Rothamsted Repository Download

A - Papers appearing in refereed journals

Pulley, S. and Collins, A. L. 2023. Using the colour of recent overbank sediment deposits in two large catchments to determine sediment sources for targeting mitigation of catchment-specific management issues. *Journal of Environmental Management.* 336, p. 117657. https://doi.org/10.1016/j.jenvman.2023.117657

Journal of Environmental Management 336 (2023) 117657

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Using the colour of recent overbank sediment deposits in two large catchments to determine sediment sources for targeting mitigation of catchment-specific management issues

S. Pulley, A.L. Collins *

Net Zero and Resilient Farming, Rothamsted Research, North Wyke, Okehampton, Devon, EX20 2SB, UK

ARTICLE INFO

Keywords:
Sediment fingerprinting
Erosion
Flood deposits
Catchment management
Large catchment

ABSTRACT

The effective management of sediment losses in large river systems is essential for maintaining the water resources and ecosystem services they provide. However, budgetary, and logistical constraints often mean that the understanding of catchment sediment dynamics necessary to deliver targeted management is unavailable. This study trials the collection of accessible recently deposited overbank sediment and the measurement of its colour using an office document scanner to identify the evolution of sediment sources rapidly and inexpensively in two large river catchments in the UK. The River Wye catchment has experienced significant clean-up costs associated with post-flood fine sediment deposits in both rural and urban areas. In the River South Tyne, fine sand is fouling potable water extraction and fine silts degrade salmonid spawning habitats. In both catchments, samples of recently deposited overbank sediment were collected, fractionated to either <25 μm or 63-250 μm, and treated with hydrogen peroxide to remove organic matter before colour measurement. In the River Wye catchment, an increased contribution from sources over the geological units present in a downstream direction was identified and was attributed to an increasing proportion of arable land. Numerous tributaries draining different geologies allowed for overbank sediment to characterise material on this basis. In the River South Tyne catchment, a downstream change in sediment source was initially found. The River East Allen was identified as a representative and practical tributary sub-catchment for further investigation. The collection of samples of channel bank material and topsoils therein allowed channel banks to be identified as the dominant sediment source with an increasing but small contribution from topsoils in a downstream direction. In both study catchments, the colour of overbank sediments could quickly and inexpensively inform the improved targeting of catchment management measures.

1. Introduction

Large rivers provide critical water resources and ecosystem services to the human populations which they support. A combination of land use change, urbanisation, structural changes to river systems and floodplains, and climate change have caused increased sediment related pressures on these river systems globally (Li et al., 2017). These pressures are causing widespread failures to meet environmental objectives (Vorosmarty and Sahagian, 2000). Specific problems associated with excessive sediment loads include reservoir sedimentation and drinking water contamination (Dargahi, 2012; Lal and Stewart, 2013), the siltation of aquatic habitats and associated harm to biota therein (Wood and Armitage, 1997; Kemp et al., 2011), harm to biota through increased pollutant fluxes (Pyle et al., 2005), increased flood risk, as well as impacts on infrastructure (Boardman and Vandaele, 2020). To mitigate these effects most efficiently requires an understanding of sediment sources, which also depends upon both erosion rates as well as connectivity between different parts of a large river system at varying scales, from hillslope erosion to sediment transport to depositional processes (Walling and Collins, 2008). The downstream impacts of anthropogenic activities within a catchment may also vary over temporal scales with it possibly taking many years for a change to manifest impacts downstream, presenting a further challenge to understanding catchment sediment sources (Owens et al., 2010). Current understanding of sediment source evolution through large catchments is generally poor (Slattery et al., 1995; Collins and Walling, 2004), and a paucity of

---

* Corresponding author.
E-mail address: adrian.collins@rothamsted.ac.uk (A.L. Collins).

https://doi.org/10.1016/j.jenvman.2023.117657
Received 19 December 2022; Received in revised form 24 February 2023; Accepted 1 March 2023

monitoring data combined with the logistical challenges associated with data collection limit the availability and generation of site-specific sediment source information (Xu et al., 2022). Given the high costs of sediment mitigation in large catchments on account of their spatial extent, the absence of reliable sediment source data is causing both societal costs associated with the damage caused by excessive sediment transfers and sub-optimal returns on the public funds invested to mitigate the sediment problem.

Sediment source fingerprinting is a widely used method to determine the sources of sediment transported through a river system (Collins et al., 2020). The method significantly reduces the resource requirements of establishing sediment sources when compared to traditional monitoring approaches, making it potentially ideal for the study of large river catchments (Collins et al., 2017; Xu et al., 2022). It, however, requires the collection of an adequately representative database of samples of different potential sediment sources within a catchment, as well as samples of target sediment sampled from key locations on the stream network. Unfortunately, in large catchments, which may cover an area of thousands of square kilometres, obtaining such a database of source samples is likely to be time consuming and expensive and not possible without substantial monetary and labour resources. Different sampling methods have been developed in sediment fingerprinting investigations to overcome this problem, which may also potentially deliver an increased understanding of the spatial evolution of sediment sources through a catchment. For example, Hardy et al. (2010) sampled sediment from the deltas of 11 tributary sub-catchments of the large Romaine River, Canada, to identify variation in sediment source composition throughout its basin. Alternatively, a confluence-based tracing approach where sediment is retrieved from two streams upstream and downstream of their confluence represents an approach where the relative contributions of sediment from each can be identified (Collins et al., 1997; Vale et al., 2016; Blake et al., 2018). However, this confluence-based approach still requires the deployment of a network of sediment samplers and adequate sampling time which may limit the number of points within a river network which can be sampled and may present a barrier to work with limited resources or timescales. The collection of channel bed sediment through resuspension methods represents an alternative instantaneous sampling method and does not require in situ samplers (Lambert and Walling, 1988). However, this approach relies on the sometimes-debatable assumption that the sediment deposited on a particular area of the bed is representative of the suspended sediment load of its upstream catchment over a range of flow conditions, and in large rivers deep water may limit the practicality of sampling. Therefore, for a catchment manager with a limited budget, adequately sampling a large river system is likely to be very challenging.

Recently deposited overbank sediment has been collected as target sediment in source tracing work by the deployment of artificial grass mats and the washing of sediment from the leaves of riparian vegetation (Lambert and Walling, 1987; Owens and Walling, 2002). Overbank deposits have also been used for geochemical mapping in large river systems (Ottesen et al., 1989). Sampling overbank sediment deposits has the advantage that they contain sediment transported during high flows when most of a river's sediment flux occurs (Wainwright et al., 2015). They can also be easily sampled wherever found, which in some rivers may be extensively along a river channel network, meaning that a large database of sediment samples can theoretically be collected over a short period of field work by a non-expert with no specialised equipment. This will, however, depend upon both the presence of depositional locations where sediment may be trapped and the time of year, as vegetation able to trap sediment may not be present all year around. Vegetation growth may also cover sediment deposits on the ground hiding them from view. The alteration of sediment properties over its extended storage might mean it no longer reflects its source, or rainfall may wash away loosely deposited sediment. Despite these potential limitations, the ability to trace the sources of a large number of sediment samples inexpensively and quickly along the length of a river can potentially significantly improve our understanding of catchment erosion and sediment delivery processes and the evolution of sediment provenance through large river systems. Therefore, greater utilisation of this opportunity in sediment research and catchment management should be further explored.

Difficulties when source tracing in large river systems are also compounded by the high costs associated with tracer analysis and analytical complexity of many tracing techniques (Collins et al., 2017). To overcome these barriers, sediment colour has been increasingly used as an inexpensive tracer (Krein et al., 2003; Martinez-Carreras et al., 2010; Brosinsky et al., 2014; Barthod et al., 2015; Pulley and Rowntree, 2016; Pulley et al., 2018; Evrard et al., 2019; García-Comendador et al., 2020; Ramon et al., 2020; Amorim et al., 2021). When measured using a conventional office document scanner, colour has been shown to have some potential to deliver comparable sediment provenance information to a composite fingerprint of many different tracer types without the requirement for specialist analytical equipment (Pulley and Collins, 2021). However, overbank sediment deposits have a high probability of being enriched in organic matter or having a particle size distribution altered during deposition processes and any tracing methodology must therefore account for these sources of uncertainty explicitly to produce reliable results. Fractionation of sediment samples to a narrow particle size range represents a simple, although time consuming, way of minimising the risks of particle size related uncertainties (Laceby et al., 2017). To mitigate organic matter enrichment, the use of hydrogen peroxide has shown significant potential when using colour for sediment source tracing, and it may also increase source discrimination based upon catchment geology allowing for the refined spatial targeting of sediment mitigation measures (Pulley et al., 2018; Pulley and Collins, 2022). However, as organic matter is likely to be a major cause of differences in the colour of sediment generated from different land uses, this treatment may also cause an unavoidable reduction in source discrimination on this basis with its necessary application to overbank sediment deposits.

At present, there is a need, therefore, for a greater understanding of sediment source evolution through large river systems since this information can be used to target catchment management efforts. A lack of published data and the substantial barriers to obtaining catchment-specific sediment provenance data using conventional costly methods significantly limit current efforts to target management efforts efficiently. However, the collection of overbank sediment deposits combined with appropriate particle size fractionation, hydrogen peroxide treatment, and its analysis using colour potentially represents a fast and inexpensive method to address this evidence gap. Accordingly, this study trialled this low-cost colour method in two large UK river basins, with the aim of informing the mitigation of catchment-specific management problems. The first is the River Wye where post-flood fine sediment deposits have caused significant damage to urban infrastructure and agricultural land with high clean-up costs. The second is the River South Tyne where its high sediment load is causing increased potable water extraction and treatment costs and the degradation of salmonid spawning habitats. The study explored whether the proposed fast and inexpensive source tracing approach can adequately determine sediment source composition evolution throughout these river systems necessary for the targeting of management measures.

2. Materials and methods

2.1. Study sites and sample collection

The River Wye is located along the England – Wales border and is the fourth longest river in the UK with a total catchment area of 4136 km^2 (Fig. 1; Fig. 2). It has a high mean annual rainfall in its headwaters of 1131 mm at Builth Wells. Downstream, rainfall is lower at 793 mm at Hereford. Elevation ranges from 118 to 66 m.a.s.l. Catchment geology consists of Devonian rocks in the southeast and older Llandovery group deposits in the northwest, with Pridoli, Ludlow, Wenlock and Ashgill

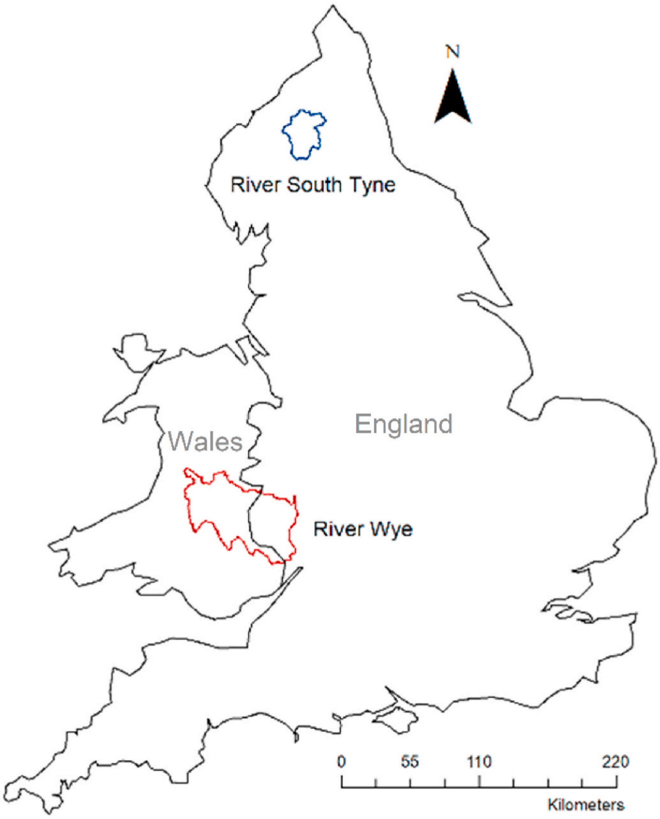

Fig. 1. The locations of the River South Tyne and River Wye catchments.

deposits in bands between them. Rock types in most of these groups are primarily mudstones and siltstones, although the Devonian deposits contain a greater proportion of sandstones. Soils over this Devonian geology are a distinctive red colour. Land use in the catchment is primarily permanent grassland in the higher altitude northwest with arable fields becoming dominant over the Devonian deposits in the southeast. The city of Hereford is a significant urbanised area in the southeast.

Flooding on the River Wye during the winter of 2020 left large quantities of fine-grained overbank sediment on floodplains within urban and agricultural areas. Much of the post-flood clear up costs resulted from geomorphic processes of erosion and deposition of this fine-grained sediment. In urban areas, insurance costs are often increased due to muddy water damage, whilst in rural areas, overbank deposits and erosion damage crops and infrastructure and render land unavailable for production (Boardman et al., 2006). Similar inundations are common in large unconfined lowland floodplains and especially in urban environments where flows have been modified by infrastructure. Tracing the sources of these sediment deposits represents a significant challenge due to the scale of the catchments affected, meaning that limited information is currently available when planning strategies aimed at reducing the costs associated with post-flood fine sediment deposits (Environment Agency, 2017).

The River South Tyne is an upland catchment with an area of 804 km^2 in the North Pennine hills in the northeast of England in the counties of Northumberland and Cumbria (Fig. 1; Fig. 3). Its mean annual rainfall at Haydon Bridge near the catchment outlet at an elevation of 60 m.a.s.l is 949 mm, whilst in its upland headwaters it is 1032 mm at Allenheads with an elevation of 402 m.a.s.l. Catchment geology is a mixture of peat on hilltops, limestone, siltstone sandstone and mudstone on hillslopes and glacial till in valley bottoms. Land use is a mixture of ungrazed heathland at high altitude and grassland for cattle and sheep grazing in most of the remaining catchment. A small proportion of its area is covered by woodland, which is primarily adjacent to the river channel. Channel banks are composed of glacial till which can be observed to be actively eroding along much of the river length. Larger landslips infrequently cause a significant quantity of subsurface material to enter the river channel. The catchment has a history of mining for lead and fluorite.

In the River South Tyne large quantities of sediment are causing significantly increased costs of potable water abstraction and treatment. In addition, the river is an important habitat for salmon and trout which are threatened by excess fine sediment inputs much of which is polluted with heavy metals from historical mining activities. As such, the local water company and Tyne Rivers Trust NGO have identified the need for a reconnaissance survey of sediment sources.

In both study catchments, the initial aim of the sampling was to retrieve a database of overbank sediments along the length of their stream networks to identify any downstream changes in sediment source. The results were then used to guide the collection of additional samples aimed at characterising the different sediment sources contributing to the overbank deposits. In the River Wye catchment, these additional samples were represented by the collection of overbank deposits from individual tributaries representative of different geological units of the catchment. In the River South Tyne catchment, a representative database of topsoil and channel bank source samples were retrieved in a small tributary sub-catchment judged to be representative of the South Tyne as a whole based upon the initial analysis of the overbank samples.

In the River Wye catchment, large overbank sediment deposits were initially located along its floodplain using aerial photographs taken after the large flood events in the late winter of 2020 (Fig. 2). These were the target problem sediment deposits which were causing damage to urban and rural land and high associated clean-up costs. A total of 40 large fine-grained deposits were sampled using a trowel in September of 2020 and labelled in sequence from the headwaters of the river to downstream of the town of Hereford. After locating the sampling locations using aerial photographs the large deposits were clearly visible for sampling in the field visits. To characterise the sediment originating from the major tributaries in the catchment draining different geological groups, overbank samples of sediment were primarily washed from the leaves of vegetation into polythene bags after a smaller high flow event in September of 2020. These samples were necessary to collect as the target former problem deposits mostly consisted of a mixture of sediment from different geological units so could not characterise each individually. The vegetation sampled was primarily the Common Nettle (Urtica dioica) and common comfrey (Symphytum officinale). Where found, sediment was also retrieved from woody debris trapped elevated above the ground in trees or fences. Between three and six replicate samples of overbank sediment were retrieved from each tributary depending upon the availability of suitable sampling locations. The mass of sample retrieved was largely dictated by the amount available for collection in each sampling location. Whilst it is only strictly necessary to collect an amount of sediment which can be seen with the naked eye and therefore captured in an image, larger masses of samples are preferable to ensure that the deposits are a homogenised sample of the material transported within a river.

In the River South Tyne, sampling took place in May of 2022 which was approximately four months since the last high flows had receded. Therefore, there were no recent deposits of sediment present on the leaves of riparian vegetation. There were, however, abundant deposits of woody debris elevated in trees along the river channel, most of which contained large amounts of trapped sediment (Supplementary Fig. 1). These deposits were sampled by hand into a polythene bag along the major tributaries of the river as well as its trunk stream in the locations shown in Fig. 4. The samples were grouped by the region of the river in which they were sampled for interpretation purposes.

It was found that overbank samples alone were not sufficient to characterise the major sediment sources in the River South Tyne due to a continuous down-stream change in sediment source, meaning that the

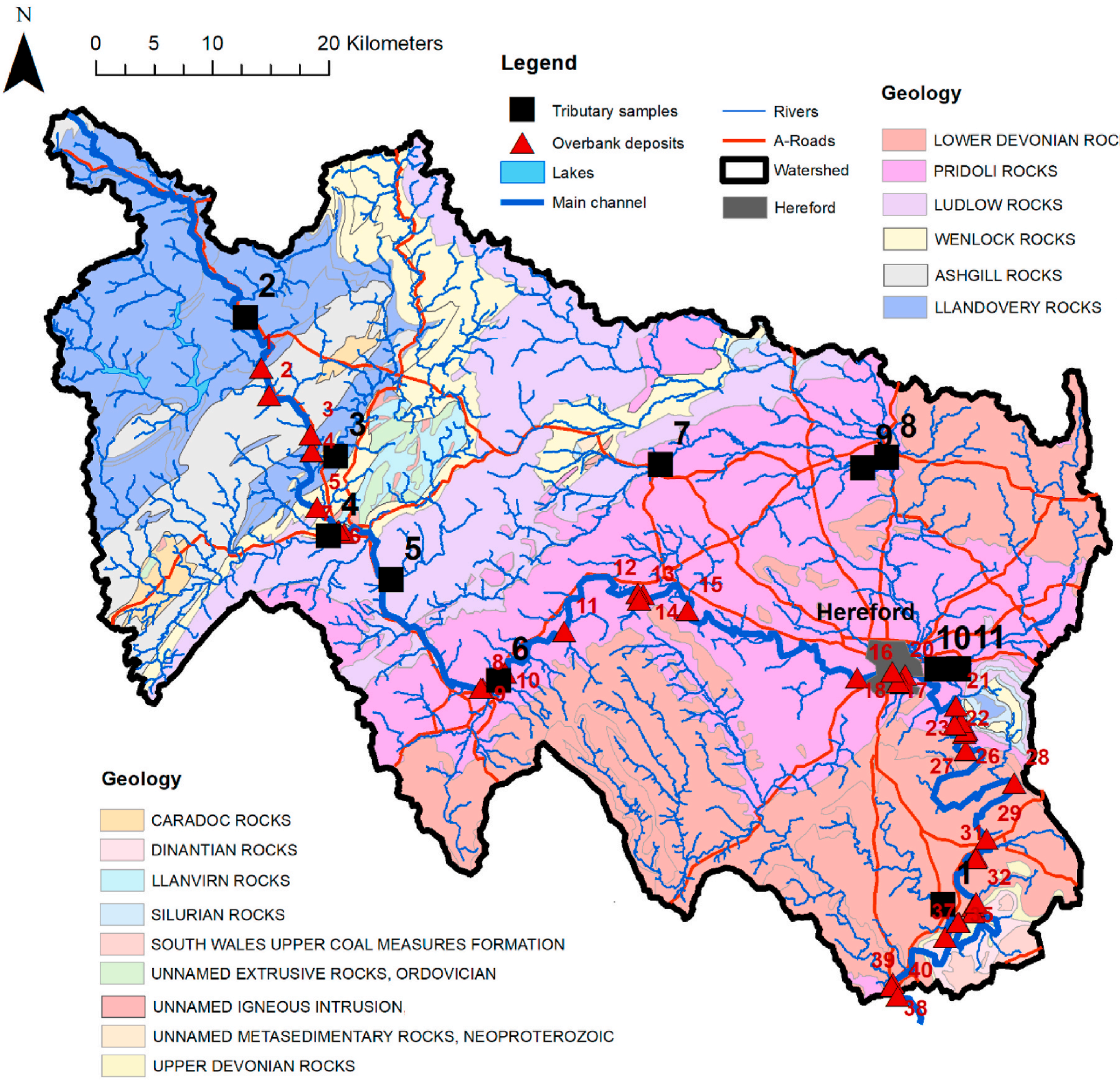

Fig. 2. Geology and sediment sampling locations in the River Wye catchment.

sediment at the catchment outlet was not solely a mixture of sediment from the major tributaries. Instead, some sediment is clearly contributed from land adjacent to the trunk stream of the Tyne downstream of the confluence of the tributaries. To further investigate sediment provenance in the context of this challenge, the River East Allen was selected for study as this showed the same downstream change in sediment source as the catchment as a whole and was sufficiently small in area for practical sampling. As most of the higher elevations in the East Allen catchment were covered by rough ungrazed moorland, which was unlikely to be a major sediment source, most of the source sampling was focused on the farmed land closer to stream channels (Fig. 5). Samples of woodland and grassland topsoils were collected to a depth of approximately 2 cm using a stainless-steel knife. Channel bank samples were collected from the lower and middle horizons of visibly eroding reaches of the banks after scraping away surface material to minimise the chances of sampling displaced topsoil material. Samples of three landslips where glacial till subsided close to stream channels were also sampled after scraping away surface material.

2.2. Sample analysis

All target sediment samples were wet sieved to a narrow particle size range before colour analysis to minimise the potential for particle size related uncertainties (Laceby et al., 2017) and to conform to the methods of Pulley and Collins (2022). The River Wye samples were sieved to <25 μm as most overbank deposits were predominantly silt-rather than sand-sized. In the River South Tyne, two particle sizes were traced. First, the <25 μm fraction was isolated as it has the greatest potential to act as a vector for pollutant transport and degrade salmonid spawning habitats. The 63–250 μm fraction was also examined as most of the sediment fouling water extraction from the river is in this size range. Whilst broader particle size ranges can be used such as <63 μm or 2 mm–63 μm, doing so increases the probability that the selective deposition of coarser or finer particles within the range can lead to changes in sediment colour unrelated to its source.

After sieving, the fine sand fraction was washed with water to remove any loosely bound organic matter leaving only mineral sediment grains. All samples were then dried and disaggregated by hand using a pestle and mortar. A subsample of each prepared sample was treated using hydrogen peroxide to remove any sediment-associated organic matter. 8 ml of 30% hydrogen peroxide was added to approximately 0.2 g of the fine silt or 1 g of the fine sand, in a clean centrifuge tube, and was left to stand overnight. The samples were then heated at 80 °C until dry. The prepared samples were packed into transparent polythene bags and an image of them was captured using a Ricoh MP office document scanner. The red, green and blue values in the RGB colour space were

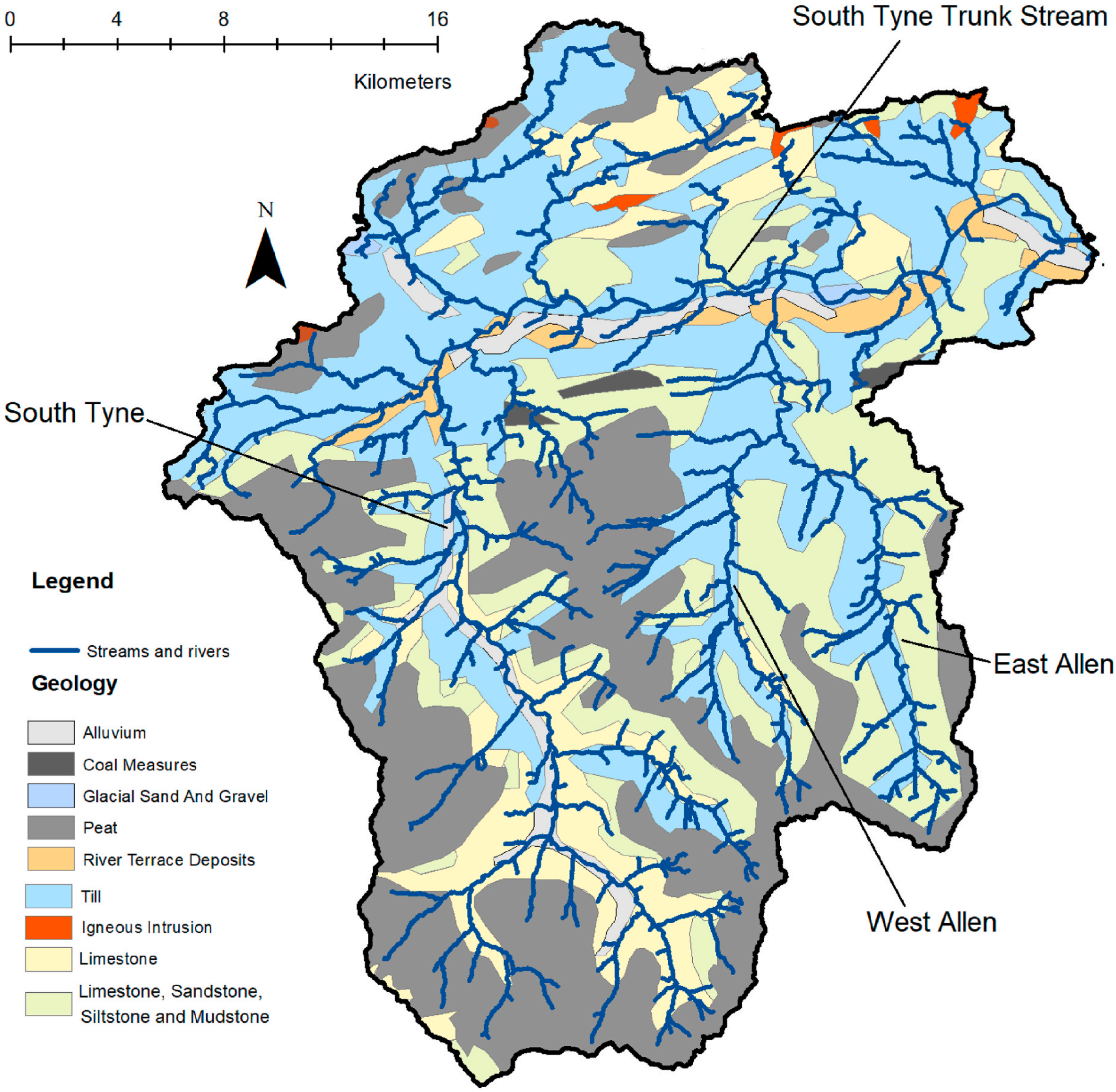

Fig. 3. Geology of the River South Tyne catchment.

captured on a scale of 0–255 in Gimp 2 open-source image editing software (Krein et al., 2003; Pulley and Rowntree, 2016; Pulley and Collins, 2021). Sediment source was interpreted using scatter plots of two-colour parameters with each source and the sediment samples appropriately colour coded and labelled. Whilst many colour parameters have been calculated from the measured red, green and blue values (e.g., Viscarra Rossel et al., 2006) red, blue and green were used in this study for their simplicity for use by non-experts, to maintain consistency with previous studies using this approach, and because of previous experience of successful source discrimination using these two colours (e.g., Pulley and Collins, 2021, 2022). However, it was found through testing different combinations of these three colours in scatter plots, that in the River Wye, using the ratios of red/green and blue/green provided superior discrimination based upon geology and therefore they were also presented in a scatter plot.The method proposed can be summarised by the following key methodological steps.

1 Collection and analysis of ‘target’ sediment samples deposited on floodplains or in woody debris from along the trunk stream and possibly the major tributaries of a large river system.
2 Collection of ‘source’ samples aimed at measuring the colour of material originating from critical sediment source areas if the samples collected in step 1 are insufficient when used alone. These samples may be tributary overbank samples draining only a specific geology or distinctive zone of a catchment or the collection of topsoil, channel bank and other potential sediment source types in a small representative sub-catchment.
3 Fractionation of samples to an appropriate and narrow particle size distribution; e.g., <25 μm.
4 Treatment of samples using hydrogen peroxide.
5 Measurement of treated sample colour and comparison of the ‘target’ sediment samples with the representative ‘source’ samples in a scatter plot to identify key contributing sources.

3. Results

3.1. River Wye

In the River Wye catchment, sediment colour best discriminated between the tributaries when the ratio of red/green was plotted against blue/green (Fig. 6). The tributaries draining the red coloured soils over

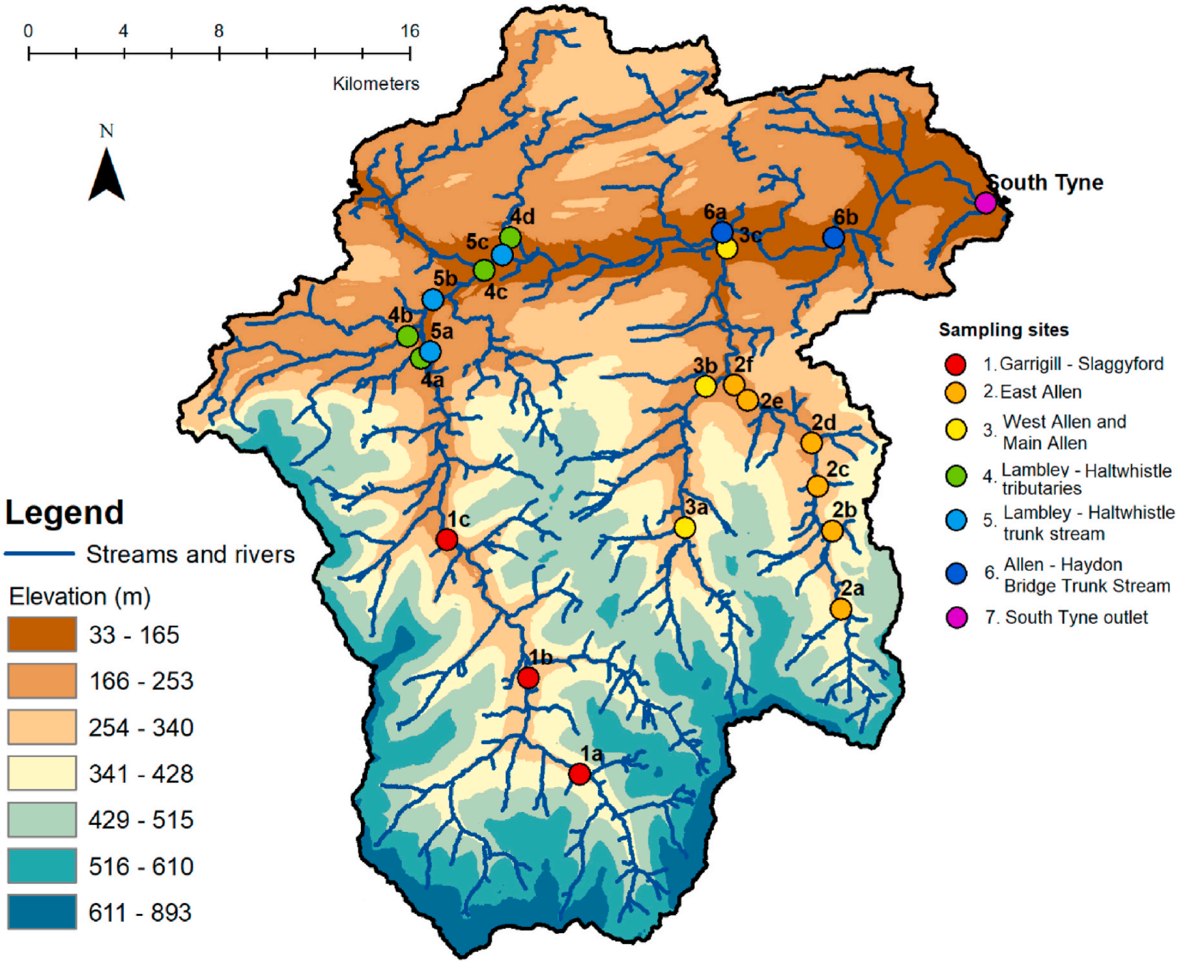

Fig. 4. Topography and overbank sediment sampling locations in the River South Tyne catchment.

the lower Devonian rocks (catchments 1, 6 and 11) had a higher red/green ratio than soils over other geologies. The urban samples have both a high blue/green and low red/green ratio. There is also reasonable discrimination between tributary sampling sites 2–5 with catchments draining the Llandovery, Ludlow and Ashgill geologies when compared to sites 7, 8 and 9 draining the Pridoli geology. The colour of the sediment from tributary site 10 falls between the Pridoli and Devonian draining tributaries reflecting the mixed geology of its sub-catchment. Replicate samples within tributaries generally have low variability in their colour when compared to the differences between tributaries even when they drain the same geological groups. The River Wye catchment can be separated into the three distinct geological regions displayed in Fig. 6 according to the colour of sediment originating from its tributaries. Accordingly, these are used for the interpretation of sediment sources.

The overbank fine sediment deposits in the upper catchment at sites 1, 2 and 3 after the extreme flooding in the spring of 2020 had a colour on the border of the Pridoli and Landovery, Ludlow and Ashgill geologies. Downstream at sites 4, 5, and 6 sediment colour was comparable to the tributaries only draining the Landovery, Ludlow and Ashgill geologies. As these latter sampling locations are downstream of a major tributary confluence, this indicates a significant change in the source of the overbank deposits here. Overbank sediment at sites 7, 8, 9 and 10 exhibited a colour, on the border or within the values found in sediment from the Pridoli geology, again indicating a significant change in sediment source takes place. This is especially important as at these sampling points the Pridoli geology only covers a small proportion of the upstream catchment suggesting much higher sediment inputs from this area of the catchment in relation to upstream sources over the Landovery, Ludlow and Ashgill geologies. From site 10 to site 20, most sediment samples have a colour that suggests a mixed contribution from sources over all three geological groups, but with only a small contribution from the Devonian geology. Downstream of site 20 where a large tributary (River Lugg), which drains a significant area of the Devonian geology, joins the River Wye's main channel, the samples fall closer in colour to the sediments from the Devonian group. At the most downstream sites 37, 38, 39 and 40, sediment colour falls closest to the Devonian geology tributary samples indicating increasing contributions of sediment from this source in a downstream direction. According to the position of the overbank sediment on the plot in Fig. 6, it is reasonable to assume a contribution of ~50% of overbank sediment from the Devonian geology at these lowermost sampling locations.

To identify sediment contributions from urban areas, it was necessary to produce a second plot of red against blue (Fig. 7). Here it is apparent that there is no significant urban sediment contribution to any of the overbank samples. Therefore, it can be concluded that the upstream area of the catchment over the Landovery, Ludlow and Ashgill geologies is not a major sediment source to overbank deposits throughout most of the study catchment. Far more sediment is contributed from the Pridoli geology and even more from the red Devonian geology in proportion to the areas of the catchment they cover. Importantly, the downstream changes in the sources of the overbank sediment, support the need for sediment management to take explicit account of the scale-dependency of the sediment fingerprinting data.

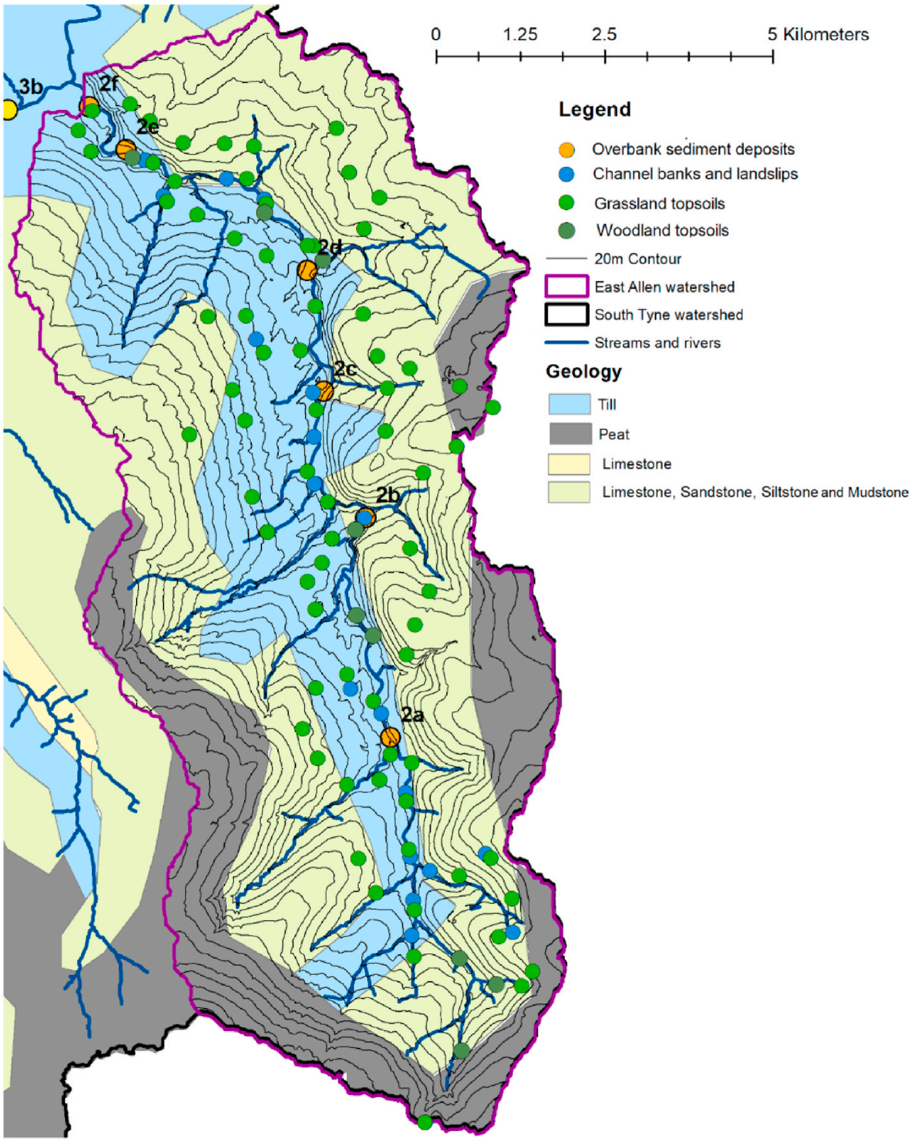

Fig. 5. Source and overbank sediment sampling locations in the East Allen sub-catchment of the River South Tyne.

3.2. River South Tyne

Both the fine silt and fine sand overbank samples collected from the upper reaches of the three major tributaries of the River South Tyne which drain headwater areas (sites labelled 1,2,3) were found to have the darkest colour (Fig. 8). Sediment colour becomes lighter in a downstream direction, being slightly darker upstream at site 5 than downstream at site 6 and the overall outlet of the South Tyne study catchment. Of particular note is site 4, which are samples retrieved from four small tributaries in the west where the sediments have a lighter colour when compared to most others, although the two samples taken at the furthermost downstream extent of the River East Allen (site 2) also have a light colour. These samples at site 4 have a dissimilar colour to those on the main channel of the River South Tyne downstream of their confluences suggesting that these sites do not contribute significantly to the total sediment yield of the study area.

The colour of the source samples retrieved from the River East Allen which was used as a representative tributary sub-catchment, provide good discrimination between the grassland topsoils, which have a light colour, and channel banks and landslip sources with a darker colour (Fig. 9). Discrimination is stronger in the sand fraction than the fine silt. Examination of the sand-sized sediment under a microscope indicates that this difference in colour was caused by the hydrogen peroxide treated topsoils mostly being composed of quartz whilst bank material contained a range of darker minerals including iron oxides, metal sulphides, and abundant purple fluorite. The colour of the overbank fine silt and fine sand retrieved from the River East Allen falls within the range of values found in the channel bank and landslip source samples (Fig. 9). There is little discrimination between the woodland and channel bank samples using colour which may be due to most woodland samples being retrieved close to the river channel where overbank sediments are deposited meaning that the soils sampled here are displaced bank material. In the context of these source samples, within the River South Tyne as a whole, there is an increase in sediment contribution from grassland topsoils in a downstream direction. However, subsurface sources remain the dominant contributor to the sampled overbank sediments.

4. Discussion

In both study catchments, there was change in overbank sediment source in a downstream direction. In the River Wye, the soils over the Devonian geology contributed a disproportionally large amount of the overbank sediment deposits near the catchment outlet in relation to the

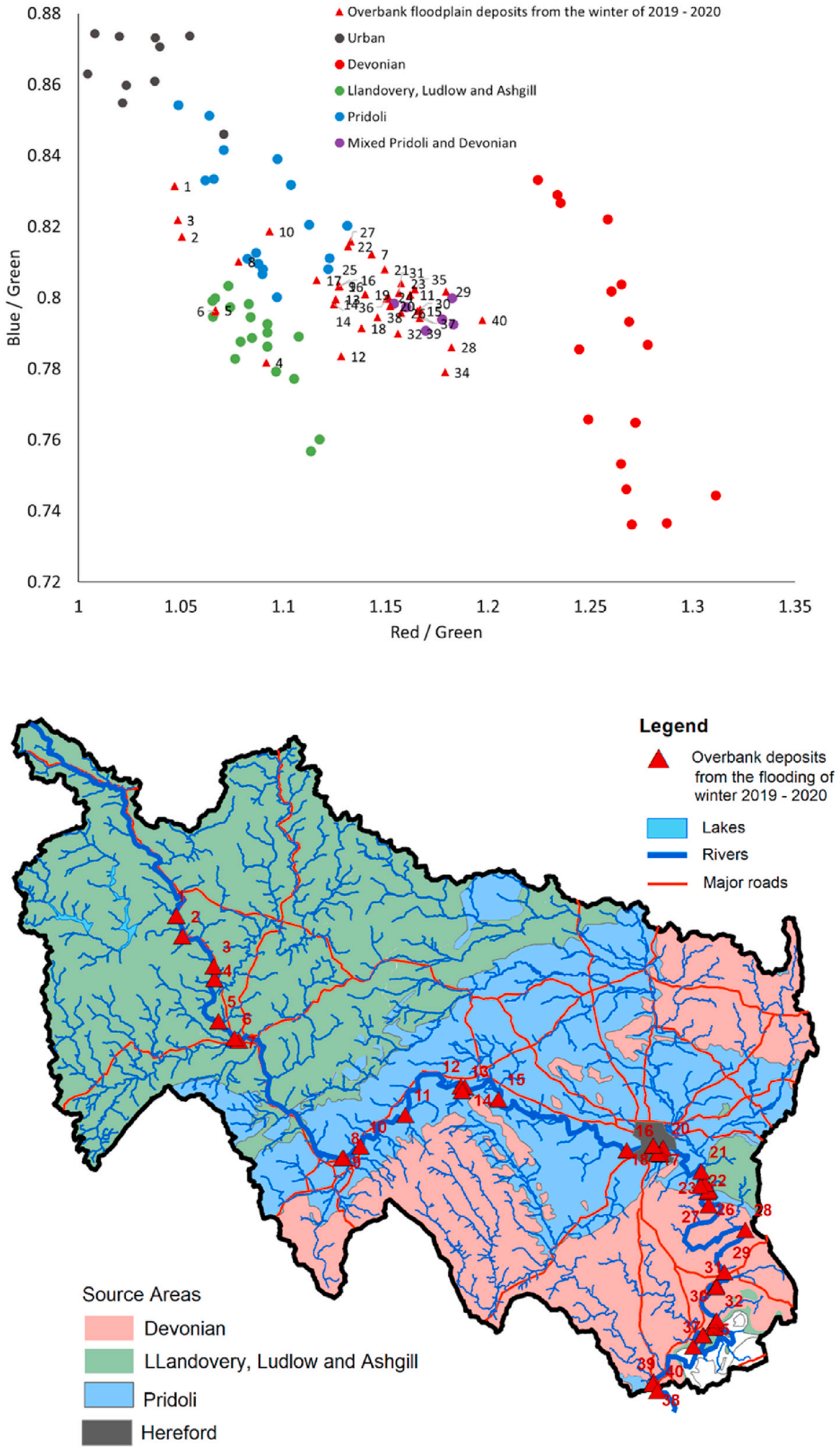

Fig. 6. Plot of the red/green and the blue/green ratios for the River Wye tributary sediment samples with a catchment map showing matching colour coded geological group source areas and the target problem overbank floodplain deposits left after the flooding during the winter months of 2019–2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

proportion of the catchment area they cover. Soils over the Landovery, Ludlow and Ashgill geologies in contrast contribute little to the overbank deposits, and soils over the Pridoli geology soils contribute an intermediate proportion. This finding can be explained as the upland areas over the Landovery, Ludlow and Ashgill geologies is primarily low erosion risk grassland with some hilltop moorland. There is an increasing proportion of high-risk arable land in a downstream direction through the Pridoli geology area with arable land dominating over the

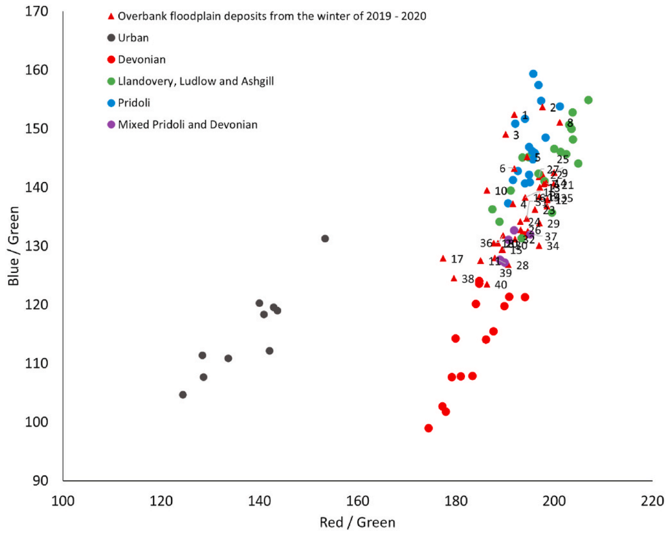

Fig. 7. Plot of the red and blue for the River Wye tributary sediment samples colour coded by geological group source area and the 'target' overbank floodplain deposits left after the flooding during the winter months of 2019–2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Devonian geology furthest downstream. Stopps (2018) measured sediment yields on the River Lugg in the east of the Wye catchment which has a high proportion of arable land and drains the Pridoli and Devonian geologies. A downstream increase in sediment yield, to 173 t km^{-2} yr^{-1} upstream of the confluence with the Wye, was found as the river became more incised and discharge increased (Stopps, 2018). A sediment yield of 51 t km^2 yr^{-1} was calculated for the River Wye as a whole, although this estimate is classified as of low quality by Walling et al. (2008) and was based on data collected in the past (1949–72) (Brookes, 1974). These findings are broadly consistent with the increasing sediment contributions from sources in a downstream direction estimated for the overbank sediment deposits in this study. The small proportion of the catchment covered by urban areas explains the low contribution of overbank sediment from this source. Carter et al. (2003) found that in the urbanised River Aire catchment in the north of the UK, road dusts contributed 19–22% of its sediment load. However, this catchment of 1932 km^2 supporting a population of approximately two million people is heavily urbanised when compared to the River Wye catchment. Therefore, the ~0.6% of the River Wye catchment area which is covered by the city of Hereford would not be expected to contribute significantly to the overbank sediment deposits unless highly localised sediment transport processes were operating. It is also probable a significant proportion of the sediment yield of the River Wye is being deposited overbank which may result in much of the sediment entering the river from upstream sources being removed from the channel before reaching the downstream sampling locations. For example, Walling and Owens (2003) found that approximately 27% of the sediment entering the large River Swale in North Yorkshire, UK, was sequestered onto the floodplain.

In the River South Tyne catchment, much of the area is covered by ungrazed moorland with thick well vegetated peat deposits which is likely to be of little risk to erosion. Very little of the erosion which is common in many drained and degraded UK peatlands was observed within this catchment during sampling (Artz et al., 2019). The remainder of the catchment is mostly covered by grassland for cattle and sheep grazing which, like in the River Wye catchment, is generally of low erosion risk. For example, a mean suspended sediment yield from grassland fields at the North Wyke Farm Platform in the southwest of the UK was calculated at 23 t km^2 yr^{-1} (Pulley and Collins, 2019). This estimate is broadly in line with the sediment yield of 25 t km^2 yr^{-1} which was calculated for the nearby River North Tyne from a reservoir sedimentation study (Walling et al., 2008). Additionally, an unpublished 2010 study of the South Tyne catchment by Envirocentre, Glasgow, and Newcastle University using discharge and SSC measurements generated a sediment yield estimate of 40.6 t km^2 yr^{-1} (Tyne Rivers Trust; Pers. Comm). Given that many field boundaries here are stone walls which present a significant barrier to field - river sediment connectivity, only a small proportion of the eroded grassland sediment would be expected to reach the river channel and contribute to this sediment yield. In addition, woodland is often adjacent to stream channels which was suggested by Pulley and Collins (2021) to present a significant additional barrier to sediment delivery in some other UK catchments. Therefore, a low contribution of sediment from surface sources makes sense in the context of the measured sediment yields. Eroding channel banks were observed to be high (an average of approximately 1.2 m and up to >10 m) throughout most of the stream network of the River South Tyne, and mostly unvegetated. These banks are commonly composed of erodible glacial diamicton and fluvial deposits. A comparison of a present-day map (Ordinance Survey Mastermap) of the catchment to one published in 1980 (National Grid 1:10,000) shows a highly dynamic meandering river channel which clearly has the potential to erode large volumes of channel bank material (Supplementary Figs. 2 and 3).

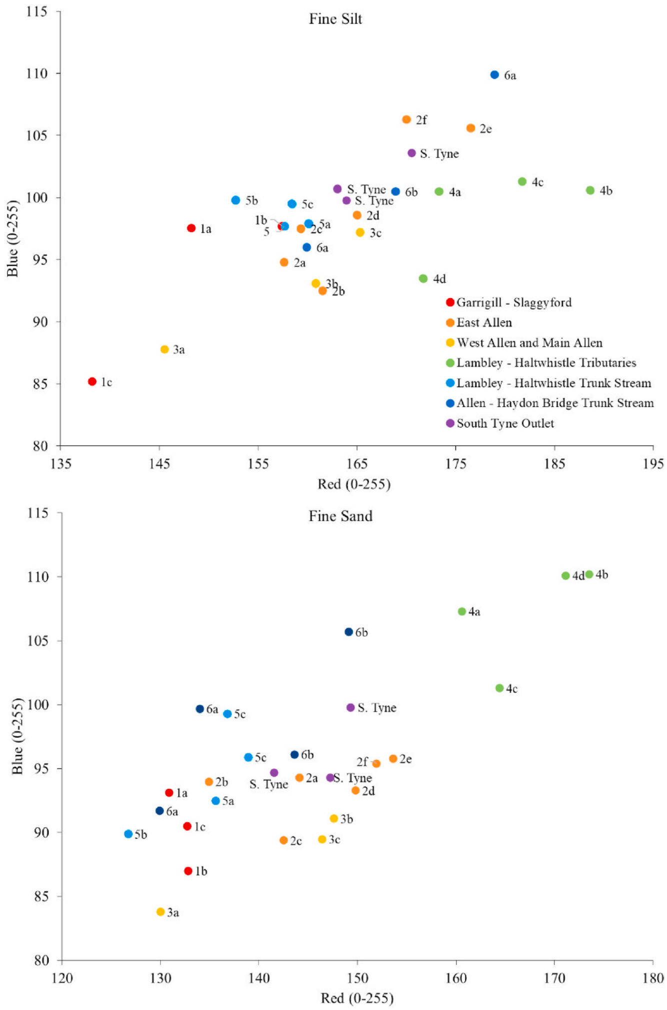

Fig. 8. Plot of the red and blue for the River South Tyne overbank sediment samples colour coded by tributary or river reach location. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The results of this study indicate the potential for the use of recently deposited overbank sediment, combined with measurement of its

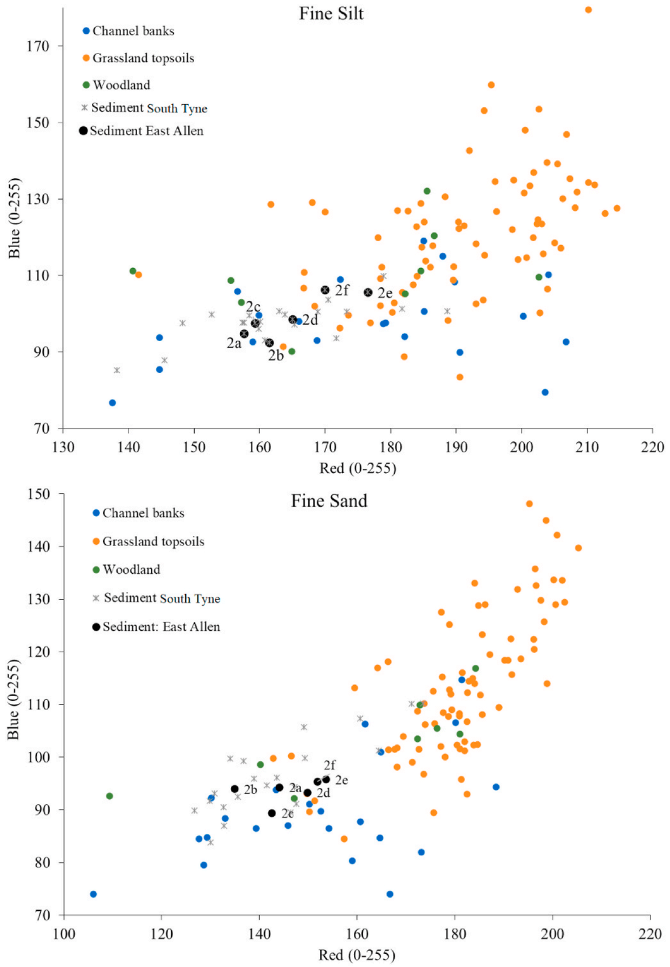

Fig. 9. Plot of red and blue for the River East Allen source and sediment samples with sediment from the entire River South Tyne catchment overlayed. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

colour, to rapidly investigate sediment source evolution through large river catchments. In both study catchments it was, however, necessary to collect a database of sediment samples representative of different source areas for the interpretation of the changing sediment colour which added to the resource requirements of the studies. The numerous large tributaries present and heterogenous geology of the River Wye catchment allowed for overbank samples from each tributary to be used to characterise sediment originating from different geologies in a similar way to confluence-based sampling approaches used with suspended sediment or bed sediment samples (Caitcheon, 1993; Collins et al., 1997; Vale et al., 2016; Blake et al., 2018). This has the advantage over sampling soils and subsurface material in a catchment as the sediment has already been eroded and transported to the river leaving less scope for particle size related tracer non-conservatism (Laceby et al., 2017).

In the River South Tyne catchment, however, a more homogenous geology removed the possibility of using a similar confluence-based sampling approach. Instead, the overbank samples were able to identify the River East Allen as a smaller representative sub-catchment with a similar downstream change in sediment provenance as the River South Tyne as a whole. Within this representative sub-catchment, the collection of a representative database of source samples was able to firmly identify channel banks as the dominant source of sampled overbank sediment as well as a downstream increase in contributions from topsoils. This sampling significantly increased the cost and labour requirements of the study using a framework closer to a conventional sediment source fingerprinting study (e.g., Collins et al., 1997). It did, however, add substantial value to the work at lesser cost than a full-scale investigation of the entire River South Tyne catchment, and the use of overbank sediment and colour further reduced cost and time requirements.

In both study catchments, the hydrogen peroxide sample treatment appears to have successfully removed organic matter enrichment as a source of uncertainty. However, it meant that it was not possible to discriminate between different land uses. Fortunately, in the River Wye increasing arable land use corresponded with changing geology, which is a condition not uncommon in large river catchments in the UK. Nevertheless, an ability to discriminate between channel banks, grassland and arable land could have further refined critical areas of the catchment for management. In the River South Tyne catchment, discriminating between land uses was of little importance due to a homogenous use of the catchment as grassland. Instead, it was critical to discriminate between surface and subsurface sources, which the different mineralogical composition of the two allowed for. The use of hydrogen peroxide does, however, increase the labour requirements of sediment source tracing studies and necessitate the use of a laboratory facility. The sieving of samples to a specific particle size fraction also requires a significant investment of labour. However, the use of overbank sediment, especially in a tributary-based sampling approach, as used here in the River Wye catchment, reduces the number of samples which must be processed when compared to a conventional sediment source tracing study linking soil source samples and target sediment samples.

In the River Wye catchment, the Devonian geology is responsible for a disproportionately high contribution to the sampled overbank sediment, reflecting the more extensive arable land in these areas. Here, it is important for mitigation measures to reduce the exposure of bare tilled soils to effective rainfall and options supported by current agri-policy include early harvesting and establishment of arable crops in the autumn, establishing cover crops in the autumn and cultivating land for arable crops in the spring rather than the autumn. In addition to ensuring that vegetation cover is better developed at high-risk times, it is also important to manage compacted arable soils both in the inter-wheeling and wheeling portions of fields. In this regard, managing any compaction in over-winter wheelings can be especially important. In addition to maximising vegetation cover and reducing soil compaction, additional interventions can target delivery pathways in, and from, arable fields, including in-field buffer strips, riparian buffer strips, re-siting gateways away from high-risk areas and establishing new hedges. To maximise the benefits of any mitigation, so-called ‘treatment-trains’ can be used, whereby combinations of the measures appropriate for arable land are deployed to target both sediment mobilisation and subsequent delivery towards the river channel.

In the River South Tyne, river bank erosion sediment sources need to be targeted by mitigation measures. Here, in the absence of substantial resources for hard engineering solutions, alternative so-called ‘green’ or ‘green-grey’ measures can be applied. The former are based on the use of vegetation and include encouragement of aquatic vegetation, coir rolls, bank stakes, faggots and brushwood, willow spiling and insertion of coarse woody material adjacent to river banks. In the case of aquatic vegetation, native plants are used to protect the toe of river banks. Coir rolls are typically sausage-shaped coconut fibre rolls installed to protect the river bank. Bank stakes are used to protect the bank toes from scour. Faggots are bundles of untreated brushwood such willow or hazel, bound together by biodegradable fibres. Willow spiling involves the insertion of willow fencing to provide physical protection of the river bank face. Coarse woody material is used to deflect eroding flows away from the river bank and can include complete trees or just the trunks. ‘Green-grey’ measures include, amongst others, vegetated rock rolls, reinforced mattresses, ripraps, gabions or concrete blocks. Rock rolls comprise netting filled with cobbles and established vegetation. These are commonly used to protect the river bank toe. Reinforced mattresses are flexible mats made from natural or synthetic materials which are used to protect the river bank face. Ripraps comprise layers of boulders which are vegetated using live-staking or growth poles. Gabions are wire mesh baskets filled with stone and soil in situ to promote vegetation growth. These can be used to protect just the river bank toe, or stacked up to buffer the entire bank face from erosive flows. Concrete blocks are typically vegetated using grass plugs or the insertion of live cuttings. Where river bank erosion rates are high, the above measures can be applied in combination to help maximise benefits.

5. Conclusions

The method presented allows for a more rapid and inexpensive investigation of sediment sources in large river catchments when compared to conventional sediment source fingerprinting approaches. Much of the work associated with this method could potentially be carried out by catchment managers or non-experts with the hydrogen peroxide treatment being the only part of the method which requires specialist facilities. Unfortunately, this treatment is likely to be essential to ensure that sediment colour and therefore, the interpretation of sediment source contributions, is not affected by the enrichment in organic matter typically observed in deposited sediments.

The method used was able to identify key sediment sources for mitigation in each study catchment. For example, in the River Wye catchment, measures aimed at reducing overbank fine sediment deposits after flooding would best be focused on mitigating sediment losses from sources over the Devonian geology including channel banks, grassland and arable land. Although depending upon the location of the overbank samples being targeted for mitigation with upstream sources contributing more to upstream deposits. Given the higher erosion rates typically expected on arable land, as well as the downstream tendency of more sediment to be contributed from the part of the catchment where arable land is most abundant the preferential targeting of this source is logical. In the River South Tyne measures to reduce channel bank erosion are clearly critical to reducing the fouling of extracted potable water by fine sand as well as harm to biota by fine silt. Comparing the position of the river channel in historical and contemporary maps was able to further refine some critical areas for mitigation based upon the results of the sediment source tracing exercise. Mitigating this source of sediment may be especially important as there is a high potential for sediment eroded from this source to be enriched in heavy metals such as lead and zinc from the mining legacy of the catchment.

The understanding of sediment source evolution at different scales throughout a catchment is also essential for improving current knowledge of geomorphic processes. Given the paucity of data currently available with which to develop this understanding and the significant logistical challenges associated with gaining such data in larger river catchments, the method reported herein could have significant benefits for future catchment-based research. For example, the results of this study have highlighted the significant effects of catchment land use and channel bank erosion on sediment sources.

Credit author statement

Pulley S: Conceptualization, Methodology, Investigation, Writing – original draft, **Collins AL**: Conceptualization, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

We gratefully acknowledge the funding awarded to ALC from Northumbrian Water and the Coal Authority via the Tyne Rivers Trust for the work on the River South Tyne catchment and the UKRI-NERC (UK Research and Innovation-Natural Environment Research Council) Urgency grant award NE/V007262/1 for the work on the River Wye. We also gratefully acknowledge Jack Bloomer and the staff at the Tyne Rivers trust for their help in planning and carrying out the sampling. Rothamsted Research receives strategic funding from UKRI-BBSRC (UK Research and Innovation- Biotechnology and Biological Sciences Research Council) and the production of this paper was supported by the institute strategic programme grant award BBS/E/C/000I0330. The authors thank the landowners in both study catchments.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.117657.

References

Amorim, F.F., da Silva, Y.J.A.B., Nascimento, R.C., da Silva, Y.J.A.B., Tiecher, T., do Nascimento, C.W.A., Minella, J.P.G., Zhang, Y., Upadhayay, H.R., Pulley, S., Collins, A.L., 2021. Sediment source apportionment using optical property composite signatures in a rural catchment, Brazil. Catena 202, 105208. https://doi.org/10.1016/j.catena.2021.105208.

Artz, R., Evans, C., Crosher, I., Hancock, M., Scott-Campbell, M., Pilkington, M., Jones, P., Chandler, D., McBride, A., Ross, K., Weyl, R., 2019. The state of UK peatlands: an update. https://www.iucn-uk-peatlandprogramme.org/sites/default/files/2019-11/COI%20State_of_UK_Peatlands.pdf. (Accessed 15 December 2022) accessed.

Barthod, L.R., Liu, K., Lobb, D.A., Owens, P.N., Martínez-Carreras, N., Koiter, A.J., Petticrew, E.L., McCullough, G.K., Liu, C., Gaspar, L., 2015. Selecting color-based tracers and classifying sediment sources in the assessment of sediment dynamics using sediment source fingerprinting. J. Environ. Qual. 44, 1605–1616. https://doi.org/10.2134/jeq2015.01.0043.

Blake, W.H., Boeckx, P., Stock, B.C., Smith, H.G., Bodé, S., Upadhayay, H.R., Gaspar, L., Goddard, R., Lennard, A.T., Lizaga, I., Lobb, D.A., Owens, P.N., Petticrew, E.L., Kuzyk, Z.Z.A., Gari, B.D., Munishi, L., Mtei, K., Nebiyu, A., Mabit, L., Navas, A., Semmens, B.X., 2018. A deconvolutional Bayesian mixing model approach for river basin sediment source apportionment. Sci. Rep. 8, 13073 https://doi.org/10.1038/s41598-018- 30905-9.

Boardman, J., Vandaele, K., 2020. Managing muddy floods: balancing engineered and alternative approaches. J. Flood Risk Manage. 13, e12578 https://doi.org/10.1111/jfr3.12578.

Boardman, J., Verstraeten, G., Bielders, C., 2006. Muddy floods. In: Boardman, J., Poesen, J. (Eds.), Soil Erosion in Europe. Wiley, Chichester, England, pp. 743–755.

Brookes, R.E., 1974. Sediment and solute transport for rivers entering the Severn estuary. Unpublished PhD thesis, University of Dundee.

Brosinsky, A., Foerster, S., Segl, K., Kaufmann, H., 2014. Spectral fingerprinting: sediment source discrimination and contribution modelling of artificial mixtures based on VNIR-SWIR spectral properties. J. Soils Sediments 14, 1949. https://doi.org/10.1007/s11368-014-0925-1. –1964.

Caitcheon, G.G., 1993. Sediment source tracing using environmental magnetism - a new approach with examples from Australia. Hydrol. Proc. 7, 349–358. https://doi.org/10.1002/hyp.3360070402.

Carter, J. Owens, Walling, D.E., Leeks, G.J.L., 2003. Fingerprinting suspended sediment sources in a large urban river system. Sci. Total Environ. 314–316, 513–534. https://doi.org/10.1016/S0048-9697(03)00071-8.

Collins, A.L., Walling, D.E., 2004. Documenting catchment suspended sediment sources: problems, approaches and prospects. Prog. Phys. Geogr. 28, 159–196. https://doi.org/10.1191/0309133304pp409ra.

Collins, A.L., Walling, D.E., Leeks, G.J.L., 1997. Fingerprinting the origin of fluvial suspended sediment in larger river basins: combining assessment of spatial provenance and source type. Geogr. Ann. 79A, 239–254. https://doi.org/10.1111/j.0435-3676.1997.00020.x.

Collins, A.L., Pulley, S., Foster, I.D.L., Gellis, A., Porto, P., Horowitz, A.J., 2017. Sediment source fingerprinting as an aid to catchment management: a review of the current state of knowledge and a methodological decision-tree for end-users. J. Environ. Manag. 194, 86–108. https://doi.org/10.1016/j.jenvman.2016.09.075.

Collins, A.L., Blackwell, M., Boeckx, P., Chivers, C.A., Emelko, M., Evrard, O., Foster, I., Gellis, A., Gholami, H., Granger, S., Harris, P., Horowitz, A.J., Laceby, J.P., Martinez-Carreras, N., Minella, J., Mol, L., Nosrati, K., Pulley, S., Silins, U., da Silva, Y.J., Stone, M., Tiecher, T., Upadhayay, H.R., Zhang, Y., 2020. Sediment source fingerprinting: benchmarking recent outputs, remaining challenges and emerging themes. J. Soils Sediments 20, 4160–4193. https://doi.org/10.1007/s11368-020-02755-4.

Dargahi, B., 2012. Reservoir sedimentation. In: Bengtsson, L., Herschy, R.W., Fairbridge, R.W. (Eds.), Encyclopedia of Lakes and Reservoirs. Encyclopedia of Earth Sciences Series. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-4410-6_215.

Environment Agency, 2017. Working with Natural Processes – the evidence behind natural flood management. In: https://www.gov.uk/government/publications/working-with-natural-processes-to-reduce-flood-risk. (Accessed 15 December 2022) accessed.

Evrard, O., Durand, R., Foucher, A., Tiecher, T., Sellier, V., Onda, Y., Lefevre, I., Cerdan, O., Laceby, J.P., 2019. Using spectrocolourimetry to trace sediment source dynamics in coastal catchments draining the main Fukushima radioactive pollution plume (2011-2017). J. Soils Sediments 19, 3290–3301. https://doi.org/10.1007/s11368-019-02302-w.

García-Comendador, J., Martínez-Carreras, N., Fortesa, J., Borràs, A., Calsamiglia, A., Estrany, J., 2020. Analysis of post-fire suspended sediment sources by using colour parameters. Geoderma 379, 114638. https://doi.org/10.1016/j.geoderma.2020.114638.

Hardy, F., Bariteau, L., Lorrain, S., Thériault, I., Gagnon, G., Messier, D., Rougerie, J.-F., 2010. Geochemical tracing and spatial evolution of the sediment bed load of the Romaine River, Québec, Canada. Catena 81 (1), 66–76. https://doi.org/10.1016/j.catena.2010.01.005.

Kemp, P., Sear, D., Collins, A., Naden, P., Jones, I., 2011. The impacts of fine sediment on riverine fish. Hydrol. Process. 25, 1800–1821. https://doi.org/10.1002/hyp.7940.

Krein, A., Petticrew, E., Udelhoven, T., 2003. The use of fine sediment fractal dimensions and colour to determine sediment sources in a small watershed. Catena 53, 165–179. https://doi.org/10.1016/S0341-8162(03)00021-3.

Laceby, J.P., Evrard, O., Smith, H.G., Blake, W.H., Olley, J.M., Minella, J.P.G., Owens, P.N., 2017. The challenges and opportunities of addressing particle size effects in sediment source fingerprinting: a review. Earth Sci. Rev. 169, 85–103. https://doi.org/10.1016/j.earscirev.2017.04.009.

Lal, R., Stewart, B.A., 2013. Principles of Sustainable Soil Management in Agroecosystems. CRC Press, USA.

Lambert, C.P., Walling, D.E., 1987. Floodplain sedimentation: a preliminary investigation of contemporary deposition within the lower reaches of the River Culm, Devon, UK. Geogr. Ann. 69A, 393–404. https://doi.org/10.1080/04353676.1987.11880227.

Lambert, C.P., Walling, D.E., 1988. Measurement of channel storage of suspended sediment in a gravel-bed river. Catena 15 (1), 65–80. https://doi.org/10.1016/0341-8162(88)90017-3.

Li, P., Tian, R., Xue, C., Wu, J., 2017. Progress, opportunities and key fields for groundwater quality research under the impacts of human activities in China with a special focus on western China. Environ. Sci. Pollut. Res. 24 (15), 13224–13234. https://doi.org/10.1007/s11356-017-8753-7.

Martinez-Carreras, N., Krein, A., Gallart, F., Iffly, J.F., Pfister, L., Hoffmann, L., Owens, P.N., 2010. Assessment of different colour parameters for discriminating potential suspended sediment sources and provenance: a multi-scale study in Luxembourg. Geomorphology 118, 118–129. https://doi.org/10.1016/j.geomorph.2009.12.013.

Ottesen, R.T., Bogen, J., Bølviken, B., Volden, T., 1989. Overbank sediment: a representative sample medium for regional geochemical mapping. J. Geochem. Explor. 32 (1–3), 257–277. https://doi.org/10.1016/0375-6742(89)90061-7.

Owens, P.N., Walling, D.E., 2002. The phosphorus content of fluvial sediment in rural and industrialized river basins. Water Res. 36, 685–701. https://doi.org/10.1016/S0043-1354(01)00247-0.

Owens, P.N., Petticrew, E.L., van der Perk, M., 2010. Sediment response to catchment disturbances. J. Soils Sediments 10, 591–596. https://doi.org/10.1007/s11368-010-0235-1.

Pulley, S., Collins, A.L., 2019. Field-scale determination of controls on runoff and fine sediment generation from lowland livestock grazing land. J. Environ. Manag. 249, 109365 https://doi.org/10.1016/j.jenvman.2019.109365.

Pulley, S., Collins, A.L., 2021. The potential for colour to provide a robust alternative to high-cost sediment source fingerprinting: assessment using eight catchments in England. Sci. Total Environ. 792, 148416 https://doi.org/10.1016/j.scitotenv.2021.148416.

Pulley, S., Collins, A.L., 2022. A rapid and inexpensive colour-based sediment tracing method incorporating hydrogen peroxide sample treatment as an alternative to quantitative source fingerprinting for catchment management. J. Environ. Manag. 311, 114780 https://doi.org/10.1016/j.jenvman.2022.114780.

Pulley, S., Rowntree, K., 2016. The use of an ordinary colour scanner to fingerprint sediment sources in the South African Karoo. J. Environ. Manag. 165, 253–262. https://doi.org/10.1016/j.jenvman.2015.09.037.

Pulley, S., Van Der Waal, B., Collins, A.L., Rowntree, K., 2018. Sediment colour as an inexpensive tracer to identify the sources of historically deposited flood bench sediment in the Transkei, South Africa. Catena 160, 242–251. https://doi.org/10.1016/j.catena.2017.09.018.

Pyle, G.G., Rajotte, J.W., Couture, P., 2005. Effects of industrial metals on wild fish populations along a metal contamination gradient. Ecotoxicol. Environ. Saf. 61, 287–312. https://doi.org/10.1016/j.ecoenv.2004.09.003.

Ramon, R., Evrard, O., Laceby, J.P., Caner, L., , Alberto Inda de Barros, C.A.P. Minella, J.P.G., Tiecher, T., 2020. Combining spectroscopy and magnetism with geochemical tracers to improve the discrimination of sediment sources in a homogeneous subtropical catchment. Catena 3535, 104800. https://doi.org/10.1016/j.catena.2020.104800.

Slattery, M.C., Burt, T.P., Walden, J., 1995. The Application of Mineral Magnetic Measurements to Quantify Within-Storm Variations in Suspended Sediment Sources. IAHS Press, Wallingford, p. 143e151. IAHS Publ. No. 229.

Stopps, J.P., 2018. Provenance and Transfer of Fine Sediment in the Lugg Catchment. PhD thesis, University of Gloucestershire, UK. Herefordshire, UK.

Vale, S.S., Fuller, I.C., Procter, J.N., Basher, L.R., Smith, I.E., 2016. Application of a confluence-based sediment-fingerprinting approach to a dynamic sedimentary catchment, New Zealand. Hydrol. Process. 30, 812–829. https://doi.org/10.1002/hyp.10611.

Viscarra Rossel, R.A., Minasny, B., Roudier, P., McBratney, A.B., 2006. Colour space models for soil science. Geoderma 133, 320–337. https://doi.org/10.1016/j.geoderma.2005.07.017.

Vorosmarty, C.J., Sahagian, D., 2000. Anthropogenic disturbance of the terrestrial water cycle. Bioscience 50, 753–765. https://doi.org/10.1641/0006-3568(2000)050[0753:ADOTTW]2.0.CO, 2.

Wainwright, J., Parsons, A.J., Cooper, J.R., Gao, P., Gillies, J.A., Mao, L., Orford, J.D., Knight, P.G., 2015. The concept of transport capacity in geomorphology. Rev. Geophys. 53, 1155–1202. https://doi.org/10.1002/2014RG000474.

Walling, D.E., Collins, A.L., 2008. The catchment sediment budget as a management tool. Environ. Sci. Pol. 11 (2), 136–143. https://doi.org/10.1016/j.envsci.2007.10.004.

Walling, D.E., Owens, P.N., 2003. The role of overbank floodplain sedimentation in catchment contaminant budgets. In: Kronvang, B. (Ed.), The Interactions between Sediments and Water. Developments in Hydrobiology 169. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-3366-3_13.

Walling, D.E., Webb, B.W., Shanahan, J., 2008. Investigations into the Use of Critical Sediment Yields for Assessing and Managing Fine Sediment Inputs into Freshwater Ecosystems. Natural England Research Report NERR007. Natural England, Sheffield.

Wood, P.J., Armitage, P.D., 1997. Biological effects of fine sediment in the lotic environment. Environ. Manag. 21, 203–217. https://doi.org/10.1007/s002679900019.

Xu, Z., Belmont, P., Brahney, J., Gellis, A.C., 2022. Sediment source fingerprinting as an aid to large-scale landscape conservation and restoration: a review for the Mississippi River Basin. J. Environ. Manag. 324, 116260 https://doi.org/10.1016/j.jenvman.2022.116260.