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RESEARCH ARTICLE

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Nature-based solutions enhance sediment and nutrient storage in an agricultural lowland catchment

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Abstract

In this paper, nature-based solutions (NBS) include: (1) natural flood management (NFM) interventions with a primary function of flood risk reduction but with additional multiple benefits for water quality improvements through the mitigation of diffuse pollution; and (2) ponds with a primary function of water quality improvement. This study assesses the ability of these NBS to trap pollutants in run-off within two small (3.4 km^2) agricultural catchments (Upper Thames, UK). The masses of sediment, phosphorus, and organic carbon trapped by 14 features (since construction 2–3 years previously) were quantified through sediment surveying and sampling. Streamflow and suspended sediment monitoring downstream of features enabled catchment yields to be calculated. The features trapped a total of 83 t sediment, 122 kg phosphorus, and 4.3 t organic carbon. Although the footprint of the features was <1% of the catchment area, they drained 44% of the total land area and captured the equivalent of 15% of the total suspended sediment yield, 10% of the total phosphorus yield, and 8% of the particulate organic carbon yield as monitored at the catchment outlet over the monitoring period. Results reveal that accumulation rates were influenced by hydrological connectivity, with greater accumulation in features constructed directly on streams (online ponds), and those offline features that filled from overbank flows. The low to moderate accumulation rates observed in offline features suggests that their floodwater storage potential is only likely to significantly reduce in the medium term, necessitating maintenance after ∼10 years. Compared with topsoil in each contributing area, trapped sediment was enriched in phosphorus and carbon in the majority of features, having on average 50% higher phosphorus and 17% higher organic carbon concentrations than surrounding arable soils, highlighting its potential value for redistribution on farmland. Monitoring results demonstrate the potential of NBS, including NFM, to mitigate diffuse pollution in lowland catchments.

KEYWORDS

catchment management, diffuse agricultural pollution, fine sediment, multiple benefits, natural flood management, organic carbon, phosphorus, soil erosion, water quality, working with natural processes

1 | INTRODUCTION

Soils are crucial to sustaining agricultural production and food security globally (FAO, 2015; Pozza & Field, 2020). However, soils are threatened by the acceleration of erosion from water due to anthropogenic pressures including land use and climate change (Borrelli et al., 2020; Ockenden et al., 2016; O'Neal et al., 2005). Intensification of the water cycle as a result of climate change is predicted to bring more intense rainfall and associated flooding, which will in turn exacerbate the issue of soil loss (Burt et al., 2016; IPCC, 2021). In temperate regions, shifts in the timing of heavy rainstorms from summer to autumn may also increase soil loss, particularly in bare arable fields where soil is susceptible to erosion following harvest (Routschek et al., 2014). Historically, agricultural landscapes and their watercourses have typically been heavily modified to enable efficient drainage and maximize crop production (Evans et al., 2007; Pierce et al., 2012). Technological advances such as the mechanization of farming and changing trends in the growing of certain crops have impacted soils in many ways and intensified their erosion over time. Increased hydrological connectivity of the land to streams facilitates the transfer of water, mobilizing soil particles and solutes into watercourses via surface run-off or subsurface drains. This has negative onsite impacts in terms of soil health and nutrient losses, but also costly and undesirable offsite consequences on downstream flood risk, water quality, and biodiversity (Boardman, 2013, 2021; Evans, 2010; Mondon et al., 2021; Pimentel, 2006).

Soil conservation practices such as no-till farming can be implemented on arable fields to help mitigate soil erosion and associated impacts, with experimental evidence suggesting that reduced tillage can significantly reduce sediment delivery on both conventional and organic farms (Seitz et al., 2019). Conservation agriculture has been found to enhance soil organic carbon and in turn improve soil structure, infiltration, and water storage, which reduce soil loss (Page et al., 2020). However, further evidence shows how conservation practices can be less economical and less effective for mitigating certain nutrient losses. Bertol et al. (2017) found that nutrient and organic carbon concentrations in run-off from no till were higher than from conventional tillage, with the cost of erosion losses from no till being 29% higher in terms of phosphate fertilizer. These differences demonstrate potential trade-offs and highlight how the effectiveness of soil conservation practices may vary considerably across different landscapes due to factors such as soil or crop type (Choden & Ghaley, 2021; Deasy et al., 2009). Although changing agricultural practices may be part of the solution, mitigating soil loss and diffuse pollution may require additional interventions.

In recent years there has been an increased interest in nature-based solutions (NBS) and natural infrastructure to mitigate environmental problems such as climate change, biodiversity loss, pollution, and hydrometeorological hazards in a more integrated way (Seddon et al., 2020; Suttles et al., 2021). One such approach being adopted in the United Kingdom and across Europe is natural flood management (NFM), which aims to work with hydrological processes to slow and store water in the landscape to deliver multiple environmental and societal benefits (Lane, 2017). NFM is part of the wider concept of working with natural processes (WWNP), which the Environment Agency describes as aiming to 'protect, restore and emulate the natural functions of catchments, floodplains, rivers and the coast' (Environment Agency, 2018; Fryirs & Brierley, 2021). NFM encompasses a broad variety of interventions, including the creation of woodland, addition of instream leaky woody dams/barriers, and construction of offline storage features. These offline features are used to temporarily hold back water in the landscape, reducing flood risk through attenuating run-off or by receiving overflow from stream channels, thereby also capturing diffuse pollutants, creating wetland habitat and storing carbon (Barber & Quinn, 2012; Evrard et al., 2008; Ockenden et al., 2014; Williams et al., 2020). Offline features typically fill from diffuse overland flow, but can also be designed to store overbank flows. On the other hand, online features can be defined as ponds receiving flow directly from a stream and are typically used as NBS for water quality improvement.

Current evidence on the effectiveness of NBS to deliver multiple benefits is limited, but the rollout of several small NFM schemes has created new opportunities for gathering empirical data (Dadson et al., 2017; Wingfield et al., 2019). Findings from the Belford catchment (northeast England) suggest that offline features are able to retain significant volumes of sediment, but online features showed a lack of retention during storm events (Barber & Quinn, 2012; Wilkinson et al., 2014). Modelled evidence suggests that peak suspended sediment and total phosphorus concentrations could be reduced by 5–10% from adding 2000–8000 m^3 of storage in the pasture-dominated Newby Beck catchment (Adams et al., 2018). Despite the policy relevance and growing interest in NBS such as NFM, the knowledge base (particularly on offline features) is lacking evidence for lowland catchments that cover large parts of the south and east of England (Lockwood et al., 2022). Questions have also been raised over the sustainability of water storage in such features, where rapid sediment deposition could diminish storage capacity over time (Lane, 2017). Evidence on their efficacy and the delivery of benefits is needed to support agri-environmental policies such as the UK government's Environmental Land Management (ELM) scheme, which could provide farmers with financial incentives for adopting NFM and other NBS, thereby increasing uptake more widely (Bark et al., 2021; Holstead et al., 2017). This study therefore aims to quantify the accumulation of sediment, phosphorus, and organic carbon in offline NFM features and online pond features within a small, predominantly arable lowland catchment. Specifically, two key research questions are addressed:

1. How has the implementation of NBS altered the catchment storage and yields of sediment, total phosphorus, and particulate organic carbon?
2. What factors influence accumulation rates within offline and online features?

The sustainability of these features over the long term is considered and the suitability of the accumulated sediment for redistribution on arable land is assessed to help inform management guidance for NFM schemes.

2 | METHODOLOGY AND METHODS

2.1 | Study site

Accumulations of sediment, phosphorus, and carbon were measured across a variety of offline and online features implemented as part of the Littlestock Brook NFM scheme, upstream of the village of Milton-under-Wychwood, Oxfordshire (Figure 1; see Figure S1 in the online Supporting Information for photographs of storage features). The studied features were constructed between February 2018 and February 2019 and vary in their design and hydrology (Table 1). Further details on the Littlestock Brook NFM trial are given by Old et al. (2019) and Robotham et al. (2021).

The Littlestock Brook catchment is located within the predominantly rural River Evenlode catchment, a tributary of the River Thames (southern England). The area upstream of Milton-under-Wychwood is drained by two sub-catchments (referred to as North and South). The North sub-catchment consists mainly of permanent improved grassland used for grazing cattle and sheep, whilst the South sub-catchment is largely arable. The area has a minimum and maximum elevation of 103 and 202 m, respectively, and an average slope of 6.3%. The western part of the catchment is underlain by a limestone geology with shallow lime-rich soils. Further down the catchment, the soils are largely seasonally wet, slowly permeable clay and loamy soils with some impeded drainage. The area receives an average annual rainfall of 765 mm and experiences an average annual minimum and maximum temperature of 5.7 and 13.1°C, respectively (Met Office, 2021).

Online features are defined as areas that are connected to a watercourse, either directly (e.g. constructed on a pre-existing

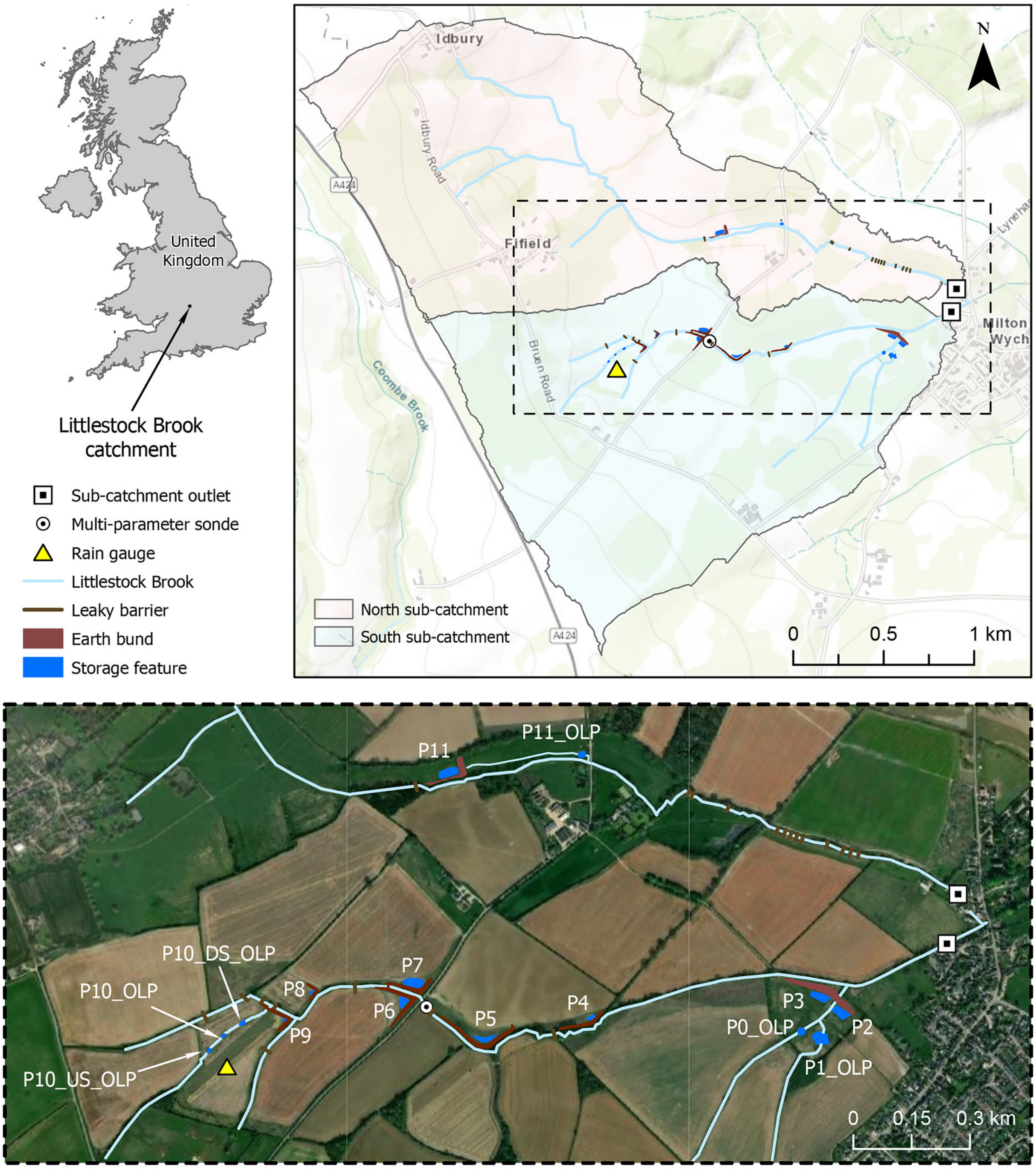

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FIGURE 1 Location of the Littlestock Brook, the NFM features, online ponds, and monitoring instrumentation within the North and South sub-catchments (both 3.4 km^2). Features and ponds are labelled according to the naming conventions detailed in Table 1.

TABLE 1 Characteristics of offline and online features in the Littlestock Brook NFM scheme. Features appended with 'OLP' denote online pond features and those without denote offline features. The 'US' and 'DS' prefixes are used to denote the most upstream and downstream features in the series of ponds, respectively

Storage feature	Construction date/ location	Max. volume (m^3)	Contributing area (ha)	Description
P0_OLP	February 2019 (South sub-catchment)	35	41.0	Permanently wet, drawdown in summer.
P1_OLP		440	30.5	Seasonally wet, connected to stream during winter.
P2		53	1.1	Seasonally wet, fills in large run-off events.
P3		514	0.4	Permanently wet, fills in large run-off events, fed by field drains.
P4	February 2018 (South sub-catchment)	857	3.9	Normally dry, fills in large run-off events, partly connected to leaky barrier spillway.
P5		3504	4.0	Permanently wet, fills in large run-off events, connected to leaky barrier spillway.
P6		2647	6.5	Normally dry, fills in large run-off events, drains easily due to connection to downslope field drain.
P7		2719	9.5	Permanently wet, fills in large run-off events, fed by upslope field drain.
P8		569	1.0	Normally dry, fills in large run-off events.
P9		860	20.1	Normally dry, fills in large run-off events.
P10_US_OLP		70	30.0	Permanently wet, drawdown in summer.
P10_OLP		90		Permanently wet, drawdown in summer, fills from outflow of P10_US_OLP.
P10_DS_OLP		95		Permanently wet, drawdown in summer, fills from outflow of P10_OLP.
P11	February 2019 (North sub-catchment)	2533	13.3	Normally dry, fills in large run-off events, connected to leaky barrier spillway.
P11_OLP		83	0.6	Permanently wet, drawdown in summer, filled by P11 outflow in large events.

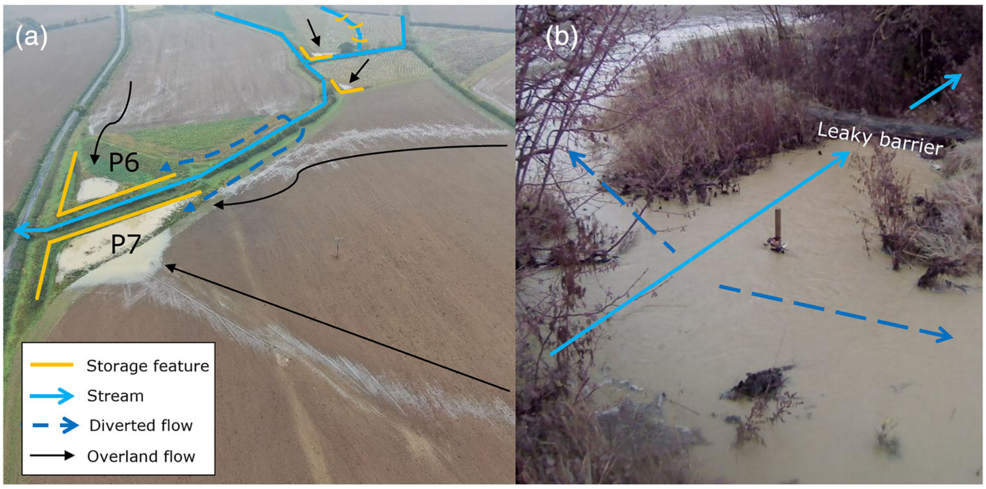

FIGURE 2 (a) Offline features (P6 and P7) filling from overland flow pathways during a storm event on 4 October 2020. (b) A leaky barrier diverting streamflow into P6 and P7 via spillways during a storm event on 23 December 2020.

stream) or indirectly (e.g. via a newly excavated channel that allows flow into and out of the area). Some indirectly connected online features are filled by seasonal intermittent or ephemeral flow. For example, P1_OLP is filled by a stream channel that flows regularly during October to March, but outside of this window the channel is only activated temporarily in response to significant rainfall. Offline features are areas that typically fill from overland flow during rainfall events (Figure 2a). However, many features are also co-located with instream wood features (leaky barriers) and spillways/swales that allow the features to fill from diverted streamflow in higher-magnitude events (Figure 2b). The contributing areas of features were estimated by a geographic information system (GIS) using the Environment Agency's National LIDAR Programme DTM (digital terrain model) 2020 at 1 m resolution. To take account of overbank flow diverted by leaky barriers during higher-magnitude storms, 'event contributing areas' were also calculated to estimate the drainage areas upstream of spillways where this phenomenon was observed. To do this, ArcMap hydrology tools were used to delineate the area draining to each spillway associated with a feature, and then the overland contributing areas of any upstream features that fell within this delineated area were subtracted to avoid double counting.

2.2 | Sediment and soil sampling

Sediment accumulations were estimated from measurements of sediment depth and bulk density. Sediment cores were sampled within each feature to determine the average bulk density of accumulated sediment. A coring device suitable for sampling soft, submerged sediment was made from 1 m-long copper pipe (2.6 cm in diameter), cut at a 45° angle on one end to aid insertion into the sediment. Six cores were taken from each storage feature (half in shallower sections closer to feature margins and half in deeper central sections). Sediment depth (down to the solid base of the storage feature) was also measured at each coring location to determine the original core length prior to any potential compaction that occurred during coring. Cores were stored in plastic sample bags and refrigerated at 4°C until being transferred into aluminium trays and oven-dried at 105°C for at least 36 h before being weighed. Dry bulk density was calculated following the guidance of Wood (2006). Loss-on-ignition (LOI) was quantified as a proxy measure for organic matter (OM) content. The samples were heated for 2 h at 500°C before being cooled in a desiccator and reweighed (Standing Committee of Analysts, 1984). OM was converted into organic carbon (OC) content using a 0.58 conversion factor chosen based on the literature (Bhatti & Bauer, 2002; De Vos et al., 2005; Rollett & Williams, 2020). The total phosphorus (TP) concentration of the sediment was determined spectrophotometrically. The ashed sample was crushed into a fine powder and combined into a bulk sample for each feature from which triplicate sub-samples of 3 ± 0.1 mg were then taken to determine average TP content. Sub-samples were mixed with 20 ml ultrapure water and analysed following the modified molybdenum blue methodology of Eisenreich et al. (1975).

Alongside the cores, additional sediment was sampled for use in determining absolute particle size distribution and characteristics using laser diffraction particle size analysis (Mastersizer 2000, Malvern Panalytical; Malvern, UK). Prior to analysis, 0.5–0.6 g sub-samples of sediment were treated with a 5% sodium hexametaphosphate solution and agitated for 5 min in an ultrasonic bath to disperse particles and prevent agglomeration.

Topsoil within each of the feature's contributing areas (listed in Table 1) was sampled for the determination of OC, TP, and absolute particle size distribution. Within each contributing area, five soil samples were taken using a trowel to dig out the top 5 cm of soil, following a W-shape pattern across the dominant land use to obtain spatially representative samples (Peters & Laboski, 2013). A total of 60 soil samples were taken across three land-use types (arable, grassland, and arable reversion). In the laboratory, 0.5–0.6 g sub-samples were taken from each soil sample for particle size analysis. The remaining soil was air-dried in aluminium trays at 30°C for at least 72 h before being crushed and sieved to <0.4 mm, also removing roots and stones from the sample. The soil was then oven-dried overnight at 105°C before being weighed. OM content was determined using LOI at 500°C and also converted to OC. The soil TP content of samples was then analysed and averages determined for each contributing area. The variability of soil properties between samples was visualized prior to averaging (see Figure S2 in the online Supporting Information for boxplots of key properties). Enrichment ratios (ER) were calculated by dividing mean constituent concentrations in sediment samples by mean concentrations in soil samples (Sharpley, 1980). Uncertainties for ER values were calculated as 95% confidence intervals using Fieller's theorem (Fieller, 1940).

2.3 | Storage and sediment volumes

The depths of accumulated sediment within each feature were surveyed along transects spanning the length and width of the feature, with measurements being taken at 1–2 m intervals. Depths were measured to the nearest centimetre from the solid base of the feature to the surface of the soft sediment layer using a metre rule. Transects were positioned so that they approximately captured the deepest section of the feature and a handheld GPS (eTrex, Garmin; Olathe, KS, USA) with a horizontal accuracy of 3 m was used to locate the start and end points of each transect. Where possible, one of the measurements was taken at a known reference point (stage board) in each feature to allow transects to be linked to this datum. Maintenance work to remove sediment from the series of P10 online ponds following their surveying in January and June 2020 meant that any future surveying would not represent the accumulation since construction. As a result, sediment depths measured for these features represent a shorter period of accumulation compared to the other features which were measured following a longer period post-construction and with no maintenance. Sediment depths were spatially interpolated using the natural neighbour interpolation method (ArcMap 10.5, Esri; Redlands, CA, USA) to estimate stored volumes. The bulk density measurements were then used to convert sediment volumes into masses, and concentration data were used to calculate total stored nutrient masses. Uncertainties are reported as standard deviation unless otherwise stated. A combination of LIDAR and real-time kinematic global positioning system (RTK GPS) (GS14, Leica Geosystems; St. Gallen, Switzerland) surveys of the features post-construction was similarly used to estimate their total storage volumes. Stage boards and water-level sensors (Rugged TROLL 100, In-Situ; Redditch, UK) were installed in 11 features (the exceptions being P0_OLP, P10_DS_OLP, P10_US_OLP, and P11_OLP) to measure water depth at 5-min intervals. Depth-to-volume relationships were derived in a GIS and used to produce time series of stored water volumes in the different features. The length-to-width ratios of features were measured by dividing length by width. To keep the metric as consistent as possible between the different types of features, lengths were defined as the distance from the inlet to the outlet.

Instream stage boards and water-level sensors located by leaky barrier spillways were used to determine when certain features were filling from the stream. The overflow elevation of spillways was surveyed with RTK GPS, with overflow into P6 during storm events also being verified with hourly time-lapse camera imagery.

2.4 | Catchment yields and water quality

Yields (±95% confidence intervals [CI]) of total and fine suspended sediment (SS), particulate organic carbon (POC), and TP were calculated at the two sub-catchment outlets using discharge and concentration data at 5-min intervals. Stream discharges were estimated using a stage–discharge rating curve developed from flow measurements made using an electromagnetic current meter (Valeport;

Totnes, UK) and the velocity–area method (Herschy, 1993). Some low-flow measurements were made using conductivity sensors (EXO1, YSI; Yellow Springs, OH, USA) and the salt dilution method (Hongve, 1987). Measured discharges ranged from 6 to 587 L s^{-1} ($n = 15$) for the South sub-catchment and 3 to 946 L s^{-1} ($n = 15$) for the North sub-catchment. Instream turbidity sensors (DTS-12, FTS; Victoria, Canada) co-located at gauging sites were calibrated against suspended sediment concentration (SSC) and TP samples taken under a range of flows using a US DH-48 sampler and automatic samplers (Sigma SD900, Hach; Loveland, CO, USA). Time series were quality controlled to remove suspect datapoints, with gaps of <12 h filled by linear interpolation if no storm events were known to have taken place during the period. Overall, turbidity/concentration data coverage was >99% for the monitoring period. Particulate OC concentration was estimated using linear regressions of SSC against particulate OM concentration of water samples at each sub-catchment outlet (South sub-catchment $R^2 = 0.97$, $n = 184$; North sub-catchment $R^2 = 0.96$, $n = 127$) and the OC conversion applied. Time series of instantaneous loads were calculated as products of discharge and concentration, and were then integrated to estimate yields over the monitored periods [Equation (1)]. Fine sediment (<63 μm) yields in each sub-catchment were estimated based on particle size distributions sampled during two high-flow events ($n = 9$ per sub-catchment). These particle size distributions were assumed to be generally representative of the stream's suspended load as large storm events typically deliver most of the total sediment yield (Chappell et al., 2004). The proportions of fine particles in the samples were averaged and combined to estimate the yields of silt and clay from each sub-catchment. The stored masses of sediment, TP, and OC within NBS features were divided by the yields leaving the sub-catchment for each monitoring period to calculate stored masses as proportions of the total sub-catchment yield. Calculations and statistical analyses were carried out in R (R Core Team, 2018).

$$\text{Flux} = \int_{t_1}^{t_2} Q(t)C(t)dt. \tag{1}$$

where Q = stream discharge, C = concentration of SS/TP/OC, and t = time.

Instream water quality parameters (including turbidity and ammonium) were also measured at hourly intervals using a multi-parameter sonde (EXO2, YSI; Yellow Springs, OH, USA) deployed as part of Thames Water's Smarter Water Catchments initiative. The sonde was located between P5 and P6/P7 (Figure 1) and operated using a pumped flow cell system which minimized sensor fouling. Rainfall was recorded at 2-min intervals using a tipping bucket rain gauge (Casella; Sycamore, IL, USA) and quality controlled using a storage rain gauge by ensuring the measurements were within 5% tolerance.

3 | RESULTS

3.1 | Sediment and nutrient storage

The total sediment, TP, and OC captured by the NBS features varied by two orders of magnitude, ranging from 0.2 to 20.1 t sediment during the 2–3 years since construction (Table 2). Bulk density of the accumulated sediment had a mean of 0.69 ± 0.23 g cm^{-3} for online features and 0.93 ± 0.22 g cm^{-3} for offline features. The total accumulated mass of sediment in the eight offline features was 47.8 t, and 39 t in the six online ponds. Cumulatively, the 13 features within the South sub-catchment stored 83 t sediment with a total volume of 108.8 m^3. The features were most effective in trapping sediment, with 14.7% of the total sediment yield and 14.1% of the fine (clay and silt) sediment yield stored compared to only 9.5 and 7.5% of the TP and POC yields, respectively.

3.2 | Factors influencing accumulation rates

Due to differences in contributing area size and the influence of spillways, we expected the hydrological regimes of the features to be notably varied. Volume–duration curves exhibited a range of patterns (Figure 3). These curves show the variation in the frequency with which the volume of water stored by each feature is exceeded in terms of a percentage of the features' estimated maximum storage volume. P3 showed the greatest retention of water with 60% of its capacity exceeded 50% of the time, equating to a median storage volume of 338 m^3. P1_OLP and P2 both displayed a similar curve shape, however P1_OLP sustained water storage year-round whereas P2 stayed essentially dry during summer. P8 filled infrequently and only ever filled to 12% (68 m^3) of its potential storage capacity during this period. P6 also had a flashy filling regime but stored significantly more water, reaching 26% capacity (688 m^3), one order of magnitude greater than P8. In comparison, P5 had a less steeply sloping curve, sustaining water storage for a greater duration and at its peak filling to 1475 m^3, 42% of its potential capacity.

On average, the sediment accumulation rate was 3.3 times higher in online features (20.8 ± 9.8 kg m^{-2} y^{-1}) than in offline features (6.3 ± 5.2 kg m^{-2} y^{-1}) when taking into account the ponded area of each feature. The length-to-width ratio of features explained some of the variation in accumulation rates, with positive relationships observed for both sediment ($R^2 = 0.42$, $p < 0.05$) and TP accumulation ($R^2 = 0.54$, $p < 0.01$). Length-to-width ratios were generally low and ranged from ~0.25 to 2.0, with P1_OLP having the highest ratio. The contributing area was also found to positively influence the sediment accumulation rate ($R^2 = 0.49$, $p < 0.05$). Differences in accumulation rate were better explained by the event contributing area, which broadly clusters the offline features into those activated by leaky barriers and those that were not (Figure 4). Features such as P9 were never observed to fill from overbank flows, whereas P6 was frequently observed to do so during event peaks in winter storms (Figures 2b and 5).

The water storage dynamics of features, along with stream-stage data at their spillways, provided insight into how features that filled from overbank flow via spillways compare to those that did not. We hypothesized that this additional hydrological connectivity would augment sediment delivery and thereby accumulation within features that received overbank flow. P6 and P9 exemplify this contrast (Figure 5). Overbank flows by the leaky barrier and spillway connected to P6 occurred in over 20 storm events between October 2019 and March 2021, and helped to fill the feature. In contrast, the threshold for overbank flow was never reached at the

TABLE 2 Yields (±95% CI), masses of accumulated sediment (t), total phosphorus (kg), and organic carbon (t) in NBS features and their equivalent proportion of the total suspended sediment, fine suspended sediment, TP, and particulate OC yields leaving the 3.4 km^2 South sub-catchment

NBS feature	Time period	Rainfall (mm)	Total sediment yield (t)	TP yield (kg)	POC yield (t)	Stored sediment (t)	Stored TP (kg)	Stored POC (t)	Total sediment yield stored (%)	Fine sediment yield stored (%)	TP yield stored (%)	POC yield stored (%)	Sub-catchment area drained (%)
P0_OLP	Feb 19–Mar 21	2126	498 ± 24	1095 ± 50	50 ± 1	5.8	8.0	0.3	1.2	1	0.7	0.6	12.1
P1_OLP						6.2	14.4	0.4	1.3	1.4	1.3	0.8	9.0
P2						0.4	0.5	0.03	0.07	0.06	0.04	0.06	0.3
P3						20.1	28.9	1.1	4.0	3.7	2.6	2.2	0.1
P4	Feb 18–Mar 21	2810	565 ± 30	1278 ± 65	57 ± 2	0.3	0.4	0.01	0.05	0.05	0.03	0.02	1.1
P5						7.0	11.0	0.3	1.2	1.3	0.9	0.5	1.2
P6						8.7	14.2	0.4	1.6	1.8	1.1	0.7	1.9
P7						10.6	16.7	0.4	1.9	2.1	1.3	0.7	2.8
P8						0.2	0.2	0.01	0.03	0.04	0.02	0.02	0.3
P9						0.6	0.6	0.02	0.1	0.1	0.05	0.03	5.9
P10_OLP	Feb 18–Jan 20	1634	160 ± 10	417 ± 26	16 ± 1	4.6	5.5	0.2	2.9	2.5	1.3	1.3	8.8
P10_US_OLP						10.7	13.1	0.8	6.7	4.6	3.2	5.0	
P10_DS_OLP	Feb 18–Jun 20	1944	207 ± 12	533 ± 30	21 ± 1	7.8	8.5	0.3	3.8	3.6	1.6	1.4	
P11_OLP	Feb 19–Mar 21	2126	605 ± 102	1614 ± 250	52 ± 6	3.8	5.9	0.2	0.6	0.7	0.4	0.4	0.2
Total†		**2810**	**565 ± 30**	**1278 ± 65**	**57 ± 2**	**83.0**	**121.8**	**4.3**	**14.7**	**14.1**	**9.5**	**7.5**	**43.5**

†P11_OLP is located within the North sub-catchment and is therefore excluded from the totals.

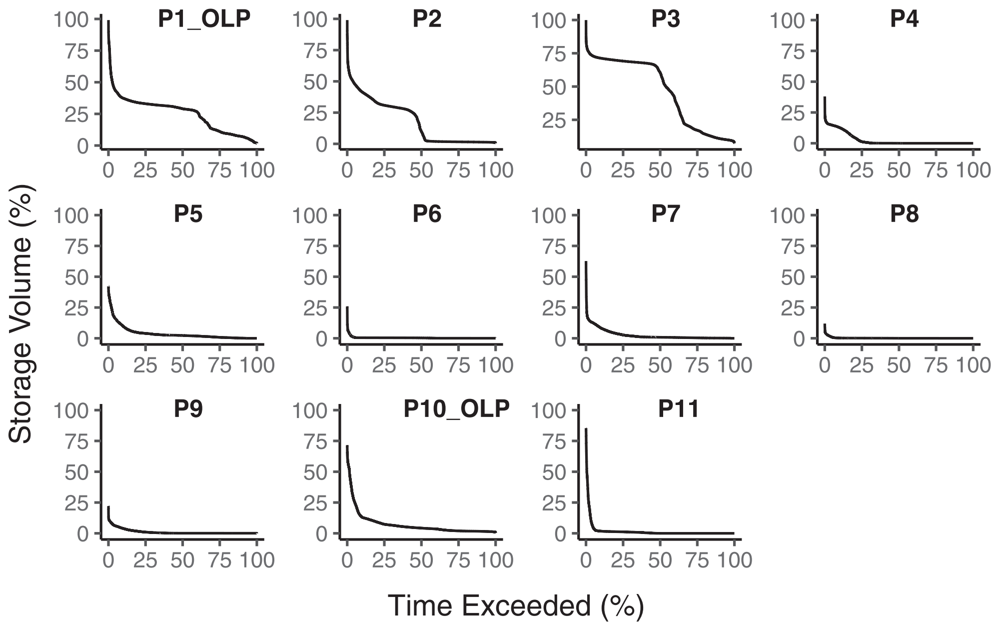

FIGURE 3 Volume–duration curves for different NBS features, showing storage volume (%) as a percentage of the maximum capacity of each feature during the 2019–2020 hydrological year. Volume was not monitored in the online features: P10_US_OLP, P10_DS_OLP, and P0_OLP.

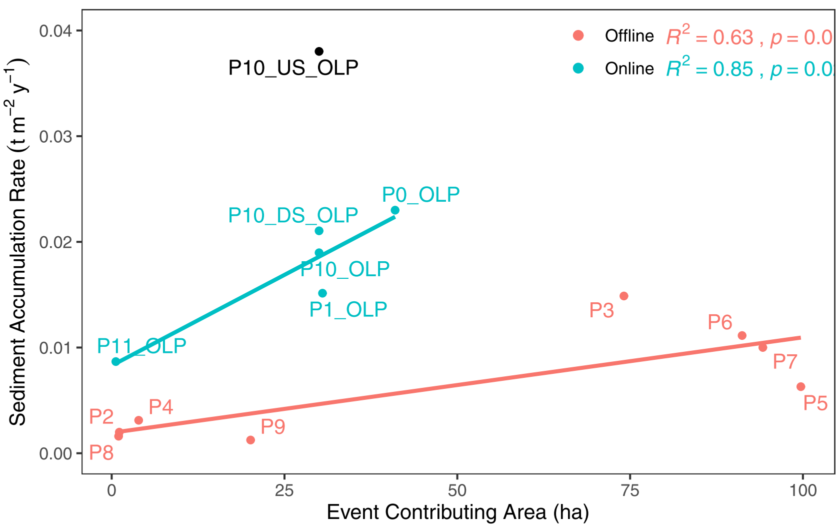

FIGURE 4 Linear regressions between event contributing area (ha) and sediment accumulation rate (t m^{-2} y^{-1}) for offline and online NBS features. P10_US_OLP is excluded from the regression.

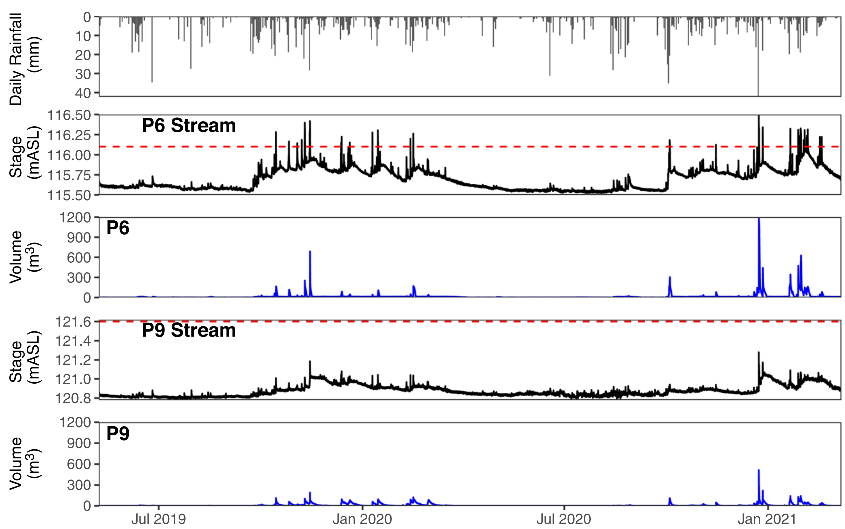

FIGURE 5 Time series of daily rainfall (mm) and stream stage (mASL) at leaky barriers and water volume (m^3) in features P6 and P9. Dashed red lines indicate the threshold at which spillways are activated. mASL = metres above sea level.

P9 spillway; even at the peak of the highest-magnitude event in December 2020, the water level was still 0.3 m below the threshold. During this event, peak storage in P6 reached over double the volume in P9. The timing of overbank flow is well aligned with stream SSC, allowing the highest sediment load to be diverted into P6 during event peaks (Figure 6).

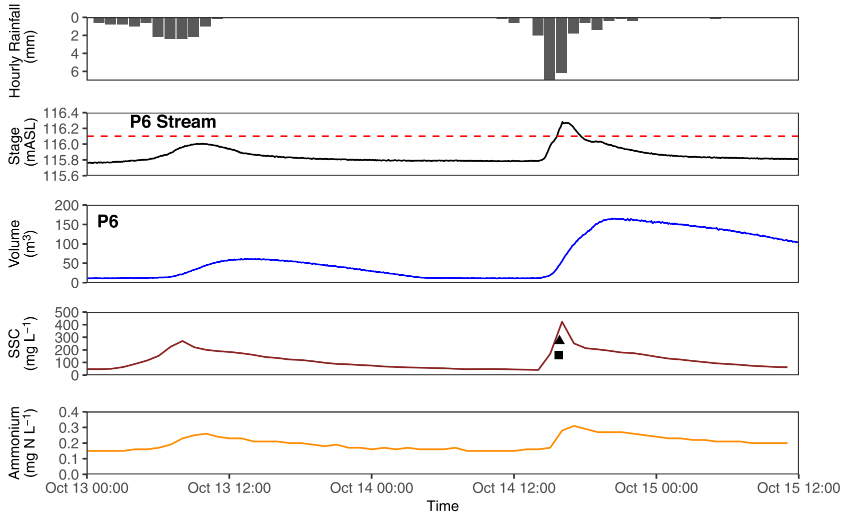

FIGURE 6 Time series of hourly rainfall (mm), stream stage (mASL) at the P6 leaky barrier, water volume (m^3) in P6, stream SSC ($mg\ L^{-1}$), and ammonium concentration ($mg\ N\ L^{-1}$) during an event in October 2019. Square = surface run-off SSC at 15:45; triangle = surface run-off SSC at 15:50.

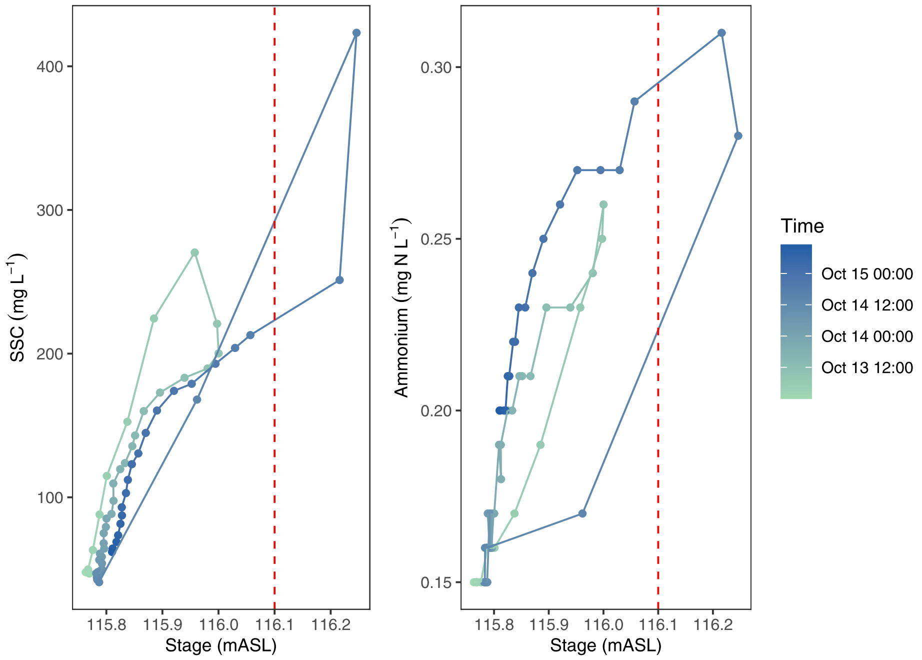

FIGURE 7 Stage–concentration relationships for SSC ($mg\ L^{-1}$) and ammonium ($mg\ N\ L^{-1}$) at the P6 leaky barrier during a storm event. Dashed red lines indicate the threshold of spillway activation.

During the October 2019 event, the filling rate of P6 was at its highest during the period in which the spillway was active, suggesting that the contribution of diverted streamflow likely exceeded that of surface run-off. Diverted streamflow was also likely to be a greater source of sediment, with run-off grab samples from adjacent fields having lower SSC than instream at the time of sampling. The relationship between stream stage and SSC shows that clockwise hysteresis occurred during the smaller October 13 event, followed by a figure-of-eight pattern in the larger event (Figure 7). The highest SSC coincided with peak stage, however the peak in ammonium concentration occurred following peak stage, showing an anti-clockwise hysteresis loop. During the event on October 14, it was estimated that a sediment load of 52 kg entered P6.

3.3 | Sediment enrichment

Sediment deposited within features was found to be significantly enriched in TP (paired samples t-test, $p < 0.01$, $n = 14$), with an average concentration 1.5 times greater than the surface soil in contributing areas. The highest TP enrichment ratio of 2.66 (1.60–3.81) was observed for P1_OLP (see Figure S3 in the online Supporting Information for a full table of ER values). On average, the sediment was composed of 86% silt and clay particles. Clay ER was typically higher for offline features, with a mean of 1.24 ± 0.32 compared to 0.76 ± 0.68 for online features. The opposite trend was seen for sand, with ER as low as 0.05 for offline features (P6) and up to 4.84 for online features (P10_US_OLP). Mean OC ER across all features was >1, however there was no apparent difference between the offline and online features.

A negative non-linear relationship was observed between median particle diameter (D_{50}) and OC content of soil and sediment (see Figure S4 in the online Supporting Information). A significant correlation was seen for samples from arable (or recently reverted arable) fields (non-linear least-squares regression, $p < 0.01$, $R^2 = 0.72$). Clay content was positively correlated with OC, though samples from permanent grassland with considerably higher organic content did not fit this relationship (linear regression, $p < 0.01$, $R^2 = 0.13$). Sediment OC content was found to be negatively correlated with bulk density (linear regression, $p < 0.01$, $R^2 = 0.33$; see Figure S5 in the online

Supporting Information). Particle size and clay content were both unable to explain the differences in TP concentration ($p > 0.05$).

3.4 | Reductions in storage capacity

In the 2–3 years since construction, the majority of features did not lose significant volumes of their maximum storage capacity as a result of sediment loading (see Figure S6 in the online Supporting Information). Average annual losses in storage capacity during the monitoring period ranged from 0.01% in P4 and P8 up to 12.9% in P0_OLP. In order to maintain their ability to fill and drain effectively during and after events, offline features require their outlets to remain sufficiently above the level of accumulated sediment, thereby helping to prevent siltation within drains. When considering the remaining storage capacity up to the drain height of features, the accumulated sediment volumes had a much greater impact. Potential further storage for sediment is most reduced in the online features, with P10_US_OLP, P10_OLP, and P0_OLP all predicted to fill beyond their outlet drain heights within 10 years (based on current accumulation rates). Whilst having a high accumulation rate, at a 10-year timescale P1_OLP is predicted to still retain >50% of its storage capacity up to its outlet. P1_OLP with its deeper design had a mean water depth of 0.71 m during autumn and winter, in contrast to only 0.3 m in P10_OLP with its shallow design and comparatively low outlet elevation. Interestingly, loss of storage capacity in P11 was negligible due to the sediment accumulation rate being too small to quantify even after more than 2 years since construction. However, P11_OLP (connected to the outflow of P11) lost almost 5% of its total storage within the same period.

3.5 | Synthesis of overall functionality of NBS

On average, online features accumulated sediment more rapidly compared to offline features. Sediment trapped in online ponds was typically characterized by low bulk density and high TP concentration relative to the soil. In comparison, offline features selectively trapped a higher proportion of fine (clay) particles. Several factors, including event contributing area and length-to-width ratio, were found to partially explain the differences in accumulation rates and the observed variation in trapped sediment properties. Instream leaky barriers enabled delivery of sediment-rich flows to offline features during storm peaks. Whilst this enhanced sediment accumulation, the observed rates were low enough to not compromise the flood storage capacity of offline features. However, online ponds with smaller capacities tended to accumulate sediment rapidly; this was enough to diminish their overall volume significantly within 3 years. The reasons underpinning observed differences are discussed in the following section, along with their potential implications.

4 | DISCUSSION

4.1 | Sediment and nutrient storage

It is evident that the construction of NBS (NFM features and online ponds) has cumulatively resulted in significant storage of sediment and nutrients in this small agricultural catchment within a timescale of 3 years. Despite having a total footprint covering <1% of the catchment area, the features were able to accumulate 83 t, the equivalent of almost a quarter of the total sediment yield leaving the sub-catchment. Within the monitoring period, both 2019 and 2020 experienced considerably wet conditions (25 and 32% above the rainfall average, respectively). In this context, the observed sediment and nutrient storage is promising and suggests that the features are delivering multiple benefits despite hydrological extremes. Furthermore, the level of observed storage is significant when considering that sediment capture is a benefit secondary to the main flood risk mitigation function of the offline features. The results of this study demonstrate that numerous small-scale landscape modifications that alter and intercept floodwater pathways are capable of delivering beneficial outcomes for diffuse pollution alongside flood attenuation. Such benefits may also function to mitigate the need for channel maintenance of higher-order watercourses, which has previously been used in conventional flood risk management approaches that aim to maintain conveyance downstream (CIWEM, 2014).

Research by Cooper et al. (2019) showed that a constructed wetland of a similar scale to the offline and online NBS features can trap over 7 t sediment during its first year of operation, having an accumulation rate comparable to P7 when accounting for contributing area. Alternative NFM approaches such as beaver reintroduction have reported similar effect sizes in terms of their sediment and nutrient storage benefits (Puttock et al., 2018). The creation of 13 beaver-engineered ponds in a small (0.2 km^2) enclosed headwater catchment resulted in the storage of $\sim$100 t sediment during a 3 to 5-year period. It is advantageous that similar magnitudes of mitigation can be achieved through contrasting NBS (i.e. those targeting flood risk reduction or water quality improvement), thereby providing a more diverse toolkit for catchment managers to best suit interventions to different land uses and settings. Table 3 demonstrates how sediment deposition rates within the NBS features are comparable to those observed in other catchments within similar pond features, as well as naturally occurring deposition on floodplains. The measured accumulation rates were most comparable to those reported by Ockenden et al. (2014) for edge-of-field wetlands intercepting agricultural runoff on silt loam and clay soils (broadly similar to the soil texture within the Littlestock Brook catchment). However, our observed accumulation rates were relatively low compared to those on sandy soils in Cumbria. Putting the results in this context highlights the importance of soil properties and the erodibility of the surrounding landscape in determining how rapidly features will accumulate sediment.

These comparisons indicate that NFM storage features are likely to have wide applicability across different catchment types within the temperate maritime climate of western Europe.

4.2 | Factors influencing accumulation rates

Accumulation rates were highly variable between features, with these differences primarily being attributed to the size of contributing areas and the extent to which features were hydrologically connected. Many of the online features had considerably higher accumulation rates due to continually receiving streamflow and capturing suspended sediment from numerous sources. For example,

TABLE 3 Comparison of sediment storage rates observed in different features within catchments in England

Type	Catchment characteristics	Location	Catchment area (ha)	Mean storage (t m^{-2} y^{-1})	Min/max storage (t m^{-2} y^{-1})	Reference
Offline NBS features	Lowland, arable/grass, silt loam/clay	Oxfordshire, England	0.4–20.1	0.006	0.001–0.01	This study
Online NBS features			0.6–41.0	0.02	0.009–0.04	
Constructed wetlands	Lowland, arable, clay	Leicestershire, England	4.0–10.0	0.005	0.0006–0.02	Ockenden et al. (2014)
	Upland, arable/grass, silt loam	Cumbria (Crake Trees Manor), England	10.0–50.0	0.04	0.002–0.1	
	Lowland, arable/grass, sand	Cumbria (Whinton Hill), England	1.5–30.0	0.4	(−0.004)–2.0	
Constructed wetlands	Lowland, arable (roadside), clay loam/sandy clay loam	Norfolk, England	23.8	0.06	0.06	Cooper et al. (2019)
Floodplain	Lowland, grass, various loams	Devon, England	27 600.0	0.0005	NA	Lambert and Walling (1987)
Beaver dam ponds	Lowland, grass, clay loam/silt loam	Devon, England	20.0	0.02	0.009–0.05	Puttock et al. (2018)

resuspended channel bed sediment mobilized during small-magnitude events will have been flushed into online ponds, whereas offline features would have received minimal sediment input under these circumstances due to insufficient surface run-off from contributing fields. Brainard and Fairchild (2012) also report significantly higher accumulation rates in ponds with inflows compared to those without. These results support the observations of Barber and Quinn (2012), who found that an online run-off attenuation feature accumulated a significant volume of silt throughout its first winter in operation. Additionally, during small events online ponds drain large areas with multiple fields, whereas during similar events offline features typically only drain single fields. Despite a subset of the offline features receiving sediment-rich redirected streamflow during higher-magnitude events, the relatively high elevation of spillways and raised design of the leaky barriers meant that this only occurred during short periods of high discharge. Whilst our study did not directly measure accumulations at an event scale, it is likely that the high-magnitude storms contributed a significant proportion of the sediment in offline features. Palmer (2012) estimated that an offline run-off attenuation feature (with a contributing area comparable to P7) retained approximately 1 t of sediment during a single event. Our estimate of 52 kg sediment entering P6 during an event is considerably less, but is likely explained by factors including the differences in catchment characteristics (e.g. slope) and also the timing of the spillway activation during the event. This event was typical of the catchment response, with clockwise SSC-discharge hysteresis being the dominant pattern observed during the monitoring period (Robotham, 2022). Clockwise hysteresis means that SSC peaks prior to discharge, potentially resulting in misalignments of spillway activations and periods of highest suspended sediment loads, thereby delivering less to features. In slowly permeable catchments, clockwise hysteresis has been associated with in-channel sediment sources where there is enhanced deposition during baseflows and a readily available sediment supply (Lloyd et al., 2016; Sherriff et al., 2016). This suggests that leaky barriers may play a role in modifying sediment dynamics during events as a result of their ability to increase in-channel storage. Reducing the porosity of barriers is likely to produce a greater backwater effect, forcing more water out of the channel and thereby increasing rates of accumulation in offline features (Muhawenimana et al., 2021). It is also likely that lowering the threshold required for overbank flow into the spillways would coarsen the grain size distribution of accumulated sediment, given typical vertical profiles of suspended sediment transport where coarse particle load increases with proximity to the streambed (Lamb et al., 2020; Lupker et al., 2011). The generally high threshold required for overbank flow into the features in this study explains, at least in part, the relatively low accumulation rates within offline features.

River restoration techniques such as reconnecting streams to their floodplains can enhance sediment deposition through increasing the frequency of overbank flows. Millington (2007) shows how floodplain deposition is closely related to overbank suspended sediment load at a restored site with instream wood jams in the New Forest, Hampshire. Following restoration, sediment deposition of 26.3 kg m^{-2} was observed upstream of wood jams over a flood season, which compares to the annual mean accumulation rate of 6.3 kg m^{-2} in the offline NBS features. This suggests that restoration techniques may be better suited to emulate natural depositional processes than NFM approaches. However, in an arable context, floodplain restoration is generally considered incompatible with land use, and so spatially targeted NBS (online and offline features) offer a good compromise for landowners and catchment managers.

Several features stood out as outliers in terms of their accumulation rate. P10_US_OLP had an exceptionally high rate compared to other online features because it is the most upstream feature in a series of three connected features. Robotham et al. (2021) showed that P10_US_OLP was generally the most effective at trapping sediment. Therefore, where NBS interventions are placed in series, features that are located farthest upstream are likely to require more frequent maintenance. P3 is also somewhat of an outlier in terms of its contributing area, with its higher accumulation potentially owing to the contribution of sediment from subsurface drainage via broken field drains. During monitored events, it was observed that P3 typically reached peak water storage later than other features, inferring that filling was not driven by rapid rainfall run-off, but via the subsurface. Studies have shown that field drains can act as pathways for sediment, particularly in fine-grained soils (Coelho et al., 2010; Stone & Krishnappan, 2002). NBS in highly modified agricultural landscapes hold potential for mitigating diffuse pollution from subsurface pathways if located appropriately.

The length-to-width ratio of features was also shown to play a role in sediment accumulation, with the performance of features improving with higher ratios, as also found by Persson and Wittgren (2003). Similarly, a moderate positive correlation between this ratio and both particle and P retention was found by Johannesson et al. (2015) in constructed wetlands in southern Sweden. Increasing length-to-width ratios gives the influent a greater residence time and opportunity to settle out fine matter (e.g. clay particles) (Fifield, 2011). Most of the offline features were constructed in field corners, thereby only taking small proportions of the field out of agricultural production, however this also restricted their length-to-width ratios (0.2–0.8) compared to online features (1.1–2.0), with the result that they trapped less sediment.

Further discussion of factors influencing accumulation rates is given in Figure S7 in the online Supporting Information.

4.3 | Sediment enrichment

In the context of this study, enrichment ratios are influenced by soil erosion processes and by the trapping efficiency of features. As expected, P enrichment was observed in the majority of features, with the three highest ER occurring in online ponds. Features with greater residence times or increased hydraulic roughness from vegetation are able to more effectively settle out finer particles with larger surface areas and typically higher P content (River & Richardson, 2018; Vargas-Luna et al., 2015). Evidence of this can be seen in 75% of the offline features, which were more enriched in clay. The permanently flowing online features showed the opposite, with a considerably higher sand ER as a result of the transition from high to low velocity upon entering the ponded area, causing rapid deposition of large particles. Coarser sediment is therefore typically found closer to the inflow of features (Cooper et al., 2019; Ockenden et al., 2014; Robotham et al., 2021).

Particle size was found to significantly influence OC concentrations, with higher organic content being associated with greater proportions of finer sediment particles. This relationship has been observed in similar field wetlands and ponds, with the larger surface area of finer particles allowing greater potential for binding of organic matter (Cooper et al., 2019; Ockenden et al., 2014). The generally higher OC and lower bulk density of sediment in online features may in part be explained by a more extensive cover of wetland vegetation, leading to greater carbon inputs into the waterlogged hypoxic or anoxic sediment (Were et al., 2020). A study of sediment in small natural ponds in Northumberland found a similar pattern, with the highest OC (up to 15%) in permanent, vegetated ponds and the lowest in temporary ponds with little vegetation (Gilbert et al., 2014). Over the 2–3 years since construction, the permanently wet features have been colonized by emergent wetland vegetation (e.g. *Typha* sp.), which is likely to enhance their overall trapping efficiency. Braskerud (2001) found that vegetation aids sediment retention by mitigating resuspension of trapped material, reducing it to negligible levels after 5 years. In future, sediment in NBS features that continue to develop wetland vegetation may become more enriched in finer particles due to greater stabilization and a positive feedback effect (Corenblit et al., 2009). Increased trapping may pose management implications if the effect of vegetation enhances the rate of accumulation to a point where flood storage capacity is significantly compromised. However, in terms of biodiversity, this feedback and natural succession may be more beneficial, whereas undergoing regular disturbance to remove sediment and maintain storage capacity will result in a plagioclimax community.

The sediment trapped within features was generally more enriched in OC compared to the arable soils in the catchment, which on average contained an OC content of 0.8% less. A similar range of OC ER have been observed in simulated rainfall erosion experiments, which showed evidence of selective transportation of OC via finer particles (Nie et al., 2015; Schiettecatte et al., 2008). This sediment has potential viability for spreading back onto surrounding fields to boost soil organic matter, which is an important property for sustaining healthy soil biology and can improve crop yield (Whitmore et al., 2017). The accumulated sediment, primarily composed of silt and clay, also shows potential for nutrient reclamation, with an average TP concentration of 1424 mg P kg^{-1}, which is 438 mg P kg^{-1} higher than the arable soils. The recovery and recycling of P is becoming increasingly important for the future sustainability of food production and could help reduce fertilizer costs for farmers and nutrient losses to waterbodies (Tonini et al., 2019).

4.4 | Considerations for NBS management and design

One of the concerns that has been raised in the literature discussing NFM approaches is the issue of flood storage capacity being consumed as a result of sedimentation (Lane, 2017). The evidence from this study suggests that in the short term, sedimentation does not pose a major threat to the ability of the offline features to function as NFM interventions. The total sediment accumulations equated to a reduction of 110.8 m^3 storage capacity across all the monitored features (<1% of total storage lost over 3 years). This leaves almost 15 000 m^3 available for potential flood storage in both sub-catchments, which drain a combined area of 6.8 km^2. Due to their smaller volume and more rapid accumulation, online ponds require more frequent maintenance to remove stored sediment. However, this is to be expected from the online ponds as they were constructed primarily to address diffuse P pollution. The results suggest that such features should undergo desilting on a biennial basis to reduce the potential risk of blocking outflow drains and the remobilization and flushing of sediment downstream (Wilkinson et al., 2010). Without appropriate management, there is a risk that online features may act as a source of sediment and pollutants (Barber & Quinn, 2012). However, evidence shows that overall, such features are still net sediment sinks despite their potential to act as temporary sources during large events (Robotham et al., 2021). Whilst more frequent desilting makes online features more expensive to maintain, they have potential for high natural capital value through their provision of semi-permanent wetland habitat. In contrast, offline features are only likely to require maintenance in the medium term, after ∼10 years of operation, with sediment removal being more easily achieved during summer, when features are dry or at their shallowest. The management of such offline NFM features should aim to strike a balance between their primary purpose of flood mitigation and their additional benefits for biodiversity and water quality. If appropriately maintained, both online and offline NBS have the potential to become long-term anthropogenic landforms of sustainable agricultural landscapes.

The design and configuration of online and offline features can play an important role in their ability to effectively intercept and store water and eroded matter. However, current best practice guidance for NFM does not typically consider optimizing intervention design for increasing the removal efficiency of diffuse pollutants (Forbes et al., 2016; Highways England, 2021; Wren et al., 2022). Our findings show that despite having length-to-width ratios below the recommended 5:1 ratio for optimal trapping efficiency, the features still accumulated significant masses of pollutants. Therefore, it can be said that diffuse pollution mitigation is still possible with interventions optimized for flood storage as opposed to pollutant removal efficiency. If a feature is found to act as a pollutant source, the issue could be remediated retroactively by introducing greater hydraulic complexity (e.g. adding berms or vegetation zones perpendicular to the direction of flow to enhance trapping; Persson & Wittgren, 2003).

Another consideration for the implementation and management of NBS features is the potential risk of harmful algal blooms forming in the nutrient-enriched stagnant water. A cyanobacterial bloom was observed in P5 during June 2021, but posed minimal threat due to its location away from livestock and routes of public access. Future climate change may increase the occurrence and intensity of blooms such as this due to the effects of warming water temperatures on algal abundance (Richardson et al., 2019). Consequently, there is a rationale for allowing marginal trees to develop, providing shade to mitigate against extreme heat and the potential for such disbenefits to occur (Kail et al., 2021). Trees may also help to mitigate the potential disbenefit of enhanced greenhouse gas emissions from temporary ponds, which have been observed as a result of sediment drying–rewetting cycles (Obrador et al., 2018; Paranaíba et al., 2020). Our results indicate that features are significant sinks for POC, however the extent to which this carbon remains *in situ* is not yet fully understood. The NFM evidence base would benefit from further empirical research into the impact of such features on biogeochemical cycles to better understand their environmental trade-offs and potential implications for pollution swapping.

4.5 | Opportunities for further study

This study used a pragmatic approach to estimate the ability of NBS features to store sediment and nutrients and puts this into the context of yields estimated from high-resolution monitoring at the catchment outlet. The surveying method used to obtain sediment accumulations was based on transects and therefore provided an estimate of sediment depths. Full bathymetric surveying covering the entire footprint of features would reduce the uncertainties of these estimates, particularly in permanently ponded features. This would overcome the need for sampling and spatial interpolation and its associated issues (Li & Heap, 2011). Additionally, a greater density of core samples and analysis of sub-samples along vertical sediment profiles would also improve estimates and allow greater insight into changes in composition and accumulation rates over time. Monitoring within a continually changing farmed landscape has inherent challenges, particularly whilst the catchment was subject to disturbance from the phased construction of interventions and changes in cropping over the three monitored years. Future studies would benefit from surveying NBS features over a longer time period, starting immediately after construction and then taking repeat measurements over multiple years following a period of acclimatization. This would better capture changes in NBS features' responses to hydrometeorological extremes, land use and management change, and ecological development, as well as the effect of any maintenance activity. This study characterizes NBS functionality within the specific context of a lowland arable catchment, but there is still a need to develop further understanding of such features in a wider range of landscape contexts.

5 | CONCLUSIONS

Online and offline NBS are net stores of sediment that are capable of accumulating significant masses of sediment and nutrients, helping to mitigate fluvial soil loss and diffuse pollution from agricultural land, whilst also creating new wetland habitat. The features within this study occupied a total surface area <1% of the catchment, yet trapped the equivalent of 15% of the estimated catchment sediment yield over 3 years without compromising high-value arable land and farm productivity. This enhanced sediment storage also accounted for the equivalent of up to 14%, 10%, and 8% of the fine suspended sediment, TP, and POC catchment yields, respectively. The majority of the monitoring period experienced above-average rainfall, with 2019 and 2020 receiving 25 and 32% above the annual average, respectively. This enabled the functioning of features to be tested under notably wet conditions that posed a higher soil erosion and diffuse pollution risk. The magnitude of sediment and nutrient mitigation observed is therefore promising in light of this context.

The design of NBS is important in optimizing their potential for both flood storage and water quality improvement. Results suggest that rates of sediment and nutrient accumulation are largely explained by differences in the hydrological connectivity and drainage areas of features. Online pond features showed higher accumulation rates, but the activation of leaky barriers and spillways (Figure S8) augmented accumulation in offline features. Based on these differences, maintenance requirements are more frequent for online features, whereas accumulation in offline features only necessitates sediment removal in the medium term to prevent reducing effective flood storage capacity. The enriched sediment stored within features shows potential nutrient reclamation benefits for farmers through redistributing on fields as a soil conditioner.

These findings provide valuable insight into the delivery of diffuse pollution mitigation by NBS in a small lowland catchment of the Upper Thames, albeit a snapshot over a relatively short period of their intended lifetime. An extended monitoring record covering a range of interannual hydrological conditions and extremes is needed to better understand the long-term impact of NBS, their multiple benefits, trade-offs, and roles within farm businesses. Interventions such as offline storage and leaky barriers are able to deliver benefits for sediment and nutrient storage beyond their primary aim of managing flood risk. NBS show good potential for use in integrated catchment management and should be incorporated into future environmental land management schemes in order to deliver their benefits more widely.

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DATA AVAILABILITY STATEMENT

Data and metadata are accessible via the Environmental Information Data Centre (EIDC): https://doi.org/10.5285/9f80e349-0594-4ae1-bff3-b055638569f8.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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