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Research article

Soil erosion, sediment sources, connectivity and suspended sediment yields in UK temperate agricultural catchments: Discrepancies and reconciliation of field-based measurements

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ABSTRACT

Robust understanding of the fine-grained sediment cascades of temperate agricultural catchments is essential for supporting targeted management for addressing the widely reported sediment problem. Within the UK, many independent field-based measurements of soil erosion, sediment sources and catchment suspended sediment yields have been published. However, attempts to review and assess the compatibility of these measurements are limited. The data available suggest that landscape scale net soil erosion rates (~38 t km^{-2} yr^{-1} for arable and ~26 t km^{-2} yr^{-1} grassland) are comparable to the typical suspended sediment yield of a UK catchment (~44 t km^{2} yr^{-1}). This finding cannot, however, be reconciled easily with current prevailing knowledge that agricultural topsoils dominate sediment contributions to watercourses, and that catchment sediment delivery ratios are typically low. Channel bank erosion rates can be high at landscape scale (27 km^{-2} yr^{-1}) and account for these discrepancies but would need to be the dominant sediment source in most catchments, which does not agree with a review of sediment sources for the UK made in the recent past. A simple and robust colour-based sediment source tracing method using hydrogen peroxide sample treatment is therefore used in fifteen catchments to investigate their key sediment sources. Only in two of the catchments are eroding arable fields likely to be important sediment sources, supporting the alternative hypothesis that bank erosion is likely to be the dominant source of sediment in many UK catchments. It is concluded that the existing lines of evidence on the individual components of the fine sediment cascade in temperate agricultural catchments in the UK are difficult to reconcile and run the risk of best management interventions being targeted inappropriately. Recommendations for future research to address paucities in measured erosion rates, sediment delivery ratios and suspended sediment yields, validate sediment source fingerprinting results, consider the sources of sediment-associated organic matter, and re-visit soil erosion and sediment cascade model parameterisation are therefore made.

1. Introduction

Catchment sediment dynamics can be conceptualised as a process cascade spanning source (erosion) – pathway (connectivity) – impact (river suspended sediment concentration and yield and impacts on biodiversity and society) (Naden, 2010). Due to the diffuse nature of soil erosion and sediment delivery, complete sets of measurements of this cascade are lacking for anything other than the smallest of temperate agricultural catchments. Here, for example, work at the turn of the century calculated detailed suspended sediment budgets for some small UK agricultural catchments; e.g., the Pang and Lambourne (Walling et al., 2006). However, there has been little recent work in the UK to replicate this integrated approach, perhaps due to the large resource requirements, difficulty in scaling plot-based methods up to catchment scale, and uncertainties or limitations associated with methods of quantifying soil erosion at larger scales; e.g., RUSLE or ^{137}Cs based erosion rates (Evans and Boardman, 2016a; Evans et al., 2017). Sediment budgets have, however, been calculated more recently internationally (e.g., Brooks et al., 2013; Howley et al., 2021). As a result, the regulation, incentivisation and on-farm advice delivered through agri-policy for mitigating the widely reported sediment problem is currently based upon a combination of a general conceptual understanding of the sediment process cascade built on disparate published research, modelling work, site specific visual appraisals of sediment

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sources and sparse long-term and reliable measurements of river suspended sediment yields. Current agri-policy has not been delivering a sufficient reduction in sediment water pollution for meeting policy targets (Poole et al., 2013; Collins and Zhang, 2016) and this most likely reflects several factors including the poor targeting of best management in the absence of detailed and extensive sediment budget data.

Within the UK, a large amount of disparate data has been gathered on the specific components of the sediment cascade including net soil erosion rates, sediment sources and river suspended sediment yields. However, these datasets are rarely assembled for the same catchments, meaning that managers and advisors frequently need to rely on more generalised understanding of catchment sediment dynamics. Importantly, within the UK, and other temperate landscapes, little effort has been directed towards reconciling the individual datasets on net soil erosion, sediment sources and suspended sediment yields to sanity check this generalised understanding for the types of temperate agricultural catchment found in the UK. Given this important gap concerning evidence reconciliation, this paper examines measured net soil erosion rates, connectivity and suspended sediment yields in UK river catchments (the locations of key studies are provided in online supplementary Figure S1). More specifically, we investigate if established knowledge of sediment sources allows for measured net erosion rates to account for the suspended sediment yields of rivers. Recently collected sediment provenance data for 15 catchments produced using a simplified colour-based tracing procedure incorporating hydrogen peroxide sample treatment, aimed at minimising potential uncertainties, is used to test the more generalised conclusions derived from the examination of existing data on erosion rates, connectivity, and suspended sediment yields. Only field-based data, and not model predictions, were considered in this work. By examining the UK, which is a relatively data-rich country, a more generalised understanding of the current evidence gaps and future research needs in similar regions globally can be developed.

1.1. Rates of net soil erosion

Much of the available data on net soil erosion for the UK was generated through the volumetric surveying of visible rill erosion features on arable land in the SSEW (Soil Survey of England and Wales) monitoring project (1982–1987; Evans et al. 2005) and in the South Downs between 1982 and 1991 by Boardman (2003). The SSEW project found that median net erosion rates along a transect within a poorly erodible clayey soil association with low relief are around 130 t km^{-2} yr^{-1}, whilst the upper ranges (>260 t km^{-2} yr^{-1}) of observed rates were associated with erodible soils containing high proportions of sand or silt (Evans et al., 2016). The maximum rates of net erosion observed were often 10 times the mean values. However, despite these high net erosion rates, at landscape scale, the occurrence of rill erosion is infrequent with an average of only ~5% of land eroded by rills and gullies each year, and in only two of the counties monitored was more than 10% of land visibly eroded (Evans et al., 2016). Therefore, at landscape scale, net erosion rates from rill erosion on arable land were found to be low. Evans (2013) used data from the SSEW project to calculate landscape scale net erosion rates of between 0.4 t km^{-2} yr^{-1} in Bedfordshire up to 33 t km^{-2} yr^{-1} for the Isle of Wight, with a mean rate for all counties examined of 8 t km^{-2} yr^{-1} calculated by Evans and Boardman (2016a). In the South Downs, Boardman (2003) calculated a higher mean net erosion rate of 490 t km^{-2} yr^{-1} for visibly eroding fields and 51 t km^{-2} yr^{-1} for the whole of the monitored landscape. This is likely to be towards the highest range of values which would be expected for a landscape in the UK given the highly erodible soils on the South Downs and concomitant history of severe muddy flooding.

Much of the sediment eroded here is deposited at the toe of a rill or within the field. As part of these volumetric measurements any visible deposits were measured and their volume subtracted from that of the erosion features, so that the erosion rates best represent actual net soil losses, rather than gross erosion. During erosion, sand grains are often left deposited on the soil surface after aggregates have been broken down whilst silts and clays are lost (Evans, 2006). Evans (2002) showed that most of the soil eroded in rills was transported out of the catchment when soils were primarily silt based, and in contrast, most was deposited within the field or catchment when soils were sandy. Within the UK, most of the suspended sediment transported through rivers (Walling et al., 2000) and deposited in lakes (Foster et al., 2011) has been shown to be silt or clay sized, although these particles are often transported in larger water-stable aggregates (Walling and Woodward 2000). Therefore, there is a general consistency between the particle size of eroded material leaving a field and that found in watercourses, reflecting the important impact of particle size selectivity as sediment moves along the cascade comprising a sediment budget. Given the net soil loss data reported herein account for deposition within field, it is reasonable to assume that soil erosion and suspended sediment yield data can be compared directly since the intermediate deposition which would be driven by particle size selectivity is accounted for. Whilst these datasets present a thorough evaluation of visible rill erosion rates they do not account explicitly for sheet wash erosion. The very limited literature available indicates that sheet wash is an increasing phenomena within the UK and accounts for soil losses of between 10 and 30 t km^{-2} yr^{-1} (Harrod, 1994; Evans et al., 2016; Evans, 2017). Recent data generated from hydrologically-isolated fields on the North Wyke Farm Platform (NWFP) in the southwest of the UK has allowed for the field-scale measurement of net soil erosion rates incorporating all erosion processes. Using the data presented by Zhang et al. (2022) for the North Wyke Farm Platform (NWFP) as well as additional data available on the NWFP data portal, a sediment yield for two arable fields of approximately 165 t km^{2} yr^{-1} was calculated. High rainfall during the three years of monitoring from 2019 to 2021 suggest that this sediment yield is likely to be higher than the long-term average. This net soil erosion rate is comparable to the range of values for visibly eroding low risk fields calculated by Evans et al. (2016) as both rill erosion and sheet wash were observed in the NWFP arable fields. The scheduled ploughing and reseeding operations undertaken on some grassland NWFP fields illustrated the impact of soil moisture on wash erosion rates of freshly tilled fields. In years when ploughing was undertaken in summer months, sediment loss from the fields increased to ~73 t km^{-2} yr^{-1} (Pulley and Collins, 2020). As these fields were partially vegetated during winter months and little rill erosion took place, this value may be a reasonable representation of the magnitude of erosion from sheet wash on arable land on sloped fields with clayey soils, high rainfall and partial vegetation cover. Interestingly, it is comparable to the wash erosion rates measured by Morgan et al. (1987) on sandier soils in Bedfordshire of 60–90 t km^{-2} yr^{-1} although the use of troughs for sampling here may have driven increased erosion (Evans, 2006). When the same NWFP fields were ploughed in autumn months and soils were saturated and unvegetated during winter, however, net erosion for the two fields increased to 257 and 313 t km^{-2} yr^{-1}, respectively (Pulley and Collins, 2020) which are close to the upper range of values for arable fields undergoing rill erosion reported by Evans et al. (2017), supporting the reliability of traditional volumetric survey work.

Pulley and Collins (2019) reported suspended sediment yields for the 15 grassland fields (i.e., net erosion rates) on the NWFP which ranged from 14 to 71 t km^{-2} yr^{-1} with a mean of 36 t km^{-2} yr^{-1}. However, these average yields are high due to the scheduled ploughing and reseeding of one third of the fields during the time period for the dataset used. Excluding ploughed and reseeded fields, resulted in a mean erosion rate of 26 t km^{-2} yr^{-1} for long-term grassland on clayey soils with high rainfall. Upadhayay et al. (2021) showed that over 90% of suspended sediment transported out of grassland fields on the NWFP was silt or clay sized, meaning that sheet wash eroded sediment from grassland is likely to have a similar particle size distribution to material in suspension in rivers and material observed to leave the field during rill erosion when rills are not directly connected to watercourses. Within the UK, rill erosion is highly unusual on grassland fields and therefore these yields only reflect sheet wash processes (identified specifically as raindrop-impacted-saturation-excess overland flow). These fields experience high mean annual rainfall of 1053 mm (R-factor ~700 J mm ha-1 h^{-1} yr^{-1}), which mostly occurs between October–March, and have high slopes of up to 12.2°; therefore, the sheet wash erosion rates measured here are likely to be at the upper end of rates for clayey soils in the UK. In the context of these new data from the highly instrumented NWFP, the sheet wash erosion rates of 10 and 30 t km^{-2} yr^{-1} reported previously appear reasonable for grassland fields but are likely to be an underestimate on arable land with low vegetation cover during wet winter months.

1.2. Catchment contemporary suspended sediment yields

Comparison of net soil erosion rates and suspended sediment yields for UK catchments is essential for understanding sediment budgets and cascades. There is, however, almost no available data available with which to make a direct comparison between net soil erosion rates and suspended sediment yield measured over the same time period, especially if ^{137}Cs based soil erosion measurements which have been shown to be unreliable (Parsons and Foster, 2011; Evans et al., 2017) are discounted. Zhang et al. (2022), however, recently measured suspended sediment loads using turbidity in the upper River Taw observatory into which the NWFP drains. Here, over 12 monitored winter months between 2018 and 2022, a total suspended sediment yield of 64 t km^{-2} at Pecketsford and 108 t km^{-2} at Lower Ratcombe was measured on the River Taw. This can be compared to the sediment losses of 36.4 t km^{-2} and 47 t km^{-2} from two grassland fields on the NWFP, and 222 t km^{-2} from two arable fields over the same time period. These sediment losses were measured using turbidity from hydrologically-isolated fields and therefore represent all particle sizes lost (almost all silt and clay sized) from the fields (Upadhayay et al., 2021). Land use in the catchment upstream of Pecketsford is 38% moorland, 44% permanent grassland and 6.5% arable, whilst at Lower Ratcombe it is 70% permanent grassland and 17.5% arable. Therefore, we might expect a catchment wide erosion rate of ~48.5 t km^2 at Pecketsford given its combination of land covers and assuming the same erosion rates measured on the NWFP apply catchment wide. A theoretical erosion rate of 68.0 t km^{-2} at Lower Ratcombe can also be calculated in the same way. Importantly, however, both of these erosion rates are considerably lower than the suspended sediment yields measured in the upper River Taw (64 t km^{-2} and 108 t km^{-2}) albeit with the caveat that uncertainty ranges were not calculated for these measurements. Channel bank erosion is, however, also likely to contribute significantly to the suspended sediment yield of these rivers (Upadhayay et al., 2022); therefore, soil erosion rates are likely to not be dissimilar to the proportion of the observed river suspended sediment yield contributed from this catchment source.

A review by Walling et al. (2008) proposed a mean suspended sediment yield, calculated using measured data from 146 UK catchments, of 44 t km^{-2} yr^{-1}, which is similar to the net soil erosion rates explored in the previous section. Importantly, the particle size distribution of suspended sediment measured within rivers has been shown to be largely silt and clay sized corresponding to the size range found to be exported from fields in erosion studies. A study of the suspended sediment load of six rivers by Walling and Woodward (2000) found median (D_{50}) absolute particle sizes of 5.8 μm in the headwaters of the Dorset Stour, 13.3 μm in the Hampshire Avon, and ~3–6 μm in the River Exe, River Culm, Warwickshire Avon at Stratford and Warwickshire Avon at Evesham. These values were obtained from river water samples pumped during flood events over a range of flow conditions. In the large Humber and Tweed catchments, less than 5% of the suspended sediment load was found to be > 63 μm in diameter (Walling et al., 2000). Similar findings have been reported for other rivers as a part of recent source apportionment work. For example, Pulley and Collins (2021a,b) found that during an extreme flood event 70% of suspended sediment retrieved from time-integrating traps fell into the <25 μm fine silt fraction in Fox Dyke, 66% in Summerstown Ditch, 55% in Woodhill Brook, 37% in the River Lyne and 56% in the River Simene. Although in catchments with sandy soils and important sediment sources which include sandy channel banks and landslips such as Blockley Brook (27%), Mills Brook (31%), and Semer Water (18%) these percentages were lower (Pulley and Collins, 2021a,b). The range of suspended sediment yields measured in different rivers is, notable. Mean values for upland rough pasture dominated catchments of 110 t km^{-2} yr^{-1} are clearly far higher than soil erosion rates found for grassland on the NWFP (~26 t km^2 yr^{-1}) which is close to the upland area of Dartmoor. Therefore, these results suggest an alternative source of sediment must be present such as increased bank erosion, landslips, blanket peat erosion or forestry (Brazier, 2004; Janes et al., 2018). For lowland catchments with limited anthropogenic impact and upland rough pasture catchments, very low suspended sediment yields of <10 t km^{-2} yr^{-1} were reported. As these yields are far below the lowest grassland erosion rate of 14 t km^{-2} yr^{-1} measured on the NWFP, this finding suggests much of the eroded sediment is stored within the catchment rather than reaching the river channel and that rates of channel bank erosion are also low. Suspended sediment yields for agricultural catchments averaged 41 t km^{-2} yr^{-1} which are high when compared to the erosion rates for grassland and more directly comparable to the typical erosion rate measured for arable land. As in the upper River Taw, the proportion of these measured suspended sediment yields which cannot be accounted for by soil erosion could originate from channel bank erosion.

Janes et al. (2018) compared the mapped historic locations of river channels in eight contrasting river catchments in England to estimate long-term channel bank erosion rates. Here, a typical catchment-wide erosion rate was calculated at 49 t km^{-2} yr^{-1}, ranging from 7 to 90 t km^{-2} yr^{-1}. When a 3.5 m buffer was applied to the channel locations to ensure mapping errors were not a major source of uncertainty, however, a lower mean rate of 27 km^{-2} yr^{-1} (3–44 t km^{-2} yr^{-1}) was calculated which equated to a mean retreat rate of 0.42 m yr^{-1}. Limited other measured sediment yield data for channel bank erosion is available; however, similarly high rates of bank profile retreat have been observed in other studies. For example, Hooke (1980) found annual bank retreat rates of 0.08–1.18 m using erosion pins in Dorset. A rate of 0.64 m yr^{-1} was reported for the River Cound by Hughes (1977) and rates of 1.75 and 2.65 m yr^{-1} were found in the Welsh rivers Rheidol and Tvfi by Mosley (1975). Micheli and Kirchner (2002) measured rates in a wet meadow of 0.24 m yr^{-1} and in a dry meadow of 1.4 m yr^{-1}. A lower rate of 0.01–0.09 m y^{-1} was measured in the River Bollin-Dean by Knighton (1973) and Lawler (1993) measured rates on a meander of 0.066 m y^{-1}.

Unlike the erosion of topsoils, which is particle size selective, the erosion of channel banks involves all particle size fractions, especially in the presence of processes including rotational slumping. As a result, the above estimates of bank derived sediment yield are likely overestimates of contributions to the suspended sediment loads of many rivers as stream power may be insufficient to transport sands, gravels, or cobbles. Particle size data for channel bank material is limited in the UK. However, a 36.7–43.2 % silt content was found in the banks of the River Arrow by Couper (2003). A content of 55% and 44% silt was found in channel margin deposits of the River Severn and Afon Tanat Vyrnwy, respectively, which may be eroded through channel migration (Taylor and Brewer, 2001). In the lower reaches of rivers where channel migration is likely to be highest, historically deposited fluvial sediments often form bank material which are finer grained than their parent material. For example, Walling et al. (1997) showed that almost all sediment in cores retrieved from the floodplains of the River Ouse was silt-sized. Therefore, it remains uncertain as to the proportion of eroded bank material which contributes to the suspended (as discrete from the bed load) sediment load of rivers. However, it is likely to be more than 50%, especially in rivers with a fine-textured parent material such as the clays, mudstones and glacial and fluvial deposits which cover a large proportion of England, especially in areas adjacent to watercourses.

Overall, these high erosion rates suggest that channel bank erosion is likely contributing most of the typical suspended sediment yield (44 t km^{-2} yr^{-1}) for UK rivers. Importantly, this conclusion does not correspond well with the reported dominance of arable topsoil sources provided by previous sediment source tracing studies for the UK (Walling, 2005).

1.3. Historical changes in suspended sediment yields

Evans (2006) estimates that based upon land use change, soil erosion rates increased by 13% between around 1960 and the 1980s and declined by 2% from 1998 to 2002 and, therefore, associated increased river suspended sediment yields might be expected. Deposited lake sediments have been used to understand the changes in suspended sediment yields caused by the intensification of agriculture. Rose et al. (2010) presented sediment accumulation rates (SAR) from 1850 to the present day for 60 UK lakes covering a range of catchment types. When comparing the SAR during 1850 to that at the cores surface, a mixed trend was observed. For small, low-lying, deep lakes mainly situated on the western seaboard of the UK, there are no substantial increases in suspended sediment yield in the four lakes sampled. For low-lying deep lakes situated in western areas of the UK, however, there are substantial increases in SAR in three of eight lakes. In small, deep, mid-altitude lakes situated in upland areas of the UK, there are significant increases in seven lakes out of the 17 sampled. For large, deep, mid-altitude lakes situated in the northern UK, one of six lakes shows an increase, and for deep mountain lakes, the two cored show no significant change in SAR. Therefore, for most lakes (65%) draining upland areas, there is no substantial increase in SAR over time.

For small, shallow, lowland lakes situated mainly in the southern UK, there were very large increases in SAR in both lakes sampled with a present-day SAR that had increased by more than three times in one lake. There were also increases for the three large, deep, lowland lakes cored. Five out of six lakes cored also exhibited increased SAR in the case of small, deep, lowland lakes situated in the western UK. Overall, increases in SAR were more substantial and more consistent in lowland lakes where intensive farming is more likely to have expanded in comparison with upland sites. One cautionary note here, however, is that SAR, has been shown to be poorly correlated with suspended sediment yield (Foster et al., 2011). However, the work by Rose et al. (2010) suggests that in lowland agricultural catchments across the UK, there is some evidence for elevated SAR post-agricultural intensification.

Foster et al. (2011) reviewed reconstructed suspended sediment yields from 19 lake catchments in the UK with dated sediment profiles covering the last 100–150 years of sediment deposition. The purpose here was to identify modern background yields pre-dating the agricultural intensification after World War II (i.e., post 1945). In the forested catchments examined by Foster et al. (2011), suspended sediment yields did not increase over time apart from in Boltby Reservoir, where a yield of 35 t km^{-2} yr^{-1} (from a background of ~10 t km^{-2} yr^{-1}) occurred briefly and was associated with documented logging operations (Foster and Lees, 1999). In the primarily upland rough grassland Llyn Geirionydd catchment, the suspended sediment yield increased from a background of 5 km^{-2} yr^{-1} to a maximum yield 12 t km^{-2} yr^{-1} and in the similar Llyn Peris catchment, the suspended sediment yield increased from ~5 t km^{-2} yr^{-1} to 40 t km^{-2} yr^{-1}; however, this was likely due to mining activities rather than agricultural land management. The March Ghyll catchment showed an increase in yield from 30 t km^{-2} yr^{-1} to 60 t km^{-2} yr^{-1} in the early 1900s but then a subsequent decrease down to ~15 t km^{-2} yr^{-1}. A high sediment yield of 300 t km^{-2} yr^{-1} between the 1940s and 1960s was found in Abbeystead Reservoir (compared to a minimum of ~60 t km^{-2} yr^{-1}) and was attributed to blanket peat erosion like that observed elsewhere in the UK (Butcher et al., 1993). Similarly, peat erosion caused an increase in suspended sediment yield to a peak of 18 t km^{-2} yr^{-1} compared to a background of 2 t km^{-2} yr^{-1} in March Haigh. All these upland rough grazing and moorland dominated lake catchments, apart from Llyn Peris, show a decrease in suspended sediment yield to close to modern background rates in recent years suggesting that changes to upland rough grazing management is not resulting in significantly higher suspended sediment yields.

Primarily pasture and arable dominated catchments also exhibited modern background yields of 5–10 t km^{-2} yr^{-1}, although for the catchment of Kyre Pool which contains soils of high erosion risk, modern background suspended sediment yields are higher at 30 t km^{-2} yr^{-1}. More specifically, for the lakes with catchments used for permanent pasture, four of the six investigated show some form of significant upward trend in suspended sediment yield from the 1950s onwards, although in Silsden reservoir, this increase occurs later. In Elleron Lake, suspended sediment yields increase from a background of 4 t km^{-2} yr^{-1} in the mid-1970s to a maximum of 12 t km^{-2} yr^{-1}, in Newburgh a recent increase from ~40 to ~75 t km^{-2} yr^{-1} took place, in Old Mill Lake yields increased to ~90 t km^{-2} yr^{-1} from ~20 t km^{-2} yr^{-1}, and in Silsden reservoir from ~7 t km^{-2} yr^{-1} to ~25 t km^{-2} yr^{-1}. In Seeswood and Groby, suspended sediment yields remain relatively stable over time. In contrast to most grassland catchments, the suspended sediment yields in two lakes (Fillingham Lake and Yetholm Loch) studied with arable dominated catchments did not substantially increase over time; however, in Yetholm Loch, this may be due to drainage diversion reducing the lake catchment area (Foster and Lees, 1999). The large increase in suspended sediment yield at Kyre Pool was attributed to land drain installation in the 1960s associated with the expansion of arable farming (Foster et al., 2002). A more recent study of Sywell Reservoir also reported a similar pre-1963 (11.2 t km^{-2} yr^{-1}) and post-1963 (11.9 t km^{-2} yr^{-1}) suspended sediment yield (Pulley and Foster, 2017).

Within UK lakes, most sediment deposits are silt or clay sized which is comparable to that found transported through river catchments and the size range found to be lost from fields as a result of net erosion. For example, in Silsden Reservoir, a median (D_{50}) particle size of 14.17 μm was found, in Elleron Lake 26.58 μm, Newburgh Priory Pond 22.94 μm, Fillingham Lake 25.11 μm, Yetholm Loch 27.00 μm, Boltby Reservoir 19.27 μm, Fontburn Reservoir 22.76 μm, Barnes Loch 26.48 μm, and March Ghyll Reservoir 16.2 μm (Foster and Lees, 1999). In Old Mill Reservoir, the D_{50} was found to be 8–15 μm (Foster and Walling, 1994) and in Seeswood Pool all sediment particles were less than 50 μm in diameter (Foster et al., 1986). In Goby Pool (David et al., 1998) and Merevale Lake (Foster et al., 1985) deposited sediments were also found to have a silt/clay texture. However, some coarser sediment particles have been found in lakes; the D_{50} of sediment in Abbeysted reservoir was 0.125 μm and, in Ponsomby Tarn, over 50% of the sediment mass was reported to be greater than sand-sized at many depths (Oldfield et al., 1999).

Comparison of the typical target modern background suspended sediment yields of 5–10 t km^{2} yr^{-1} established by Foster et al. (2011) and the average suspended sediment yield of 44 t km^{-2} yr^{-1} estimated by Walling et al. (2008) suggests around a 24–39 t km^{-2} yr^{-1} increase in suspended sediment yield has taken place in a typical UK agricultural catchment. One important caveat here, however, is that the lake catchments used by Foster et al. (2011) are generally very small, meaning that the estimated modern background suspended sediment yields were taken to be more indicative of rates of sediment delivery to river channels, rather than of suspended sediment yields in larger catchments. Regardless, the estimated 13% increase in UK soil erosion rates between ~1960 and the 1980s reported by Evans (2006) is far too low to account for the increase in contemporary suspended sediment yields relative to modern background levels. However, if sheet wash net erosion rates on arable land are consistently higher than the 10–30 t km^{-2} yr^{-1} reported previously (Harrod, 1994; Evans et al., 2016; Evans, 2017), such as the ~70 t km^{-2} yr^{-1} measured more recently on the NWFP, and indeed in Bedfordshire by Morgan et al. (1987), then the conversion of grassland to arable could account for this increase in suspended sediment yields, where such conversion has taken place, but only if almost all eroded sediment is delivered to the river channel. If sediment delivery ratios are low, however, explaining the observed increases in river suspended sediment yield relies on either high channel bank erosion rates or implausibly widespread high net erosion rates in the few fields connected to the river channel (i.e., the 500 t km^2 yr^{-1} found in the South Downs).

1.4. Connectivity

The previous sections illustrate that topsoil erosion rates within the UK are plausibly sufficient to account for the suspended sediment yields observed in rivers, but only if almost all eroded topsoil derived sediment is delivered to channels, or if there are high channel bank contributions to suspended sediment yields. The hypothesis that channel banks contribute a high proportion of the suspended sediment yields of most rivers is not supported by many previous sediment source fingerprinting results which typically identify the erosion of topsoils as the dominant source of sediment in the UK (Walling, 2005). Walling et al. (2008) collated sediment source fingerprinting data from 49 UK catchments studied at the date of publication and concluded that, on average approximated, 85% of sediment in UK rivers originates from a combination of grassland and arable topsoil sources. However, this could only be the case if channel bank erosion rates are at the lower end of the range (3–44 t km^{-2} yr^{-1}) measured by Janes et al. (2018) (with a 3.5 m buffer for measurement uncertainty) since their mean river bank erosion rate of 27 t km^{-2} yr^{-1} (49 t km^{-2} yr^{-1} with no buffers) accounts for a substantial proportion of the mean suspended sediment yield of 44 t km^{-2} yr^{-1} proposed by Walling et al. (2008) even if much of the channel bank material eroded is too coarse to be transported as suspended load. Given the generally comparable published topsoil erosion rates and catchment suspended sediment yields, an 85% contribution of sediment from topsoils would also require almost all eroded topsoil sediment within a catchment to be delivered to the river channel. This assumption is not supported by most published literature. Work establishing sediment budgets for UK catchments indicated that very low sediment delivery ratios were present with as little as 1% of eroded sediment being delivered to the catchment outlet in catchments, such as the Pang and Lambourne (Walling et al., 2006; Walling and Collins, 2008). In the small Lower Smisby and Rosemaud catchments higher sediment delivery ratios of approximately 20% and 17% were calculated (Walling et al., 2002). These sediment delivery ratios are clearly inconsistent with the erosion rates and suspended sediment yields described in the sections above. One plausible reason for this discrepancy in these sediment budgets is the use of ^{137}Cs to calculate soil erosion rates. The use of ^{137}Cs for this purpose has now been established to be unreliable and to overstate the magnitude of water-related erosion meaning that SDRs calculated using such soil erosion estimates will be too low (Parsons and Foster, 2011; Evans et al., 2017). Equally, soil erosion estimates from commonly used modelling approaches such as RUSLE, which are also used for sediment budgets, have also been suggested to predict erosion rates that are too high in relation to field-based measurements (Trimble and Crosson, 2000; Brooks et al., 2014; Evans and Boardman, 2016a). For example, Panagos et al. (2015) used RUSLE to calculate a mean erosion rate for the UK of 238 t km^{-2} yr^{-1} which exceeds even the erosion rate of 165 t km^{-2} yr^{-1} measured on arable land on the NWFP with steep slopes during the extreme high winter rainfall of 2019–2021 (the 5th wettest winter on record in the UK).

Given this background, it may be the case that the sediment delivery ratios of UK catchments are widely underestimated by researchers and catchment practitioners. However, even if these sediment budget studies have underestimated SDRs it is implausible that almost all eroded sediment from a catchment will be immediately delivered to river channels within a single year. It remains difficult, therefore, to reconcile the current evidence base on soil erosion rates and suspended sediment yields. Sediment losses to floodplains, through overbank deposition during inundation events, also increase the discrepancy between soil erosion rates and river suspended sediment yields. Published work here, for example, has suggested that long-term sediment storage on river floodplains can represent ~40–50% of the annual suspended sediment load delivered to the river channel system in large (800–>3000 km^2) river basins (e.g., Walling et al., 1998).

Direct measurements of source to stream connectivity within landscapes are extremely challenging and therefore early work on small catchment sediment budgets are the only catchment scale sediment delivery ratio (SDR) measurements available in the UK. Direct observations of connectivity have, however, been made. For example, Boardman et al. (2019) mapped runoff from 180 fields in the River Rother catchment and found that runoff from 103 of these was connected to the river at various times. Of these, 40% were directly connected to the river or connected through other fields, 29% connected by culverts under roads, 16% by roads, and 15% by ditches. The River Rother is known to have excessive sediment problems so likely represents very high connectivity for a UK catchment. In the River Wissey catchment, runoff was observed for ten years by Evans (2017) and related to rainfall quantity. Drains in the landscape were found to be most connected to river channels with flows occurring for 62% of the monitored time. Runoff down tracks and roads occurred on an average of 47 days per year when rainfall was $\geq$ c. 5 mm, and over half of storms with rainfall above this amount initiated higher streamflow. Runoff from farmland occurred in storms with >~10 mm of rainfall 14 days per year provided that soils were saturated. When over 20 mm of rainfall occurred, runoff could be initiated even on dry soils if infiltration rate was exceeded. Therefore, sediment delivery to river systems clearly occurs within landscapes. Yet measured SDRs are not available to directly quantify connectivity. However, research has shown the effectiveness of buffers and barriers within landscapes at preventing sediment delivery which can be used to gain further insight into sediment delivery ratios (Fryirs, 2013). A recent test of 12 m width riparian buffer strips on a field near the NWFP found that buffers vegetated by willow reduced unbuffered sediment losses by 44%, deciduous woodland buffer strips by 30% and grass buffer strips by 29% (Dunn et al., 2022). These reductions are likely to be lower on a whole field scale due to greater potential for flow accumulation and concentration for breaching buffers (Dillaha et al., 1986). However, efficacy ranges upwards of 50% are common in other research published globally (Dorioz et al., 2006). Sediment trapping by buffer strips is also particle size selective with coarser particles preferentially retained, which corresponds to the findings of erosion studies and within-stream and lake monitoring (Hayes et al., 1979; Hickey and Doran, 2004). This high efficacy supports a low SDR in UK catchments as regulation currently requires a 2 m green buffer along all watercourses. Sediment delivery ratios have been directly measured for 367 very small plot-scale catchments within eroded fields across England and Wales (Evans, 2002, 2006). Here, it was found that fine textured deposits within fields were largely absent due to being lost to watercourses and sediment delivery was highly dependent upon storm intensity and crop type. The mean sediment delivery from the catchments to watercourses was 5 t km^{-2} yr^{-1}, ranging from 1 to 19 t km^{-2} yr^{-1} compared to a mean erosion rate of ~12 t km^{-2} yr^{-1} indicating a similar field scale SDR (~50%) to that measured for buffer strips. As most fields within catchments are not adjacent to watercourses, this data suggests that very low SDRs such as measured in the Pang and Lambourne catchments using alternative approaches (Walling et al., 2006) are reasonable to assume for others in the UK.

Connectivity is well established to increase with higher magnitude rainfall-runoff events, with concomitant greater energy of overland flows allowing for sediment from more distal sources to breach buffers and barriers and reach watercourses (Fryirs, 2013). However, Pulley and Collins (2021a,b) traced the sources of fine (<25 μm) sediment sampled in eight English rivers and found that in most cases, sediment sources did not vary over time even when extreme wet events were recorded. Sherriff et al. (2018) also noted a similar consistency over time in sediment sources in three lowland intensive agricultural catchments in

Ireland. These results suggest that sediment connectivity may be fairly consistent for <25 μm sediment over a range of flow conditions with barriers such as field boundaries or buffer strips either not being breached, or consistently being breached during storm events of different magnitudes. Additionally, sediment deposited on channel beds or in proximity to the channel during the falling limbs of storm events may be remobilised during periods of low flow during summer months. Within the Rive Ouse catchment, for example, Walling et al. (1998) calculated that approximately 10% of the annual sediment yield was stored on the channel bed. Therefore, bed sediment acting as a short-term intermediate store of the relatively small load of sediment which is transported during the summer is another plausible explanation.

1.5. Summary of the existing evidence base for the sediment cascades in UK river catchments

Current field-based data for net soil erosion, sediment sources and suspended sediment yields in UK river catchments can be summarised by the following salient, but inconsistent, points:

- On arable land, rill erosion is infrequent and accounts for ~8 t km^{-2} yr^{-1} at landscape scale, although this could be as low as 0.4 t km^{-2} yr^{-1} on flatter clayey soils, and in individual highly erodible fields could be as high as ~500 t km^{-2} yr^{-1}.
- Sheet wash erosion is widely considered to account for 10–30 t km^{-2} yr^{-1}, although new data from the NWFP and indeed, older plot experiments data suggests rates could plausibly be as high as ~70 t km^{-2} yr^{-1} in many fields.
- Combined, these estimates suggest the assumption of an average net erosion rate for arable land of ~38 t km^{-2} yr^{-1} at national scale in the UK might be reasonable.
- On grassland, with steep slopes and high rainfall on the NWFP, average net wash erosion rates have been measured at 26 t km^{-2} yr^{-1} although on flatter fields with lower rainfall, rates can be as low as 14 t km^{-2} yr^{-1}.
- For channel banks, a mean erosion rate of 27 km^{-2} yr^{-1} with a corresponding wide range of 3–44 t km^{-2} yr^{-1} has been measured although rates in headwater streams are likely to be on the lower-end of this range. Without a 3.5 m buffer, as a precaution against mapping inaccuracies, this rate could be as high as 49 t km^{-2} yr^{-1}, ranging from 7 to 90 t km^{-2} yr^{-1}. As all particle sizes are eroded from banks, a proportion of this yield (likely significantly less than 50%) may be deposited within channel and not contribute to the suspended sediment yield of a river.
- Suspended sediment yields are highly variable but an average of 44 t km^{-2} yr^{-1} has been reported, which is comparable to expected net soil erosion rates on arable land.
- Suspended sediment yields in catchments prior to agricultural intensification post WWII were in the range of 5–10 t km^{-2} yr^{-1} which is low, even when compared to measured sheet wash erosion rates on grassland.
- Catchment suspended sediment yields have increased by an average of 24–39 t km^{-2} yr^{-1} since the intensification of agriculture in the 1950s.
- Sediment delivery ratios are likely far lower than 50% in most catchments.
- Almost all sediment mobilised and delivered from most soils, transported through watercourses and deposited in lakes is silt and clay sized.
- According to modelling and quantitative sediment source fingerprinting using out-dated methodologies, ~85% of the suspended load of UK rivers is contributed from eroding topsoils.

The preceding review and summary strongly suggests that existing understanding of the individual components of the sediment cascade collected independently of each other, appear incompatible when combined. This finding has been noted previously by Evans (2006). Given that more data is currently available than in 2006, especially for the magnitude of sheetwash in some locations in the UK, the discrepancies among datasets for the components of the sediment cascade appear an ongoing problem. It therefore must be considered which parts of current understanding of catchment sediment cascades in UK catchments may be incomplete or unreliable.

Rates of rill erosion on arable land have been measured in large scale surveys and correspond to the range of values measured recently on the NWFP and are therefore likely to be broadly reliable but spatially variable. There is, however, a significant paucity of information on net sheet wash erosion rates, especially on arable fields. River suspended sediment yields can be measured at a single point on a river through stage and turbidity monitoring making them likely to be of high reliability if appropriate uncertainty ranges are presented. However, catchment suspended sediment yield is not static and will change with inter-annual hydrological conditions. However, the broad agreement between the yields calculated using deposited lake sediments and contemporary monitoring gives confidence that calculated suspended sediment yields fall within a consistent general range and that the mean value reported for the UK is reasonable. Knowledge of sediment delivery ratios is severely limited due to the very few sites for which sediment budgets have been assembled and the potentially unreliable methods used for estimating soil erosion rates in those budgets based on an integration of measurement and monitoring techniques. However, the measured effectiveness of barriers such as riparian buffers in experimental studies, both in the UK and indeed globally, clearly suggests that low sediment delivery ratios from eroding topsoils are entirely plausible. Whilst previous reviews of estimates of sediment sources in UK catchments suggested the dominance of eroding topsoils in arable fields (Walling, 2005), the procedures associated with the fingerprinting approach have evolved over recent years, with far more attention directed towards more in-depth consideration of particle size effects (Laceby et al., 2017) modelling uncertainties and problems with equifinality (Collins et al., 2017, 2020). Therefore, given this recent refinement of sediment sourcing procedures and growing global consensus on them (Collins et al., 2020), reliable knowledge of catchment sediment sources and sediment delivery might be considered the most uncertain aspect of current understanding of the sediment cascades in UK river catchments. Accordingly, to provide an initial attempt to resolve the discrepancies between previously measured net erosion rates, sediment sources and suspended sediment yields identified in this review, the provenance of fine silts (<25 μm) is examined in 15 catchments. This examination aimed to determine if the commonly accepted assumption that the erosion of agricultural topsoils is the dominant source of sediment in most UK rivers is supported, or if instead, alternative sources such as channel bank erosion, are most important. A simplified sediment tracing method was used to limit the potential impacts of organic matter enrichment, particle size and unmixing modelling which may have caused erroneous results in some previous UK based tracing work. The sediment source data is then interpreted in the context of the expected net soil erosion rates and suspended sediment yields for the study catchments to determine if the three datasets can be reconciled.

2. Materials and methods

2.1. Tracing approach

The tracing approach used aims to reduce the potential sources of uncertainty associated with many of the previous sediment source fingerprinting studies conducted in the UK as the literature review has suggested that these may have delivered unreliable results. The primary drivers behind the selection of the method used was the removal of organic matter, limitation of particle size related uncertainties and avoidance of equifinality related uncertainties in unmixing modelling

(Collins et al., 2017, 2020). The potential for particle size effects is reduced by tracing a narrow <25 μm size range, as the <63 μm range most used in previously published tracing studies is coarser than the generally low D_{50} values for sediment found in UK lakes and rivers evaluated in sections 1.2 and 1.3. Eroded sediment within rivers has also been shown to be enriched in organic matter when compared to fractionated samples of its sources (Schiettecatte et al., 2008; Koiter et al., 2018). This represents a major source of uncertainty as many tracer types are associated with organic matter and therefore organic enrichment may lead to misleading sediment source results (Nederbragt et al., 2006). Beyond specific tracers such as mineral magnetism this source of uncertainty has not been removed from previous tracing work. Additionally, this uncertainty could be increased as discrimination between sources such as channel banks and topsoils could be caused by differences in their organic matter content and therefore the basis for source discrimination could be completely lost due to sediment transport processes. Finally, organic matter could be transported independently of the mineral sediment and therefore originate from a different source to the mineral fraction that makes up most of the suspended sediment load. As a result of these issues, organic matter was removed from all source and sediment samples in this study. This step does, however, come with trade-offs. The first is that many tracer types are associated with organic matter, such as radionuclides and many chemical elements (Koiter et al., 2018). Therefore, these tracers cannot be reliably used after organic matter removal. Other tracers such as mineral magnetic signatures are not affected in this way although can be heavily impacted by the amount of very fine clay sized particles within the sediment and therefore could compromise the aim of this study to minimise the scope for particle size related effects (Hatfield, 2014). Other tracers could potentially be altered by adsorption, dissolution or other chemical processes or may have high associated measurement uncertainties if they are found in low concentrations (Collins et al., 2020). For this reason, sediment colour was chosen as the colour of the mineral sediment is not impacted by the removal of organic matter, has low measurement uncertainties, and high within-stream conservatism (García-Comendador et al., 2023). As colour represents the bulk minerology of the sampled sediment, it has less potential to be altered by changing chemical conditions present within a watercourse than most other tracer types which may occur in low concentrations and not be strongly bound to the sediment. Whilst colour is affected by particle size effects these are more limited than for other tracer types which adsorb to the surface of sediment and are therefore highly controlled by specific surface area. The colour-based approach does, however, have the disadvantage of reducing the potential for source discrimination, in part, due to the limited number of colour tracers available, and in part due to the removal of organic matter as a basis for source discrimination. As a result, the key question as to whether the sediment is likely to have originated from the erosion of arable topsoils or channel banks is determined qualitatively using simple biplots and quantified differences between source and sediment colour to reduce the well-documented uncertainties (i.e., equifinality) associated with using either frequentist or Bayesian unmixing modelling approaches for source apportionment with multiple different source groups and limited tracer availability. Whilst this approach does not provide percentage contributions from each source group, it is sufficient to determine which sediment source is likely to be of most importance in the rivers investigated. This is especially as catchment-specific knowledge is also used to qualitatively interpret the colour results which is important given the characteristics of many of the catchments studied. A Mann-Whitney *U* test and linear discriminant analysis was performed for all catchments to assess if, after treatment, colour could adequately discriminate between key sediment sources (Supplementary Table 2).

2.2. Sample collection

A combination of recently published and new sediment provenance data was assembled for 15 catchments in England and Wales. These were primarily selected for study at the request of the Catchment Sensitive Farming agri-environment initiative, which covers all catchments in England and Wales, and by other catchment managers due to perceived sediment-related pressures. They cover a range of soils and land uses with different erosion risks (Fig. 1; Figs. S2:14; Supplementary Table 1).

Suspended sediment and source sample data was used from the River Simene, Mills Brook, Semer Water, River Lyne, Blockley Brook, Woodhill Brook and Fox Dyke and was collected between November 2017 and July 2020 by Pulley and Collins (2021b). Suspended sediment in the River Avon at Patney and Holbeck/Wath Beck (sampled from Jan–May 2021 and May–June 2021) were investigated by Pulley and Collins (2022) and overbank sediment in the River Wye and River South Tyne was source traced by Pulley and Collins (2023). Results for Derril Water (sampled Oct 2022–Jan 2023), Aylesbeare Stream (Jan–Feb 2022), Lamorna Stream (Feb–Mar 2023) and the River Neet (Sept–Oct 2022) are previously unpublished data produced by the same methods as Pulley and Collins (2022).

In all catchments where suspended sediment was traced, it was collected using time-integrating samples based upon the design of Phillips et al. (2000). The traps were positioned either at the catchment outlet or at strategic locations along the stream network; e.g., in major tributaries. Traps were positioned at approximately 60% of the water depth at the time of installation, which was typically at low flow, and as close to the centre of the channel as accessibility permitted. Samples of overbank sediment (used in the River Wye, River South Tyne and Lamorna Stream) were collected from woody debris trapped above ground in trees and fences, and in the case of the River Wye, recent deposits on the floodplain surface were also sampled. These floodplain deposits were collected using a steel trowel whist sediment was washed from woody debris in a plastic bag using native river water. For the eight catchments studied by Pulley and Collins (2021a,b), multiple sediment samples were collected over a three-year period. Here tracing all fractions (mineral and organic) of the <25 μm sediment using conventional quantitative sediment source fingerprinting showed no significant changes in sediment source with flow condition, other than in Fox Dyke, where subsurface field drains were important seasonally. Accordingly, at the other sites, only a single sampling period during ~3 wet months was traced in the later studied catchments (Holbeck/Wath Beck, River Avon at Patney, Derril Water, Aylesbeare Stream, Lamorna Stream and the River Neet). For the samples collected over the three-year period, data for only a ~3 month sampling period of high flow are presented here due to the observed lack of change in sediment sources.

Sediment source samples were retrieved from all land uses and geologies throughout the catchments apart from in the River Wye where the overbank sediment collected from tributaries draining different geological units were used as the source samples (Pulley and Collins, 2023). All samples were collected as a composite of 3–5 bulked individual source samples collected from a ~3 m radius of the sampling point. Samples of cultivated, grassland and woodland topsoils were collected from the top 2 cm of the soil profile using an enamelled stainless-steel trowel. Channel banks were also sampled using a trowel from the bottom two-thirds of the bank profile to avoid sampling displaced surface material. Subsurface material which may have originated from field drains in Fox Dyke was sampled using a gouge corer to a depth of 20–30 cm, discarding the top 5 cm which was characteristic of topsoil material. Landslips were sampled to a depth of 10 cm after scraping away the top 1 cm of material to avoid contamination. Channel bed mud deposits in Woodhill Brook were grab sampled to a depth of 20 cm.

2.3. Sample preparation and analysis

Fine silts (<25 μm) were traced to reduce the possibility of particle-size related uncertainties affecting sediment provenance results. However, this fraction is also the most easily transported by water and delivered to rivers and has the highest potential for contaminant transport and environmental harm (Horowitz, 1991). Therefore, if fine

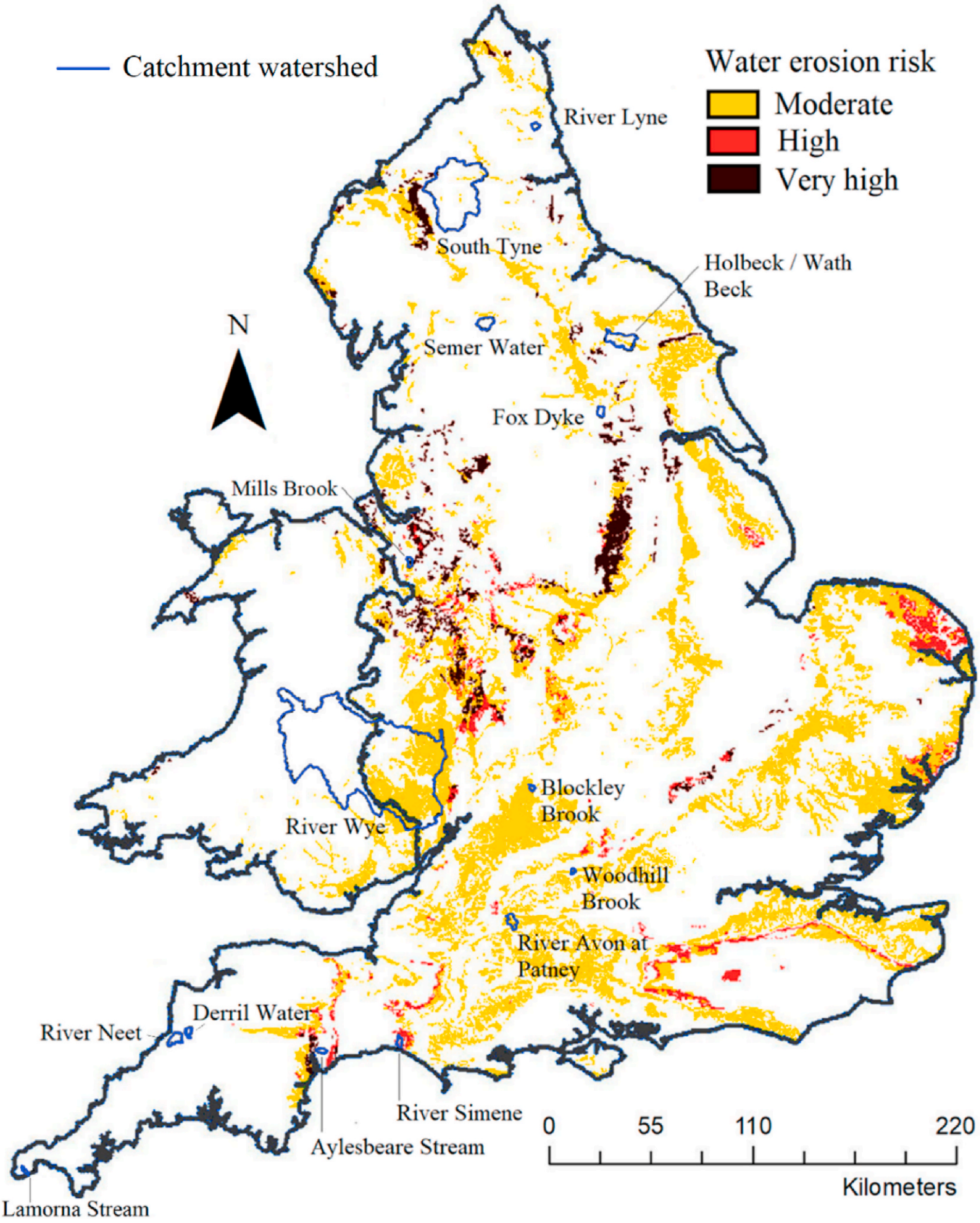

Fig. 1. The locations of the study catchments overlain over the soil erosion risk map for England and Wales. Detailed maps of individual catchments are provided in the SI (after Evans, 1990; Evans et al., 2017).

silts from topsoil sources are found not to be delivered to stream channels (i.e., acting as sediment sources as opposed to just areas of erosion; *sensu* Collins and Walling, 2004) it can be inferred that coarser less easily transported particle size fractions are also not delivered from the same sources (Laceby et al., 2017). All source and sediment samples were gently passed through a 25 μm stainless steel mesh using deionised water and manual agitation. The sieved samples were oven dried at 50 °C.

Hydrogen peroxide was used to remove the organic fraction of the source and sediment samples. Here, 8 ml of 30% hydrogen peroxide was added to approximately 0.2 g of each sample in a 50 ml centrifuge tube; the samples were left to react overnight and then heated at 80 °C until dry (Pulley and Collins, 2023). Where this treatment was not originally used (i.e., by Pulley and Collins, 2021b), all source and sediment samples were re-processed with hydrogen peroxide to ensure a consistent procedure across the study sites reported herein. Sediment colour was measured by disaggregating the treated samples and scanning an image of them inside transparent plastic bags using a Ricoh MP colour scanner. The red, green and blue values in the RGB colour space were captured on a scale of 0–255 in Gimp 2 open-source image editing software (Pulley and Collins, 2021a). Simple colours comprising red, green and blue are used, rather than a variety of colour indices, as it was found in most catchments that colour indices were generally highly correlated with either red or blue.

2.4. *Sediment source identification*

To determine if the colour of the mineral fraction of fine-grained sediment supports the hypothesis that most sediment in UK rivers does not originate from cultivated topsoils, a two-stage approach was used. First, the summed difference between the red and blue values (on a scale of 0–255) of the sediment at the catchment outlet and the median value for each source group was calculated. A smaller difference suggests that a particular source is more likely to contribute sampled sediment than another.

Sediment provenance was also interpreted using scatter plots and box plots of primary colours (red and blue), and ratios of colours (red, green and blue) were used in the River Wye catchment where they improved source discrimination. Green was not used alone in the scatter plots as it is generally an intermediate between red or blue. Sediment provenance derived from these plots is interpreted qualitatively based upon field-based observations of catchment characteristics in support of the numerical examination of differences between source and sediment colour. Scatter plots have the advantage in that they allow the values of one tracer to be compared to those of another. The interpretation of these plots has been validated against conventional quantitative sediment source fingerprinting data by Pulley and Collins (2022). In the catchments where qualitative source fingerprinting has been conducted these new colour-based results tracing the mineral sediment are used to validate the conclusions of the original work which traced the untreated sediment. Where sediment fingerprinting has not been previously used, the new results are interpreted alone. Box plots showing 0th, 25th, 50th, 75th, and 100th percentile ranges of all source groups and sediment at the catchment outlet are also provided in the online supplementary material and are referred to within the results section to identify if the colour of the sediment falls within the range found in a particular source or in a position suggesting a mixture of sediment mobilised and delivered from different sources.

Whilst the approach used has the disadvantage of not calculating numerical percentage contributions from each source, it avoids potential uncertainties due to equifinality in unmixing modelling which has long been recognised as a problem when many potential source groups are identified as being active within a catchment. (Collins et al., 2017, 2020). A qualitative approach was also considered appropriate as with the limited number of tracers judged to be appropriate for use after hydrogen peroxide treatment, source discrimination was, in some cases, not sufficient to calculate precise numerical contributions from each source.

Whilst river suspended sediment yields are likely to vary significantly spatially and temporally, any published sediment yields for nearby comparable river catchments were considered in the interpretation of the sediment provenance results as were the published net soil erosion rates for England and Wales explored in the introduction. By combining these fundamental datasets, it was determined if they can be reconciled with each other with regards to producing a simplified representation of the fine-grained sediment cascade.

3. Results and discussion

3.1. The provenance of mineral sediment in 15 UK rivers

In The River Neet, Derril Water, Aylesbeare Stream, Lamorna Stream, River Wye, Woodhill Brook, the River South Tyne, River Avon at Patney and the River Lyne catchments, source discrimination was good using colour with over 75% of source samples classified into their respective groups in the linear discriminant analysis (Supplementary Table 2). In Mills Brook, Blockley Brook, and the River Simene catchments, only 70–75% of source samples were classified correctly, although there remains significant differences between the source group populations. In Fox Dyke, there was no significant difference between the source group populations although the colour of the subsurface source samples was at the lower range of values found in the topsoils allowing for the conclusions of Pulley and Collins (2021a,b) to be broadly validated later in the section. Whilst there is a significant difference between the colour of the source group populations in Semer Water, source discrimination provides no significant additional information over the conventional sediment source fingerprinting performed by Pulley and Collins (2021a,b) other than to not contradict its conclusions.

In 10 of the 15 catchments investigated, the colour of channel banks or the channel bed was most similar to that of the sediment samples supporting the hypothesis of this paper that they are a more important source of suspended sediment than agricultural topsoils. In the River Lyne and Mills Brook catchments, woodland had the most similar colour despite the presence of high erosion risk arable soils in the catchments. Similarly, in the River Avon at Patney, soils over the greensand and peat in the flat valley bottom had a more similar colour to the suspended sediment than the high erosion risk sloped arable land over the chalk geology. This finding may reflect the fact that channel banks are not significantly eroding here. In Semer Water and Holbeck/Wath Beck, there were limited differences in colour between the source groups and therefore it is not possible to make a meaningful comparison. Only in the River Wye catchment does the sediment of a primarily arable area (Devonian geology) have the most similar colour to the sediment samples.

Larger differences are most related to how variable colour is between sources. The characteristics of the individual catchments is used to further interpret sediment provenance in this section.

The colour of the sediment samples in the River Neet and Derril Water have the lowest mean difference from channel bank median colour than any surface source and discrimination between source groups was strong (Table 1; Supplementary Table 2). Sediment colour also falls outside of the 0th – 100th percentile range of red and blue values found in agricultural topsoils and within the range of blue values found in channel banks, suggesting they are the dominant sediment source (Fig. 2a and b; Fig. S15). In Aylesbeare Stream, the sediment has a high blue in relation to red suggesting there may be some topsoil contributions to the sampled sediment (Fig. 2c). Examination of the sediment in all three catchments using a microscope showed that topsoil sources here are composed primarily of quartz whist channel banks are a mix of darker coloured minerals. It is therefore likely that the selective transport of different mineral fractions or bed incision are causing sediment colour in some sediment samples to be darker than in the sampled sources (Fig. 2a,b,c). A suspended sediment yield was measured for the River Exe catchment into which Aylesbeare stream flows at Stoodleigh, Devon, of 28 t km^{-2} yr^{-1} and in the upper Exe at Pixton, Devon, of 19 t km^{-2} yr^{-1} (Walling and Webb, 1987). A similar yield of 26 t km^{-2} yr^{-1} was also measured in the nearby River Clyst (Walling and Webb, 1987). Within all three of these catchments, channel banks were observed to be tall and visibly eroding. Janes et al. (2018) calculated high channel bank erosion rates for the River Exe of 90.7 t km^{-2} yr^{-1} using raw maps to compare channel locations, and 38.8 t km^{-2} yr^{-1} with 3 m buffers to reduce the impact of mapping uncertainties. Given that these estimates included the meandering trunk streams of the River Exe catchment, channel bank erosion rates in headwater tributaries, like Aylesbeare Stream, Derrill Water and the River Neet, are likely to be considerably lower. However, the estimates of bank erosion combined with low sediment yields are consistent with the finding that banks are the dominant source of suspended sediment. The finding that grassland is contributing a negligible amount of sediment to Derrill Water and the River Neet suggests that the eroded sediment from grassland (~26 t km^{-2} yr^{-1}) measured on the nearby NWFP must almost all be trapped within the catchment suggesting a low SDR. There is likely some contribution from topsoils in Aylesbeare Stream; however, catchment land use is 58% pasture and 42% cultivated land and, therefore, a much higher overall soil erosion rate than in the other two catchments would be expected. This is clearly not resulting in a proportionally higher contribution from topsoils when compared to the two pasture dominated catchments.

The catchment of Lamorna Stream is also in the southwest of the UK

Table 1
The summed difference between source group median red and blue and sediment red and blue (each measured on a scale of 0–255) at the catchment outlets; the most similar sediment source colour to the sediment is highlighted in bold. Catchment maps and descriptions are provided in supplementary information.

	Cultivated	Grassland	Channel banks	Woodland	
Derril Water	59.4	65.8	**36.2**	57.9	
River Neet	49.7	55.8	**30.5**	41.6	
Aylesbeare Steam	30.3	33.4	**21.7**		
Lamorna Stream	34.3	30.4	**5.2**	6.1	
Rive South Tyne		45.4	**17.0**	24.6	
Mills Brook[a]	22.9	18.3	18.4	**14.3**	
	Agricultural topsoils	Bed Sediment	Channel Banks/subsurface	Woodland	
Blockley Brook[a]	30.9		**13.35**	18.5	
River Lyne	11.9		22.75	**5.4**	
Woodhill Brook	22.4	**1.1**	8.6		
Fox Dyke[b]	19.4		**9.5**		
	Clay silt and limestone	Mudstone	Channel Banks	Sandstone (sloped arable)	
River Simene[a]	7.35	14.45	**6.6**	10	
	Devonian (sloped arable)	Pridoli	Llandovery, Ludlow and Ashgill	Urban	
River Wye	**3.3**	31.4	35.1	54.05	
	Valley bottom pasture	Channel banks and subsurface	Hillslope topsoils	Landslips	
Semer Water[b]	12.95	14.7	**6.2**	12.6	
	Chalk (sloped arable)	Channel banks	Alluvium	Greensand	Peat
River Avon	26.3	31.35	10.6	**8.45**	11.9
	Sandstone hills (sloped arable)	Clay	Channel banks	Clay Silt and Sand and Gravel	Limestone
Holbeck/Wath Beck[b]	25.15	46.2	**18.5**	22.2	23.35

[a] Catchments with only moderate source discrimination.
[b] Catchments with poor source discrimination.

(Fig. 1) and again, channel banks have the most similar colour to the sediment sampled at the catchment outlet (Table 1; Fig. 2d; Fig. S15). The mean red and blue values for the sediment fall within the 25th – 75th percentile range for channel banks and outside of the corresponding ranges for both grassland and cultivated topsoils. No suspended sediment yields have been published in this part of the UK with which to make a comparison to likely soil erosion rates. However, given the presence of high erosion risk crops and visible rill erosion (Fig. S3), rates are likely to be high and therefore the SDR low.

For Woodhill Brook, an arable catchment in south midland England (Fig. 1), the colour of the sediment is most similar to the thick channel bed mud deposits present here (Table 1; Fig. 2e; Fig. S15). The mean red value of the sediment also falls within the 25th – 75th percentile range for red of the bed mud deposits whilst falling outside of the corresponding range in topsoils. High erosion rates of these large volumes of bed material are likely the major driver of this sediment provenance rather than low sediment delivery from topsoils. However, the presence of riparian woodland and a metalled pathway along much of the river's length, as well as flat riparian areas, likely reduce field-stream connectivity. There are no suitable published suspended sediment yields for comparison here.

For the River Simene, the difference between sediment colour at the catchment outlet and the median values for the source groups suggests possible contributions from channel banks, sloped arable land over the sandstone geology, and soils over the clay, silt and limestone geologies to sediment sampled at the catchment outlet, although source discrimination using colour was limited (Table 1; Supplementary Table 2). The colour of soils over the flatter mudstone geology, which is mostly used as grassland, have the most dissimilar colour. However, a change in sediment source between the middle and upper (MM, MT, Top) sampling sites and the catchment outlet (BM) can be observed in the scatter plot (Fig. 2f) suggesting a significant change in sediment source, and therefore, high sediment losses from the area of sandstone in the lower catchment (Fig. S5). This sloped area covers a relatively small proportion of the catchment and is used primarily as arable land. Widespread rill erosion was observed on arable fields here and, in places, the river breached its banks to flow over tilled soil. The SSEW survey of UK rill erosion by Evans (1990) showed the soil associations present in this area to be of high risk of erosion (Fig. 1). Due to the high erosion risk soils and visible rill erosion, quantities of eroded sediment from the cultivated fields in the lower catchment are likely to be at the upper end of those measured in the SSEW project (>260 t km^{-2} yr^{-1}). A metalled path and woodland buffer was observed to border the river in this location but was breached in several places by concentrated overland flows and was only present on one side of the river channel meaning the highly erodible fields are likely to be well-connected to the river channel.

The catchment above the MM site is approximately 7 times larger than the area of sandstone suggesting low erosion rates or low SDRs are present in this area. Much of this area is utilised as grassland which the data from the NWFP indicates is likely to have an erosion rate ~10 times lower (~26 t km^{-2} yr^{-1}) than the sandstone area. Therefore, the sediment load dominated by the heavy erosion of the sandstone area is plausible given available data. Channel banks were observed to be high and visibly eroding in some locations but were often well-vegetated, suggesting that they are not likely to have a high erosion rate at catchment scale in this specific case. No suspended sediment yield data is available for a catchment close to the River Simene; however, the likely high erosion rates and SDR expected from the sandstone area is clearly able to account for the magnitude of suspended sediment yield that could be expected in this catchment.

In the case of the River Wye, the sediment at the catchment outlet has the most similar colour to that of sources over the Devonian geology and source discrimination was strong (Table 1; Table S2). Pulley and Collins (2023) also showed two major changes in sediment source took place along its length (Fig. 3a). The first is downstream of the confluence of a major tributary with both arms draining the upland area. This may be due to the larger effective catchment area of the tributary when compared to the trunk stream due to the presence of two large lakes. The more significant change in sediment source is an increasing down-stream contribution of sediment from the lowland area of the

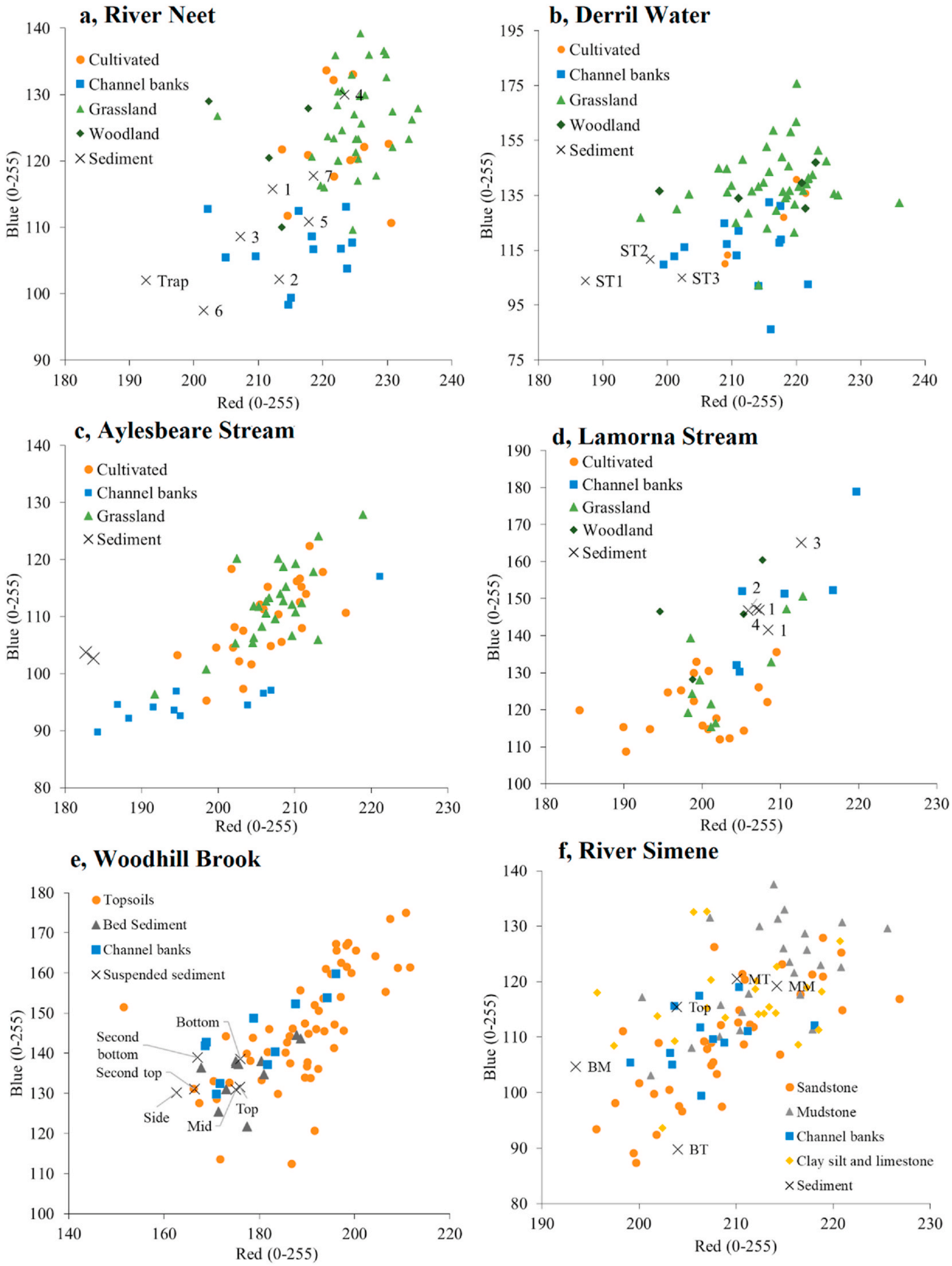

Fig. 2. Source and sediment red and blue for the first six catchments (a, River Neet, b, Derril water, c, Aylesbeare stream, d, Lamorna stream, e, Woodhill Brook, f, River Simene) studied, Mann-Whitney U tests and a DFA for significant differences between colour tracers in critical source groups are provided in Supplementary Table 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

catchment over the Devonian geology which is mostly used as arable land (Table 1; Fig. 3; Fig. S6).

The mostly arable soils in the west of the catchment in areas mostly dominated by the Devonian geology were assessed in the SSEW monitoring project to be of moderate erosion risk (<260 t km^{-2} yr^{-1}) when compared to a low erosion risk for the mostly grassland in the remainder of the catchment (Fig. 1; Evans et al., 2016). Approximately 25% of the catchment area is covered by the Devonian geology suggesting that to achieve 50% of the suspended sediment load of the Wye, soil erosion and sediment delivery must be double that of the grassland. Due to the moderate soil erosion risk in the Devonian area, it is plausible that this is the case, although significant sediment deposition on the well-developed floodplain may mean that much of the eroded sediment from the upland grassland areas does not reach the downstream portions of the catchment.

Measured suspended sediment yields in the River Wye catchment largely correspond to these tracing results. For the upland areas of the catchment, a yield of 13.2 t km^{-2} yr^{-1} was measured in Stretford Brook (PSYCHIC (pers. Comm.) in Walling et al., 2008). Within upland areas of the catchment, river channels are normally wide with low, stony, and

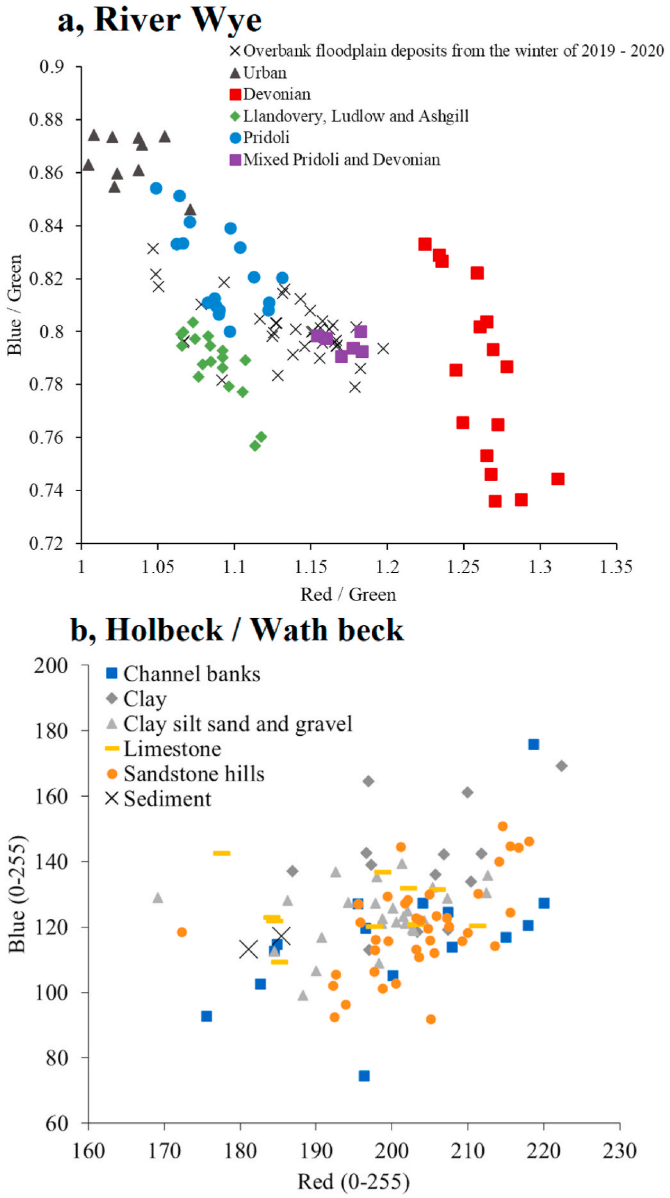

Fig. 3. Source and sediment red: green and blue: green ratios for the River Wye (a) and red and blue for Holbeck/Wath Beck (b); Mann-Whitney U tests and a DFA for significant differences between colour tracers in critical source groups are provided in Supplementary Table 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

well-vegetated channel banks. Therefore, this yield is generally consistent with the modern background sediment yields proposed by Foster et al. (2011) and the erosion rates expected for a dominant grassland sediment source when assuming a low SDR.

For the mostly arable Devonian geological area, in Worm Brook in the south of the Wye basin, a yield of 27.7 t km^{-2} yr^{-1} was measured. For the larger River Frome in the far east draining half Devonian and half Pridoli geologies, a yield of 40.5 t km^{-2} yr^{-1} was measured (PSYCHIC (pers. Comm.) in Walling et al., 2008). Here, data was not available to estimate the relative contributions of sediment from channel banks when compared to surface sources, although high and visibly eroding channel banks in this part of the catchment, such as the River Lugg, suggest a significant bank erosion contribution is more likely. A much higher suspended sediment yield of 173 t km^{-2} yr^{-1} was measured in the River Lugg in the east of the Wye catchment from 2009 to 2012 by Stopps (2018). This sediment yield was observed to increase in a downstream direction as discharge increased and the channel became more incised possibly indicating a high contribution of sediment from bank erosion. The high sediment yield found here suggests a significant topsoil contribution is also likely, as the maximum channel bank erosion rate of 90 t km^{-2} yr^{-1} measured in any of the limited number of catchments studied by Janes et al. (2018) is significantly lower than the local measurements of suspended sediment yield. However, this sediment yield is also higher than expected net soil erosion rates on arable land at a landscape scale.

Turning to the catchment of Holbeck and Wath Beck, whilst source discrimination was poor using colour (Table S2), it was found that the colour of the suspended sediment fell on the outside range of values found in the source samples suggesting sediment inputs from a highly localised area. The sampled sediment was most similar in colour to sources from the eastern flat valley floor containing soils over the clay silt and sand and gravel, and limestone geologies as well as channel banks (Table 1; Fig. 3b; Fig. S11; Pulley and Collins, 2022). The mean red and blue values of the sediment fell outside of the 25th – 75th percentile ranges in the sandstone hills area which contained most of the high erosion risk sloped arable land (Fig. S16). This was explained by a low stream density in the sloped and widely cultivated sandstone hills area, some of which Evans et al. (2017) classifies as being of moderate erosion risk. The streams present were also most often bordered by woodland or grassland fields or sizable grass buffers presenting significant barriers to sediment transport. In contrast, most arable land within the catchment is on the flatter valley floor area and the stream density here is higher. For the large nearby River Swale at Leckby Grange, a suspended sediment yield of 33.5 t km^{-2} yr^{-1} was measured by Wass and Leeks (1999), although this river also drains the upland Yorkshire Dales for part of its length. Wass and Leeks (1999) also calculated a higher yield of 58.4 t km^{-2} yr^{-1} for the River Swale at Catterick Bridge which almost entirely drains the Yorkshire Dales. Therefore, these results suggest a slightly lower yield than 33.5 t km^{-2} yr^{-1} is appropriate for the lowland parts of the River Swale. A yield of 21.6 t km^{2} yr^{-1} was also calculated for the large River Aire at Beale Weir by Wass and Leeks (1999). However, this catchment mostly drains flatter ground and some large urban areas. A suspended sediment yield of 25 t km^{-2} yr^{-1} was calculated for the River Esk by Walling and Webb (1981). This catchment is closer in location to Wath Beck/Holbeck, and the similarity of this estimate to the more recent and more robust sediment yields measured in similar rivers in the region suggest a yield of 25 t km^{-2} yr^{-1} is reasonable.

The part of the catchment determined to contribute most of the sediment covers approximately 22% of the total catchment area. Therefore, for a suspended sediment yield of 25 t km^{-2} yr^{-1} to be achieved, a soil erosion rate of over 100 t km^{-2} yr^{-1} combined with a high SDR would be required. As the area in question is flat without highly erodible soils, such high erosion rates are implausible. Channel banks were also observed to be well vegetated and almost no eroding reaches of bank were encountered during field sampling for sediment source fingerprinting; therefore, it is likely that contributions from this source are minimal. Therefore, it is more likely that the suspended sediment yield of the catchment is significantly lower than those published for nearby rivers as sediment source, yield and net erosion rate cannot be reconciled.

In the case of the River South Tyne (804 km^{2}) the mean difference between the sediment and channel bank colour was lower than for any other source group and source discrimination was good (Table 1; Supplementary Table 2). Similarly, the mean sediment red and blue values at the catchment outlet fell within the 25th-75th percentile range found in the channel bank source samples but outside of the corresponding range for grassland topsoils (Fig. 4a; Fig. S17). Whilst the colour of the sediment and woodland topsoils were similar, woodland only covered a small proportion of the catchment and so is not a plausible major source of sediment. Its similar colour to the sediment was likely due to it being

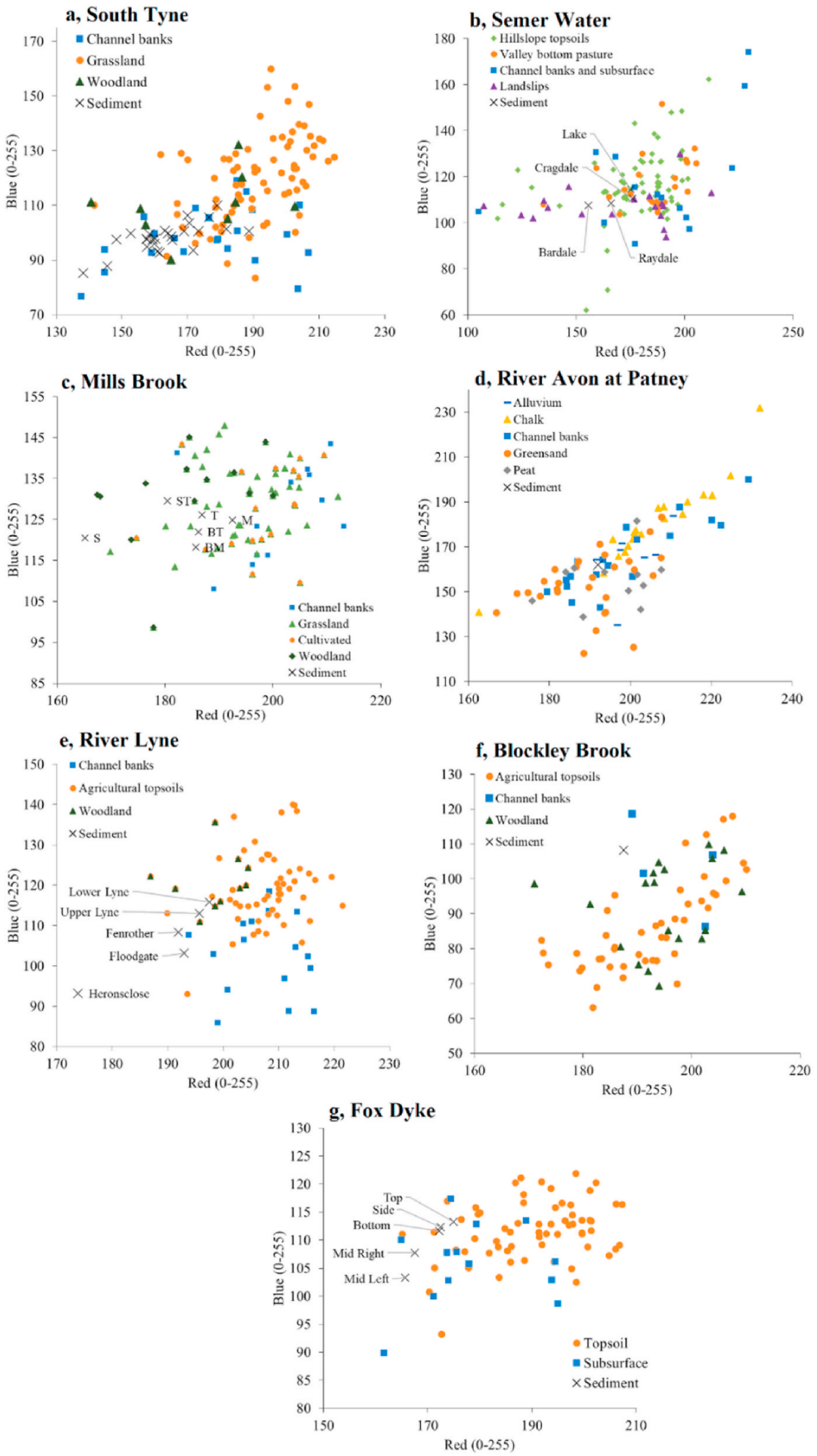

Fig. 4. Source and sediment red and blue for the remaining seven catchments studied (a, River South Tyne, b, Semer Water, c, Mills Brook, d, River Avon at Patney, e, River Lyne, f, Blockley Brook, g, Fox Dyke); Mann-Whitney U tests and a DFA for significant differences between colour tracers in critical source groups are provided in Supplementary Table 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

positioned mostly adjacent to the river channel where overbank sediment deposits form. Channel banks here can be observed to be tall and visibly eroding. Using the method of Janes et al. (2018) to compare the mapped historic channel location (1972) to the present-day channel location, on the West Allen tributary of South Tyne, allowed for an approximate estimated suspended sediment yield of 42 t km^{-2} yr^{-1} from bank erosion (See map in SI of Pulley and Collins, 2023). An unpublished 2010 study of the South Tyne by Envirocentre, Glasgow, and Newcastle University using discharge and SSC measurements generated a suspended sediment yield estimate of 40.6 t km^{-2} yr^{-1} (Tyne Rivers Trust; Pers. Comm, 2022). Therefore, bank erosion rates can plausibly account for the suspended sediment yield measured here. Since this catchment is steep sloped with high annual rainfall, a high grassland sheet wash erosion rate such as the 26 t km^{-2} yr^{-1} measured on the NWFP would be expected. This eroded sediment is clearly not reaching the river in large quantities as if it were, ~40% of the 40.6 t km^{-2} yr^{-1} suspended sediment yield would be from grassland sheet wash. Large flat valley bottom floodplains border the river along most of its length which when combined with stone field boundaries and riparian woodland, likely provide an effective buffer to sediment delivery from eroding hillslopes.

For the catchment of Semer Water, the colour of the sediment is most like that of the hillslope topsoil source, although it is also comparable to the other source groups due to poor source discrimination (Table 1; Supplementary Table S2). The red and blue values of the sampled sediment are closer to the 25th −75th percentile range for landslips than valley bottom or hillslope topsoils (Fig. S17). Pulley and Collins (2021a) found roughly equal contributions of sediment from hillslope topsoils, valley bottom farmland and landslips and subsurface sources with minimal contributions from hilltop peat deposits. The new hydrogen peroxide treated colour data is broadly in agreement with this finding although adds little additional information.

Sediment yields from the Yorkshire Dales have been measured at 15.3 t km^{-2} yr^{-1} on the River Wharfe at Tadcaster (Wass and Leeks, 1999), and separately, on the River Wharfe at 13 t km^{-2} yr^{-1} by Walling et al. (1998). Both measurements, however, include a significant area of flatter agricultural land not representative of the Semer catchment reported herein. A likely more representative sediment yield of 58.4 t km^{-2} yr^{-1} was measured by Wass and Leeks (1999) on the River Swale at Catterick Bridge which almost entirely drains the Yorkshire Dales area in which Semer Water is located. As this suspended sediment yield is significantly higher than what might be expected for grassland sheet wash, it suggests that significant, landslip, peat erosion or channel bank erosion is also contributing. This is supported by the mixed sediment provenance identified in Semer Water. This higher sediment yield and the more varied sediment sources found in Semer Water, when compared to the River South Tyne, may be a result of a smaller proportion of the river channel being bordered by a flat floodplain allowing for a higher SDR. Channel banks were also far shallower and throughout most of the catchment were not heavily eroding, also helping to explain a mixed sediment provenance not dominated by high bank erosion rates.

For Mills Brook, the colour of the woodland, grassland and channel bank source samples is most like the sediment sampled at the catchment outlet despite only moderate source discrimination (Table 1; Supplementary Table 2). The mean red and blue values of the sediment fall outside of the 25th – 75th percentile range of all source groups apart from red for woodland and blue for channel banks (Fig. 4c; Fig. S17). Therefore, sediment colour here does not clearly identify its provenance. However, the colour of arable topsoils in this catchment is most dissimilar to that of the sediment suggesting that they are unlikely to be its dominant source.

Three arable fields with a total area of 0.18 km^2 were observed to be undergoing rill erosion between the ST and M sampling sites. Given the presence of rill erosion, a noticeable change in sediment provenance would be expected within the stream downstream of these arable fields given that Evans et al. (2016) found rill erosion rates of >260 t km^{-2} yr^{-1} on erodible soils and some soils within the Mills catchment are of very high erosion risk (Fig. 1). It is therefore likely that the narrow woodland and bushy buffers and the ~15 m of flatter ground close to the stream channel were sufficient to prevent most eroded field sediment from reaching the stream. No suitable suspended sediment yield estimate was available for this catchment or any immediately nearby, although a suspended sediment yield of 34.8 t km^{-2} yr^{-1} was measured for the River Wyre (Walling and Webb, 1981). This catchment is approximately 50 km from Mills Brook but shares broadly similar geology, topography and land use. Rowan et al. (1995) calculated a much higher sediment yield of 192 t km^{-2} yr^{-1} in the upper Wyre catchment; however, this part of the catchment contains a large proportion of moorland unlike that of Mills Brook and therefore might experience high bank erosion such as found in the River South Tyne reported herein.

Turning to the River Avon at Patney Bridge, the mean difference in colour between topsoils over greensand and peat on the flat valley floor and the sampled sediment is the lowest of any source group and source discrimination was good (Table 1; Supplementary Table 2). The red and blue values of the sampled sediment fall outside of the 25th–75th percentile range in the chalk source group which contains the only sloped arable land in the catchment (Fig. 4d; Fig. S17). Therefore, fine sediment is indicated to mostly originate from the valley bottom area suggesting that despite the higher erosion risk of the sloped arable fields over the chalk geology (classified as moderate risk by Evans, 1990, Fig. 1) most eroded sediment from here is not reaching stream channels. The low stream density on the chalk hills and flat valley floor acting as a buffer here likely explains this finding. Three sediment yields have been measured in the River Avon catchment at: Chitterne – 16 t km^{-2} yr^{-1}; at East Avon – 4.95 t km^{-2} yr^{-1} (PSYCHIC pers. Coms. To Walling et al., 2008), and 4.5 t km^{-2} yr^{-1} at Amesbury (Heywood and Walling, 2003). These yields are low compared to those measured in most other UK catchments which may be explained by the low stream density and shallow well-vegetated channel banks. Given these yields are much lower than expected net soil erosion rates on the moderate erosion risk chalk hillslopes, a low SDR for this area and low channel bank erosion rates are likely.

In the River Lyne catchment, the mean difference between the woodland source group colour and the sediment sampled at the catchment outlet is lower than for the other source groups and source discrimination was good (Table 1; Supplementary Table 2). The mean red value of the sediment again falls closer to the 25th – 75th percentile range of the woodland source group than the corresponding ranges for either arable topsoils or channel banks indicating high sediment contributions from this source (Fig. 4e; Fig. S17). The scatter plot also shows that the sediment blue values fall between the woodland topsoil and channel bank source samples (Fig. 4e). Woodland borders the stream in most of the upper and middle catchment (Fig. S12). Similarly, channel banks in the upper and middle parts of the catchment are visibly eroding in some areas; however, the low amounts of sediment retrieved from the traps here suggest bank erosion rates are low and longitudinal connectivity is disrupted by the pond present along the stream channel. The poaching of land adjacent to river channels by livestock was observed in the lower catchment as well as some narrow riparian buffers which may explain higher topsoil contributions here. No nearby suspended sediment yield estimates have been published for this area.

For Blockley Brook, the mean difference between the sediment and source colour was lowest for channel banks, although source discrimination was limited. (Table 1; Supplementary Table 2). However, the sediment sample was a very similar colour to the visibly eroding channel bank sample retrieved in the lower catchment, whilst the other bank samples with a dissimilar colour were retrieved from shallow banks in the upper and middle catchment which are unlikely to erode significantly (Fig. 4f). The sediment was indicated by Pulley and Collins (2021a,b) to be highly organic and originate mostly from woodland, with a ~25% contribution from localised downstream channel bank sources. After hydrogen peroxide treatment, the mineral fraction of the sediment is indicated to come from localised bank erosion sources supporting the original published conclusion. Despite the abundant sloped arable fields present within the catchment, the large areas of riparian woodland clearly prevent almost all topsoil sediment delivery to the stream. There are no suitable suspended sediment yields which can be considered for the Blockley Brook catchment, although given the lack of sediment inputs from topsoil and limited area of erodible channel banks, its yield is likely to be low.

In Fox Dyke, the colour of the subsurface source samples is more like the sampled sediment than topsoil sources although source discrimination using colour here was limited (Table 1; Supplementary Table 2). The red and blue values of the sediment also falls within the 25th-75th percentile range for the subsurface samples but outside of this range for red in topsoils (Fig. S17). Pulley and Collins (2021b) also found an absence of ^{137}Cs in the sediment samples retrieved during periods of low rainfall which suggested that sediment from subsurface sources delivered through field drains, dominates when rainfall is low. When rainfall was higher, a high ^{137}Cs activity was found suggesting a greater topsoil contribution. Chapman et al. (2005) found that in two catchments in the midlands of the UK, most sediment transported through field drains originated from topsoil sources. Therefore, it is plausible that a significant amount of the topsoil contribution indicated within Fox Dyke is also transported through the field drains. Sediment yields measured from field drains within the UK are sparse; however, in four land drains, Chapman et al. (2005) measured yields of 96.4–97.8, 7.0–62.6, 27.0–51.6 and 98.0 t km^{-2} yr^{-1}. Whilst these high sediment yields from land drains may be highly site-specific, they highlight the potential for high rates of sediment delivery when compared to most measured rates of net soil erosion and low surface SDRs. Measured suspended sediment yields from flat areas of the east of England are very limited; however, a low yield of 3–5 t km^{-2} yr^{-1} was estimated for the River Wensum by Sear et al. (2006). This estimate was, however, made using limited turbidity monitoring and a calibration not specifically measured in this river, so the estimate has high uncertainty. However, considering the flat poorly erodible soils are likely to have low erosion rates and sediment delivery ratios, it is not unexpected that even a small amount of sediment loss from field drains can contribute much of the sediment yield of Fox Dyke.

3.2. Reconciling the sediment budgets of UK rivers

Channel bank erosion likely contributes a higher proportion of sediment to most of the rivers studied than topsoil sources. This finding contradicts previous overviews of available evidence from published sediment source fingerprinting suggesting that agricultural topsoil erosion dominates the sediment loads of rivers on a broadly national scale (Walling, 2005; Walling et al., 2008). Only in the Rivers Simene, and Wye, were moderate and high erosion risk arable fields identified as possibly key sources of the sampled sediment.

High and moderate erosion-risk arable fields are often not connected to stream channels due to landscape buffers and barriers. A key buffer in the catchments studied is riparian woodland. This is particularly the case in the Blockley Brook catchment, as well as to a lesser extent in most of the other catchments studied (Derril Water, Lamorna Stream Aylesbeare Stream, River Neet, Mills Brook, Holbeck/Wath Beck). Mills Brook is the clearest example where arable fields were not found to be a major sediment source at catchment scale despite visible rill erosion in some of them. This was likely due to a low SDR despite minimal riparian buffers being present. Similarly, in the Holbeck and Wath Beck and River Avon at Patney catchments, fields over the moderate erosion risk hilly areas did not contribute sediment to watercourses due to woodland and grassland buffers and a low stream density. In Fox Dyke, the presence of subsurface field drains presented an efficient pathway for sediment delivery which bypassed such buffers which control sediment delivery via the surface runoff pathway only.

Given these findings, the most logical way to reconcile measured net soil erosion rates and river suspended sediment yields is to conclude that existing measurements of soil erosion rates and interpretations of sediment delivery ratios are broadly correct on a national scale and that most sediment from eroding topsoils is mostly deposited within a catchment instead of being delivered to a watercourse. As net soil erosion rates are generally comparable to river suspended sediment yields, most sediment found in UK rivers cannot originate from topsoil sources. Therefore, as the results of this study show, channel banks must often be the dominant source of sediment in a significant proportion of UK rivers. This finding would also be consistent with the finding that fine-grained sediment sources did not change significantly with flow condition by Pulley and Collins (2021b) as channel banks are always well-connected to the river network and the delivery of eroded material is not dependent upon field-channel connectivity. The commonly held assumption that the accelerated erosion of arable land is driving increased sediment yields on a national scale is therefore likely incorrect, if the trends observed in the catchments investigated apply nationwide. Instead, accelerated soil erosion may only have a significant impact in more localised areas, such as in the River Simene or River Wye, where both erosion and SDRs are high. It is therefore necessary for further research to evaluate how widespread catchments, such as the River Simene, with a suspended sediment yield dominated by topsoil erosion, are.

If channel bank sources do dominate the sediment yield of many or most UK rivers, then it means that previous sediment source fingerprinting studies may not have generated accurate results in many catchments. Reviews by Walling (2005) and Walling et al. (2008) collated sediment source fingerprinting results in the UK conducted up to the date of publication and summarised that the average contributions were 8% from woodland, 41% from pasture/moorland, 35% from cultivated land and 22% from channel banks. This is clearly inconsistent with published net erosion rates and suspended sediment yields as well as the findings for most catchments investigated in this study. For example, a sediment source fingerprinting study on the River Exe suggested only a 5% contribution of sediment from banks (Collins et al., 1997). This finding is inconsistent with the sediment yield of the catchment, the high rates of channel bank erosion found by Janes et al. (2018) and the tracing results generated for Aylesbeare Stream within the Exe catchment reported herein. It is also of note that the original sediment source fingerprinting study conducted by Pulley and Collins (2021a;b) in the River Simene failed to detect the high contributions of sediment from the arable fields in the lower catchment that were found by the new work herein after the hydrogen peroxide treatment. Whilst there is insufficient data available to definitively suggest that in some or many catchments sediment source fingerprinting has not been accurate, uncertainties associated with particle size distribution, organic matter enrichment and statistical and modelling procedures are widely reported (e.g. Collins et al., 2017; Laceby et al., 2017; Collins et al., 2020). The removal of organic matter in this study was a critical difference to previous work conducted in the UK. Additionally, many older sediment source fingerprinting studies traced the <63 μm fraction without confirming if that size fraction was most appropriate for the target sediment sampled and the tracers used. Additionally, until recently, virtual or artificial mixtures were not used for validation of predicted source proportions. Instead, goodness-of-fit was used, but this simply confirmed reliable source-weighted prediction of measured tracer concentrations in the target sediment samples and not of actual source contributions (Collins et al., 2017). This also could have generated significant scope for erroneous results due to mathematical equifinality.

3.3. Future research directions

Whilst the results of this study indicate that mineral sediment is likely to originate from channel banks in most UK catchments, the sources of its associated organic matter may differ due to its low density and greater ease of transport. For example, in the upper River Taw, Upadhayay et al. (2022) showed a significant contribution of sediment-associated organic matter from agricultural topsoils during extreme winter rainfall. It has been shown that the organic matter content of sediment from different sources and its oxygen demand greatly affect its toxicity (Sear et al., 2016). Therefore, considering the sources of sediment-associated organic matter in future research and catchment management may deliver a greater potential for delivering aquatic environment benefits when compared to confirming the contributions of channel bank derived mineral sediment with its generally low organic matter content. This must be balanced, however, against the known importance of sand-sized material, which is more likely to reach river channels from juxtaposed channel banks rather than more distal surface sources, initiating an important process cascade associated with the entrapment of fine inorganic and organic material in the interstices of channel beds and the concomitant detrimental impacts on aquatic ecology. Such considerations underscore the subtleties that are needed when seeking to understand the widely reported sediment problem and the urgent need for its improved management.

This review and data integration exercise clearly points to a number of additional future important research needs:

- Addressing the paucity of contemporary data on measured sheet wash net erosion rates on both arable land and grassland, especially in the context of changing weather extremes
- Addressing the data gap for catchment scale channel bank erosion rates
- Addressing the lack of reconstructed lake sediment yields in lowland arable catchments with which to directly measure increases in suspended sediment yields associated with agricultural intensification and any subsequent reductions due to the introduction of agri-environment schemes and in-field interventions for sediment control
- Improving data for sediment connectivity and delivery ratios at catchment scale, including the impacts of key and often widespread features such as riparian or infield buffer strips and hedgerows
- Validating sediment source fingerprinting results against field-based measurements of net erosion rates and suspended sediment yields in sentinel catchments to ensure the data are reconcilable.
- Re-visiting model parameterisation to ensure that modelled sediment cascades better represent the evolving empirical evidence base.

4. Conclusions

The primary purpose of this work was not to discredit any previous research but, instead, to examine the compatibility of data collected independently for different components of the sediment cascade in UK river catchments. Based on our work herein, there is a significant possibility that, in many catchments, channel bank erosion is a much more important sediment source, than previously reported.

Importantly, for catchment management in the UK, and indeed, similar temperate agricultural catchments worldwide, the widely held assumption that sediment originates primarily from arable land or topsoil sources more generally is likely to misinform the targeting of best management interventions, causing a risk of continued non-compliance with environmental policy objectives for water quality due to a lack of resistance to elevated erosion and sediment delivery resulting from increasing abiotic stresses associated with widely reported wet weather extremes and climate change.

CRediT authorship contribution statement

S. Pulley: Writing - review & editing, Writing - original draft, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **A.L. Collins:** Writing - review & editing, Writing - original draft, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: A. L. Collins reports financial support was provided by Biotechnology and Biological Sciences Research Council. A.L. Collins reports financial support was provided by Catchment Sensitive Farming. A.L. Collins reports financial support was provided by Natural Environment Research Council.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.119810.

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