help enable the mainstreaming of NFM in future flood risk management. Further investment and funding mechanisms for NFM were made by the UK Natural Environment Research Council (NERC) to build robust evidence.

This study reports the findings from two UK projects namely the Littlestock Brook Natural Flood Management (NFM) pilot in the River Evenlode catchment located in the upper reaches of the Thames basin and the LANDWISE (Land Management in Lowland Catchments for Integrated Flood Risk Reduction) project (funded by NERC) within the Thames catchment, UK.

(a) Leaky woody dams (b) Storage ponds (c) Afforestation (d) Soil/land management

Fig. 1. Common Natural Flood Management (NFM) measures.

2 Method and Materials

The Littlestock Brook is a 16.3 km^2 sub-catchment of the River Evenlode catchment (430 km^2); located in the upper reaches of the Thames basin in West Oxfordshire, UK. The first phase of NFM measure implementation began in March 2017, with the installation of 12 woody dams. The next three phases of delivery (2018-2020) implemented interventions in the upper catchment including soil management measures on steep clay slopes and along overland flow pathways; creating nutrient retention ponds and sediment traps in fields; constructing 15 riparian field corner bunds to store over-land run-off; and installing a further 15 in-channel, bank-full woody dams (Fig. 2). A woodland creation scheme by Forestry Commission delivered 14.4 ha of new riparian woodland to improve interception of rainfall and run-off and sequester carbon over time. Milton-under-Wychwood is at the confluence of two tributaries draining the upstream study area that is comprised of two predominantly rural sub-catchments, each 3.4 km^2 and referred to as North and South (Fig. 2). This NFM pilot intensely monitored upstream of the Milton-under-Wychwood flood receptor. The comprehensive hydrometric (stream water level, stage-discharge, rainfall and storage water level) and water quality monitoring network were established to monitor the functionality of the NFM pilot. Water quality monitoring was set up to investigate the multi-benefits of the NFM pilot (3-7).

In the LANDWISE project, broadscale and detailed surveys of field sites under different land uses, land management practices and soil types within the Thames catchment, UK, were undertaken (Fig. 3). The broadscale survey focussed on five soil types within two geology types (carbonate and mudstone); across arable land, permanent grassland and broadleaf woodland (8). As the very near-surface soil condition exerts a critical control on the partitioning of rainfall into infiltration and runoff, the broadscale survey sampled the top 50 mm of soil, measuring soil properties including dry bulk density (along with calculations of inferred porosity), texture, structure, aggregate stability and organic matter. Samples were taken from 164 fields (across the field site locations - yellow dots given in Fig. 3), which given 6-15 sample replicates per field according to land use, resulted in a total of ~1800 samples. In addition to these quantitative measurements, qualitative observations of soil surface conditions were also undertaken.

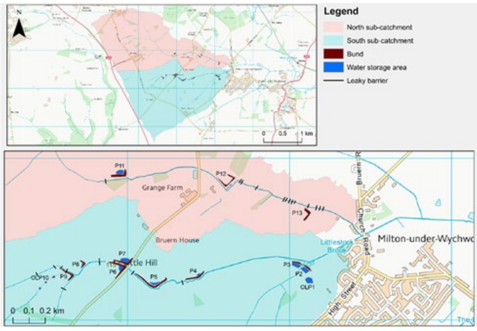


Fig. 2. Littlestock Brook NFM features in the North and South sub-catchments. Storage features appended with ‘P’ and ‘OLP’ where ‘P’ denotes pond and ‘OLP’ denotes online pond features.

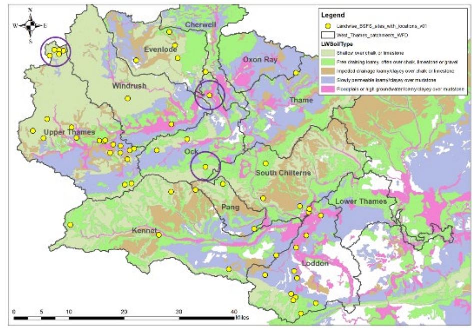


Fig. 3. LANDWISE broadscale and detailed survey field site locations and simplified soil/geology types across the Thames catchment. Soils Data © Cranfield University (NSRI) and for the Controller of HMSO 2022.

The detailed survey focused on conventional and innovative farming systems, including arable crop rotations with grass, controlled traffic, cover crops, and min/zero till. In the detailed survey, soil properties including dry bulk density (with inferred porosity), soil moisture retention, saturated and unsaturated hydraulic conductivity were measured at different depths in the soil profile and over the 2021 growing season, including repeats in Spring, before harvest and/or after harvest (9). The replicated measurements were made in 7 fields/land parcels at 3 locations, on Chalk, Limestone and Mudstone geologies, as shown by the purple circles in Fig. 3.

3 Results and Discussion

3.1 Littlestock Brook NFM intervention-scale monitoring

Water level data of the Flood Storage Areas (FSA) have been analysed to assess the effectiveness of the south sub-catchment (3.4 km^2) FSAs, which have an estimated combined storage capacity of 15,717 m^3. Major storm events observed in each water year from 2019/2020 to 2021/2022 have been analysed, with return periods of up to 5.5 years. These events were identified from the south sub-catchment outlet discharge time-series, estimated using the methods detailed in (4). This analysis has been done in the south sub-catchment due to the availability of LiDAR or survey data for the FSA interventions. For the largest and most intense events, the amount of water stored is highest which indicates that higher stream water levels result in more overbank flow at spillways and leaky barriers which is then directed into the FSAs to be stored. For larger events, this shows that the NFM potential for floodwater storage is greater. The hydrograph in Fig. 4 shows successful attenuation of the flood peak that is demonstrated by decreased discharge due to floodwater storage during the rising limb, event peak and at the start of the falling limb. On the falling limb, FSA drainage increased the discharge. During the most intense rainfall event, results showed reductions in flood peaks across all events, ranging from 14.2% to 55.2% (4). Throughout all events, at least 40% of total storage capacity remained available, suggesting that larger events than those analysed here could be successfully attenuated.

Suspended sediment and associated nutrients across catchments of the Littlestock Brook NFM scheme were also monitored. Over the 2-3 years since construction, the equivalent of 15% of sub-catchment sediment yield was trapped by FSA features where the sediment accumulation rates varied greatly between features (4-6). This stored sediment also accounted for 10% of the Total Phosphorus (TP) and 8% of the Particulate Organic Carbon (POC) yields. The sediment accumulation rates do not appear to compromise the primary water storage function of the FSAs. They are most likely to need maintenance to remove sediment every 10 years, which has benefits as the accumulated sediment is generally fine and enriched in nutrients thereby potential providing a valuable resource to re-apply to the agriculture field, also potentially offsetting any long-term soil erosion and loss.

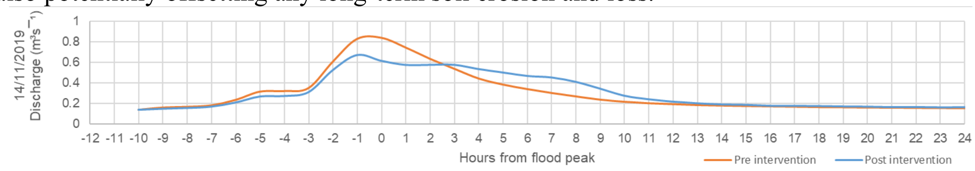
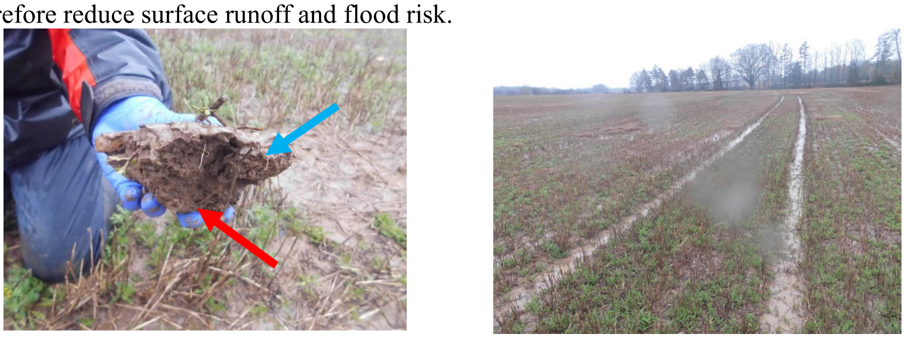


Fig. 4. Event hydrograph for discharge pre- (orange) and post-FSA interventions (blue).

3.2 LANDWISE surveys

The LANDWISE field surveys were undertaken during a wide variety of weather conditions. From an NFM perspective, this usefully allowed catchment hydrological processes to sometimes be observed during potential flood-generating conditions. For example, Fig. 5 shows the soil near-surface response to a heavy rainfall event in January 2020. This heavy silty clay soil, under conventional (non-NFM) arable agricultural management, exhibited surface sealing which can be attributed to low soil aggregate stability (samples failed lab aggregate slaking test). As a result, the soil surface has very low permeability preventing infiltration and generating surface water ponding (Fig. 5a). This ponded water then follows the highly compacted agricultural vehicle 'tramlines' which serve as preferential overland flow pathways, quickly conveying runoff to the receiving watercourse and increasing flood risk. Although the measured soil organic matter in this field is reasonable (3.6% mean) and the soil porosity inferred from dry bulk density is typical for the soil type (0.53 cm^3/cm^3), the arable management involves annual full inversion ploughing, a long-term repeated spring barley cropping pattern, minimal control of traffic and no organic amendments. It is likely that implementation of land management NFM measures such as min till, more diverse crop rotation, controlled traffic and increasing organic matter would, through improved soil structure and aggregate stability, reduce surface sealing and increase soil porosity, and therefore reduce surface runoff and flood risk.



(a) Near-surface soil hydrology (b) Preferential overland flow pathways

Fig. 5. LANDWISE example qualitative observations – hydrological response to a winter rainfall event on heavy clay soil under conventional (non-NFM) arable agricultural management. Panel (a) shows an extracted near-surface soil sample – the soil surface is sealed causing rainfall to pond (blue arrow), whilst the underlying soil remains unsaturated (red arrow). Panel (b) shows ponded water in the same field moving as surface runoff along preferential overland flow pathways (agricultural vehicle 'tramlines')

As demonstrated (Fig. 5), the near-surface soil condition exerts a critical control on hydrological processes. The LANDWISE survey results highlight several land management NFM measures which, through increased soil hydraulic conductivity and porosity, can improve the ability of soils to absorb rainfall, reducing surface runoff and therefore reducing pluvial and fluvial flood risk. For example, Fig. 6 shows the relationship between near-surface soil organic matter and porosity (estimated from dry bulk density accounting for variable organic matter percentage, see (8) for details) for the ~1800 broadscale survey samples. It is apparent that there is a strong positive non-linear relationship between organic matter and soil porosity. As illustrated by the arrows, this implies that a modest increase in soil organic matter from a low starting point (e.g. from 2 to 5%) can significantly increase soil porosity (e.g. from 38 to 51%). The figure also shows that for any particular soil organic matter content, there can be wide variation in the associated soil porosity (soil organic matter itself tends to be rather consistent within individual fields). This can often be attributed to variations in soil compaction between general infield areas, trafficked areas and un-trafficked margins due to land management practices. As also shown in Fig. 6, an example arable field under conventional (cf. organic), min-till and controlled traffic (yellow dots) was found to have significantly higher soil porosity compared to typical (trend line) values. Similarly, an arable field under organic farming with diverse rotation and zero till (purple dots) was also found to have significantly higher porosity. Such examples illustrate the potential of innovative agricultural practices, alongside increasing soil organic matter (promoted through recent approaches such as regenerative agriculture to improve soil health), to improve the ability of soils to absorb rainfall and provide NFM benefits.

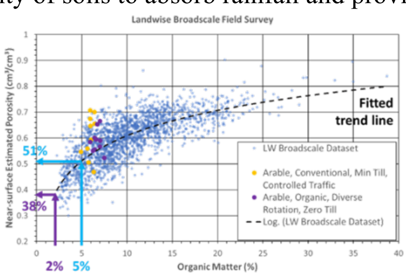


Fig. 6. LANDWISE Broadscale survey – near-surface soil organic matter vs. soil porosity (representing the full range of field conditions – infield, trafficked tramlines and headlands, un-trafficked margins), with example data from fields with innovative arable land management practices highlighted.

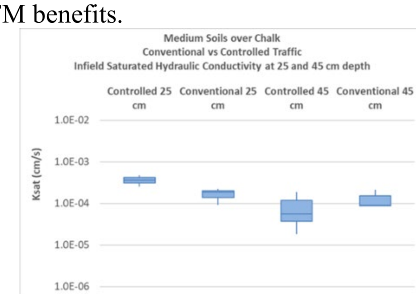


Fig. 7. LANDWISE Detailed survey – saturated hydraulic conductivity at two depths on similar soils under conventional and controlled-traffic farming systems

The controlled traffic arable field highlighted above was also included in the LANDWISE detailed survey, with a comparison against a more conventional nearby field on similar soil. As shown in Fig.7, controlled traffic with min till and cover crops resulted in higher saturated hydraulic conductivity, K_{sat}, at 25 cm depth compared to the more conventional arable field (generally with min till but occasional ploughing due to grass in rotation). As anticipated, due to increased consolidation and increased bulk density with depth, K_{sat} was significantly lower at 45 cm depth for both fields. It appears that the combination of controlled traffic and min till, along with higher soil organic matter, increases both near-surface soil porosity and topsoil hydraulic conductivity, through reduced compaction and improved soil structure. This has the potential to increase infiltration into the soil, percolation through the soil and water storage in the topsoil, providing benefits to the crops themselves and for flood risk reduction.

4 Conclusions

The analysis of the Littlestock Brook NFM intervention-scale monitoring data during the study period showed successful attenuation of all storm event discharge peaks (up to 55% reductions) and that over 40% of the total storage volume remained available throughout all events. The Flood Storage Areas were able to provide multiple benefits through significant sediment trapping, particularly during the larger storm events where features were connected to the stream via spillways. The LANDWISE project results showed that whilst increased organic matter (e.g. through organic farming, incorporating crop residues and adding organic amendments) significantly improves soil porosity and structure, innovative arable management practices (e.g., controlled traffic and min till) can also improve soil structure/porosity, increase saturated hydraulic conductivity and therefore NFM potential to the flood risk. This research work enabled assessment of the effectiveness of the NFM interventions, within the limits of the range of conditions during the monitoring period.

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