Sources of fine-grained sediment in the River Chess and potential options for mitigation of the sediment problem

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Executive Summary

The Chilterns Conservation Board and River Chess Association, as part of the Smarter Water Catchment initiative funded by Thames Water, have been working to identify sources of pollution degrading the River Chess and undertake appropriate mitigation options. However, little information is available on the sources and quantities of fine-grained sediment which may be causing a reduction in ecological status. Accordingly, this project was commissioned to trace the sources of fine-grained sediment retrieved from the river. Samples of suspended sediment were collected between June 2022 and May 2023 and samples of sediment deposited on the channel bed were collected in August 2022 and February 2023. 117 samples of potential sediment sources comprising channel banks, urban road dusts, rural road verges, and woodland, grassland and cultivated topsoils were also retrieved. All samples were sieved to <25 μm and treated using hydrogen peroxide to remove sediment-associated organic matter. The colour (red and blue) of the source and sediment samples was measured inexpensively using an office document scanner and open-source image editing software using a recently developed innovative tracing method. Sediment source was interpreted visually using scatter plots of sediment and source samples. It was found that both suspended and bed sediment originated almost entirely from channel bank erosion but with a moderate contribution of sediment from urban road dusts in the most upstream reaches of the river close to Chesham. There was no indication of any significant sediment inputs from topsoil sources, nor a change in sediment source during different flow conditions. Suspended sediment yield was estimated at six sites along the River Chess using monitored flow combined with suspended sediment concentration. Yields ranged from 0.15 - 1.16 t km^2 yr^{-1}. The suspended sediment yield at Latimer Park was higher at 5.90 t km^2 yr^{-1}; however, the accuracy of this estimate is questionable due to an extremely noisy dataset caused by fouling of the sensor. These yields are all considerably lower than the 44 t km^2 yr^{-1} average for a UK catchment, but are typical of those measured in other chalk streams. Low stream density and a lack of sediment transport pathways within the catchment are likely the main cause of the absence of topsoil inputs and the low suspended sediment yield. Despite the low suspended sediment yield of the Chess, annually 70 tonnes of suspended sediment were found to be transported through it at the Elms Lake site. Therefore, for cultivated topsoils to even contribute 5% of this suspended sediment yield, would require 3.5 tonnes of sediment to be delivered to the river via roads annually given the lack of other

transport pathways, which is an implausibly large amount and would require extremely high soil erosion rates from the areas of agricultural land draining onto roads.

Whilst channel banks are the dominant source of fine-grained sediment, they are low in height, which combined with a lack of flashy high flows in the river, likely suggests bank erosion rates are likely to be low. However, targeted work to reduce cattle poaching may deliver some benefits since cattle were observed to enter the stream to drink in some locations. In addition to excess sediment inputs and/or retention, any sediment-related pressures within the Chess are likely due to the highly organic nature of the sediment which will have a high oxygen demand and cause the degradation of ecologically important benthic habitats when it accumulates within them. This would most likely manifest itself in terms of sub-lethal impacts on aquatic organisms. In freshet catchments, this sediment would be remobilised and flushed away during high flow events. However, in the River Chess with its groundwater-driven flow regime, which is modified by in-line ponds, such flows are rare and therefore the low amounts of sediment entering the river are not remobilised effectively and transported downstream.

Non-Technical Summary

The Chilterns Chalk Streams Project has been working to identify sources of pollution degrading the River Chess and undertake appropriate mitigation options to reduce it. However, little information is available on the sources and quantities of fine-grained sediment which may be harming water quality and ecology. Fine sediment acts as a pollutant by smothering critical channel bed habitats as well as by transporting other pollutants such as nutrients in association with it.

Accordingly, this project was commissioned to assess the sources of sediment retrieved from the river by the Chilterns Chalk Streams Project. Samples of sediment in the water column which is actively being transported through the river were collected monthly between June 2022 and May 2023. Samples of sediment deposited on the channel bed gravels were collected in August 2022 and February 2023. The colour of the sediment was compared to its potential sources within the river catchment to confirm key sources.

The colour (red and blue) of the sediment was measured using an office document scanner and open-source image editing software. Colour was selected as the property to confirm sediment sources as it remains stable during transport and sediment sources typically produce different coloured sediments. Sediment source was interpreted visually using scatter plots of sediment and source samples. It was found that both sediment in the water column and on the river bed originated almost entirely from channel bank erosion but there was a moderate (<50%) contribution of sediment from urban road dusts in the most upstream reaches of the river close to Chesham. There was no indication of any significant sediment inputs from agricultural topsoils, nor a change in sediment source during different flow conditions. The same sediment source result for the channel bed and suspended sediment suggests that much of the suspended sediment in the river has originated from the remobilisation of sediment deposits on the channel bed.

Suspended sediment yield is typically expressed as the mass of sediment contributed from a square kilometre of a river catchment per year. For UK rivers, an average yield of 44 t km^2 yr^{-1} has been reported previously. In the River Chess, suspended sediment yield was measured at six sites using flow data from Environment Agency monitoring multiplied by the concentration of sediment in the water. Measured suspended sediment yields ranged from 0.15 - 1.16 t km^2 yr^{-1}. The suspended sediment yield at Latimer Park was higher at 5.90 t km^2 yr^{-1};

however, the accuracy of this measurement is questionable due to a large amount of noise associated with the fouling of the turbidity sensor as well as a short monitoring period. These yields are low for a UK catchment and also low compared to those reported for other chalk streams (e.g., 1.4 to 12.5 t km^{-2} yr^{-1} in the Hampshire Avon which is largely, but not wholly, draining chalk).

A low density of stream channels means that little agricultural land at risk from erosion is adjacent to a water course. Additionally, agricultural fields are often separated from the river by areas of low-erosion risk semi-natural land presenting a further barrier to sediment delivery. Whilst some sediment runoff has been observed to take place along roads, the small amount of land connected to the catchment in this way cannot yield a large enough amount of sediment to be detected in the river when compared to the much larger quantities originating from channel banks.

Whilst channel banks are the dominant source of sediment, they are low in height, which combined with a lack of flashy high flows in the river suggests bank erosion rates are likely to be low. However, remedial work to reduce the trampling of banks by cattle may deliver some benefit. Rather than being related to excess sediment inputs, any sediment related pressures within the Chess are likely due to the highly organic nature of the sediment, which will have a high oxygen demand and cause harm to channel bed habitats when it accumulates within them. In catchments with flow dominated by surface runoff, this sediment would be remobilised and flushed away during high flow events. However, in the groundwater-fed River Chess, such flows are rare and therefore the low amounts of sediment entering the river are not remobilised effectively and transported downstream.

1. Background

This report presents the results of an investigation into the sources of fine-grained sediment degrading the River Chess, which is a partly urbanised river flowing through Buckinghamshire and Hertfordshire, UK. The River Chess is a vulnerable chalk stream habitat which has been classified as having only moderate ecological status due to a variety of causes including physical modifications to the river, high phosphate concentrations from sewage effluent discharges, and riparian and instream activities causing bank erosion (Environment Agency, 2021). Driven by a need to improve the status of this waterbody, the Chilterns Chalk Streams Project run by the Chilterns Conservation Board and funded by the Thames Water Smarter Water Catchment initiative have been working to identify key sources of pollution degrading the river for helping select and target appropriate mitigation options. Planned improvements by Thames Water to increase the capacity of the sewage treatment works and reduce phosphorus concentrations in treated effluent from 2 mg l^{-1} to 0.25 mg l^{-1} will reduce pollution from this specific source. However, diffuse sediment and nutrient losses from agriculture, channel banks and urban areas remain potential causes of water quality degradation. At present, little information on the sources of fine-grained sediment for the River Chess is available to guide the selection and targeting of mitigation efforts. Although monitoring by citizen scientists and erosion risk mapping have both identified possible soil erosion hotspots and muddy flows during storm events, both approaches have known limitations. These include drastically over predicted rates and extents of soil erosion by models (Evans and Brazier 2005; Bircher et al. 2022), and difficulties in observing diffuse sediment losses from sheet wash and channel bank erosion. Therefore, this study applies a novel sediment source tracing method developed by the authors at Rothamsted Research, which uses sediment colour, to rapidly and accurately identify the dominant sources of the fine-grained sediment degrading the River Chess.

Walling and Collins (2005) and Walling et al. (2008) used sediment source fingerprinting data available at the time, and based on what are now old methodologies, to identify that typically 85-95% of fine-grained sediment entering UK rivers is contributed from surface sources, most of which is from cultivated land. However, the methods underpinning those source data are now outdated due to factors such as a lack of source apportionment validation using virtual sample mixtures and the analysis of a broad (typically <63 µm) particle size range, and more recent work has illustrated that the dominant sediment sources can vary substantially between individual UK catchments. Therefore, assuming that agricultural topsoils are the dominant source of sediment contributing to a given river carries risks, including those for selecting and targeting the most appropriate mitigation measures. This could potentially result in a mismatch between the expected and actual outcomes of catchment management if agricultural topsoils are not an important source of fine-grained sediment. For example, in the Nene River basin, UK, channel banks were determined to be the dominant source of sediment (Pulley and Foster, 2017) and in Ettrick Water, channel banks contributed approximately half of the sediment load (Owens et al. 2000). A similarly high contribution from banks was also found in Worm Brook (Walling et al. 2008). In the Hafren catchment, commercial forestry was found to contribute 78% of sediment (Collins et al. 1997a,b) and in the upper Severn, it contributed just under half of the sediment load (Collins et al 1997a,b). In the Jubilee and Belmont catchments, approximately half of their sediment loads were contributed from subsurface drains (Russel et al. 2001). In catchments such as the Barle, Batherm and Dart (Russel et al. 2001) as well as the Rhiw (Collins et al. 1997a,b) and Wharf (Walling et al. 1999), grassland sources dominated sediment inputs. Therefore, site-specific sediment provenance information is essential to ensure improved cost-benefit is derived from targeted catchment management.

Sediment fingerprinting is a widely used method for the identification of sediment sources which can be performed over a large range of spatial scales and flow conditions (Klages and Hsieh 1975; Collins et al. 1997a; Owens et al. 2016). It is founded on comparing the properties of a sample of sediment retrieved from a river to samples of its potential sources. Sources are typically classified by land use categories such as cultivated land, grassland, woodland, and channel banks, although classification can also be based upon other attributes such as geology (Collins et al. 1998). Source fingerprinting has the advantage of far smaller resource requirements than the direct measurement of sediment losses from a spatially extensive range of catchment sources (Collins and Walling, 2004). The fingerprinting approach has been used internationally to address a wide range of catchment management goals (e.g., Collins et al. 2001; Collins et al. 2010b; Douglas et al. 2010). For example, the Catchment Sensitive Farming evidence prospectus (Collins 2015; Environment Agency, 2017) describes sediment fingerprinting as a method which has been used by officers (carried out by contractors) as a diagnostic tool to apportion in-river sediment to key sources. It has also been used to show changes in sediment sources after catchment management intervention work, including channel bank fencing schemes (e.g., Collins et al. 2010a).

As part of a large research project conducted for Catchment Senstive Farming (CSF) between 2017 and 2020, the authors of this work traced the sources of fine-grained sediment in nine priority catchments in England and Wales. The work found that fine-grained (<25 μm) sediment sources did not change significantly when comparing periods of low flow to the extreme wet weather during the winter of 2019-2020, meaning that if mitigation options are targetted appropriately, future resistance to an increasing frequency of extreme wet weather associated with climate change is likely to be provided through targeted catchment management interventions (Pulley and Collins, 2021a). However, in other rivers, changes in sediment source have been observed with spot sampling during different flow conditions such as in the River Ouse by Walling et al. (1999) and River Aire by Carter et al. (2003). Therefore, further catchment-specific investigations into changing sediment sources with flow condition are required.

It was also found by Pulley and Collins (2021b) that sediment colour showed significant potential to be an alternative, inexpensive and effective way to trace sediment sources. In all but two of the nine catchments studied, colour was able to identify the dominant sources of sediment contributing to streams almost as well as a high cost conventional sediment source fingerprinting exercise using multiple different tracer types (e.g., radionuclides, geochemistry). In the two catchments where sediment colour was not found to be an effective tracer, this was attributed to a combination of poor source discrimination and the possible alteration of sediment through organic matter enrichment during its mobilisation and delivery. One potential way to overcome these problems is the treatment of samples using hydrogen peroxide to remove organic matter, which may also increase source discrimination based upon catchment geology or soil type (Pulley and Collins, 2022). In two recent studies on the River Avon at Patney and in Wath Beck / Holbeck, the use of hydrogen peroxide significantly improved the refinement of critical sediment source areas when compared to the use of untreated colour alone (Pulley and Collins, 2022). Based upon these recent lessons and developments, we use sediment colour combined with hydrogen peroxide treatment, to identify the dominant sources of sediment degrading the River Chess. This approach has advantages over alternatives as it does not require the classification of source groups *a priori*, which may limit the potential refinement of critical sediment source areas. Colour also represents the bulk mineral properties of the sediment and is therefore difficult to alter during delivery within stream (García-Comendador et al. 2023), and the hydrogen peroxide sample treatment mitigates the problem of within-stream enrichment of sediment-associated organic matter.

2. Study catchment

The River Chess is a chalk stream with flow naturally dominated by groundwater inputs; however, much of its flow is currently contributed by water released from sewage effluent discharges. Due to groundwater-dominated flow regimes, chalk streams are often affected by excessive channel bed sedimentation as flashy high flows able to mobilise bed sediment are infrequent (Heyward and Walling, 2003). Within the River Chess, a series of ponds along its length also act to reduce the intensity of high flows which may also exacerbate this problem. Suspended sediment yields of chalk streams are typically low, with measured values of 1.4 to 12.5 t km^{-2} yr^{-1} found in the Hampshire Avon (Heyward and Walling, 2003) and 9 to 12 t km^{-2} yr^{-1} in the River Piddle Dorset (Walling and Amos, 1999) compared to a mean yield of 44 t km^{-2} yr^{-1} in all UK catchments (Walling et al. 2008).

The River Chess catchment has an area of 96.6 km^2, a mean slope of 3.88° and land use is 12% urban, 36% arable/horticulture, 34% grassland and 18% woodland (Figures 1-3). The catchment is underlain by an extensive unconfined chalk aquifer with deposits of alluvium and terrace gravels adjacent to river channels (Figure 4). Soils are freely draining slightly acid but base-rich becoming lime-rich and loamy in a downstream direction. River channels are only present in the middle – lower catchment with dry valleys present in the extensive area of upper catchment, upstream of Chesham. It is currently unclear if sediment is transported through these dry valleys to a watercourse. Streams in the lower catchment are generally bordered by flat alluvial deposits which form a barrier between agricultural land and the river channels. However, in some locations, grassland fields are adjacent to river channels and livestock can be observed to be poaching banks. Sediment flows from arable fields to river channels have also been observed along roads by citizen scientists in the Mudspotter project run by the Chess Smarter Water Catchment project. The extensive rural road network in the catchment and widespread damaged road verges also represent potential sources of fine-grained sediment. The towns of Chesham and part of Amersham are in the upper catchment and the river enters Rickmansworth in the lower catchment. The impermeable urban surfaces and high connectivity through storm drains creates the potential for polluted urban road dusts to enter the river.

Figure 1: Arable fields overlooking the Chess Valley in the middle catchment.

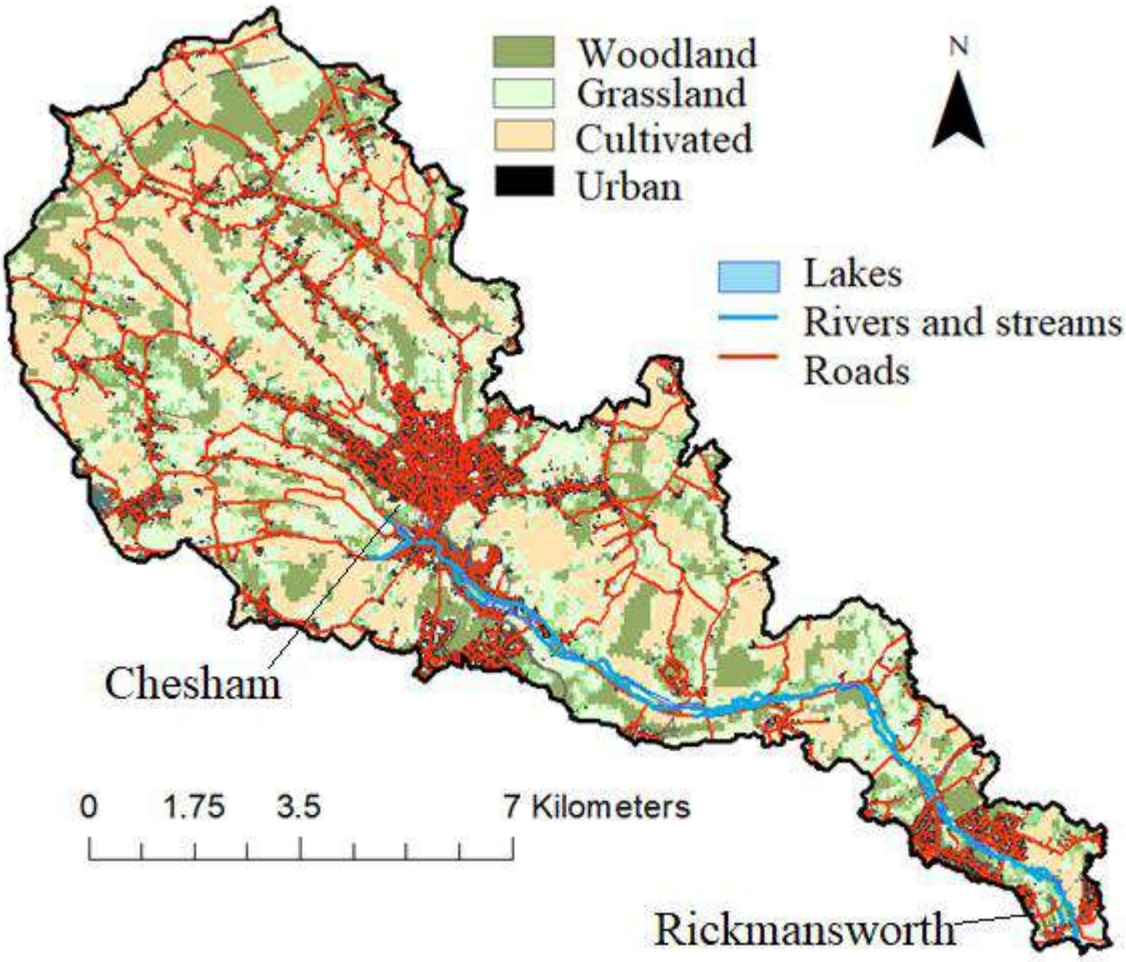


Figure 2: Land use in the River Chess catchment.

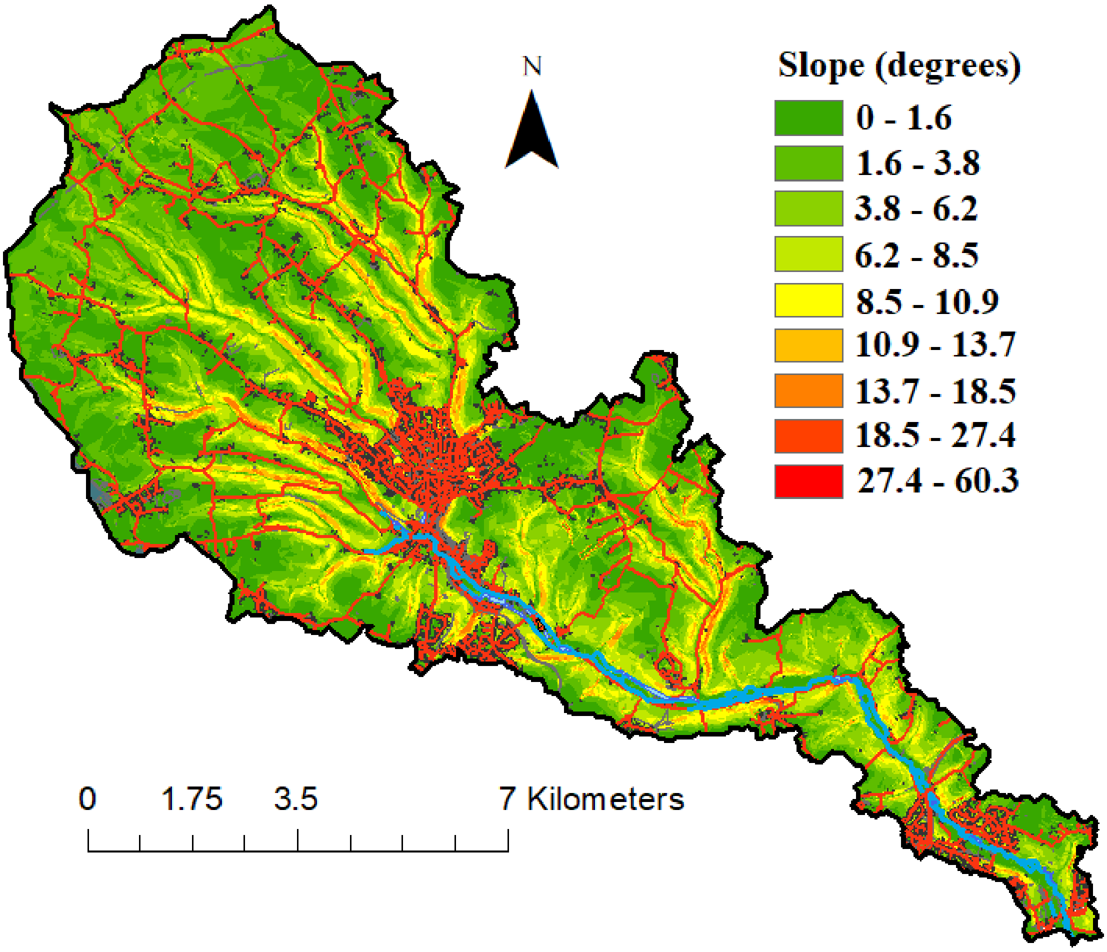


Figure 3: Slope in the River Chess catchment.

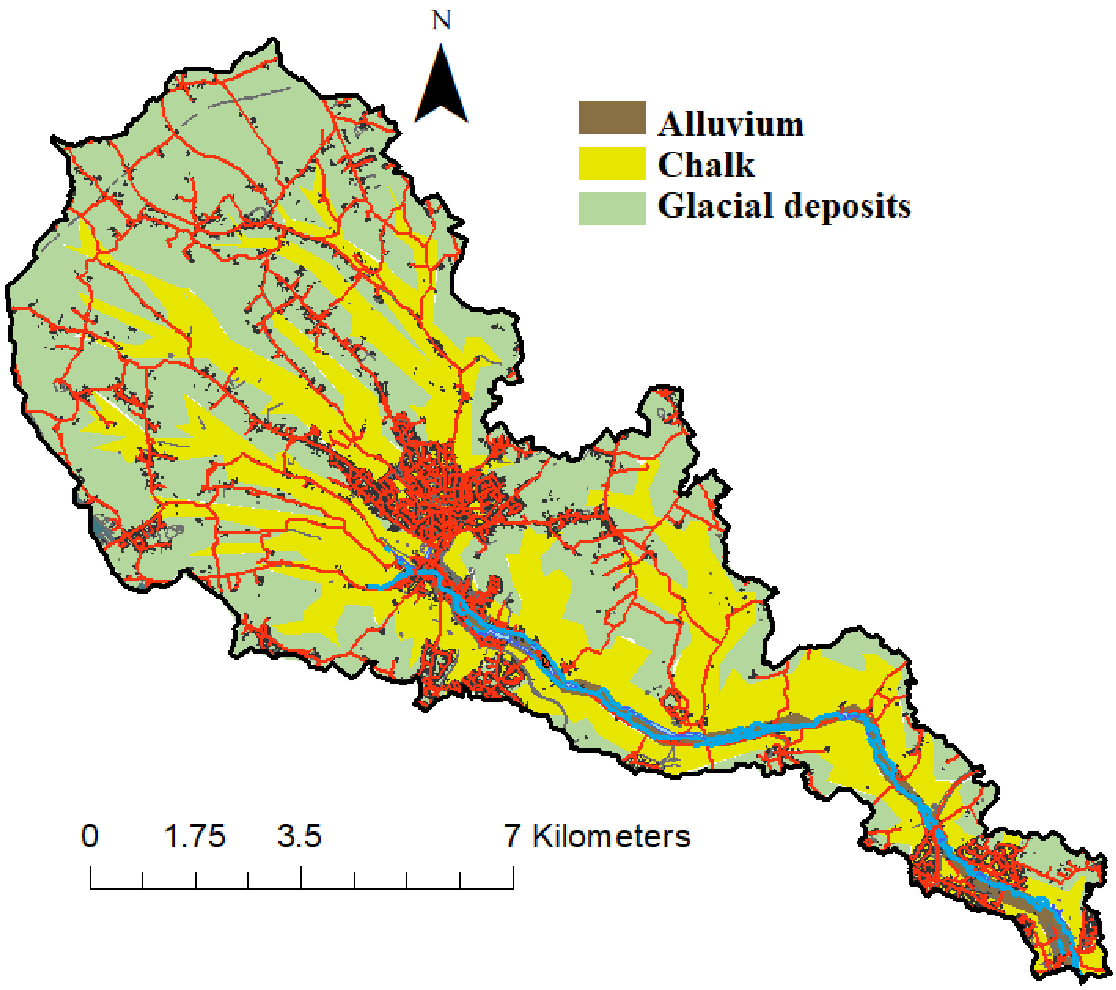


Figure 4: Geology of the River Chess catchment.

Flows during the sampling period were characterised by a drop in river levels during summer months and a rise during the winter (Figure 5). However, small peaks in flow associated with rainfall events can be observed during all flow conditions. The largest peaks occurred during January, April and May 2023 which correspond to peaks in groundwater levels. Flow during the 2022-2023 study period were not a-typical of that found in recent years, although were lower than those found in many years and are especially lower than those occurring pre-1990 and in years with more extreme rainfall such as the winter of 2019 – 2020 which has been noted to be the 5th wettest recorded in the UK (Figure 6).

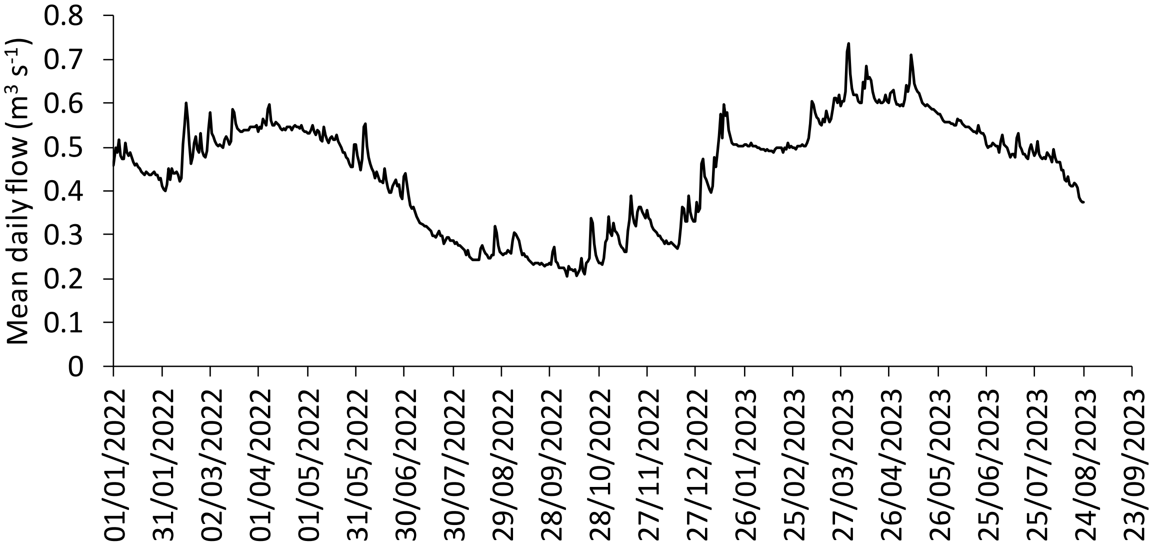


Figure 5: Mean daily flow from January 2022 to September 2023 from Environment Agency Flow Station 39088 at Rickmansworth. Contains Environment Agency information. All data is available under the Open Government Licence v3.0. © Crown Copyright 2024.

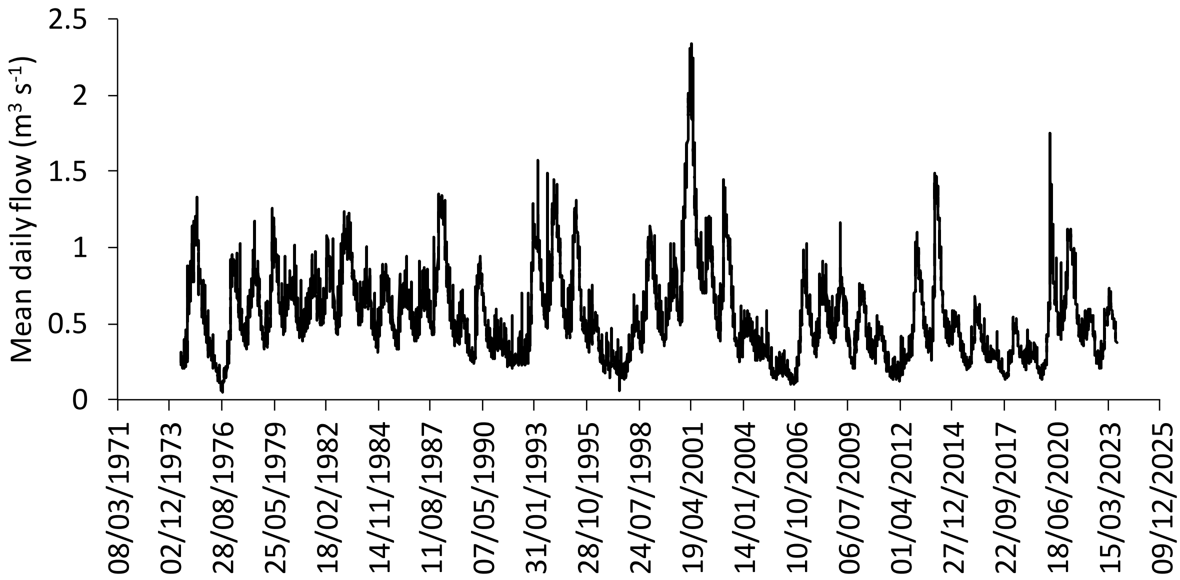


Figure 6: Long-term time series of mean daily flow data from Environment Agency Flow Station 39088 at Rickmansworth. Contains Environment Agency information. All data is available under the Open Government Licence v3.0. © Crown Copyright 2024.

3. Methods

The River Chess represents a challenging catchment for sediment source tracing which requires a suitably robust methodology. The first challenge is the large number of potential sediment sources. The catchment geology is a combination of superficial deposits and chalk. If classifying sediment sources by land use then many tracer properties may be different between the same land use over different geologies. Therefore, source groups in the catchment could be classified as: chalk arable, chalk grassland, superficial geology arable, superficial geology grassland, road verges, woodland, urban runoff and riverbank erosion. Due to mathematical equifinality (Rowan et al. 2000), however, an unmixing model, normally applied in a conventional quantitative source tracing procedure, is unlikely to deliver reliable apportionment with more than 3-4 sources necessitating their combination and a loss of spatial resolution.

The second challenge is that the River Chess is heavily modified with widened sections forming ponds. Due to disrupted flow conditions, sediment will likely accumulate on channel beds where it may be altered under anoxic reducing conditions and it may become enriched in organic matter or be chemically altered. In addition, soluble pollutants from sewage treatment will associate with the sequestered sediment. The presence of areas of slower flow along the river channel where it has been widened, this raises the potential for coarser sediment particles to be deposited into ponds and for the finest particles to be transported downstream. These processes will affect the tracer properties of the sediment so that they no longer reflect those of the key contributing sources.

As a result of these challenges, the colour-based tracing method is used which fractionates sediment and sources samples to <25 µm to standardise particle size, uses hydrogen peroxide to remove organic matter, uses colour which is less susceptible to within-stream alteration than most other tracer types, and uses a qualitative source apportionment approach not dependent upon *a priori* source group classification.

3.1. Sediment and source sampling

To retrieve representative samples of suspended sediment, time-integrating traps based upon the design of Phillips et al. (2000) were installed by the Chilterns Chalk Streams Project at 9 locations along the stream's length (Figure 7). Each trap consisted of a 1000 mm length of 110 mm diameter plastic soil pipe which was sealed at both ends with a 4 mm diameter hole drilled into each to allow flow to enter/exit the trap. The traps were emptied monthly between June 2022 and May 2023. At the Elms Lake site, the trap was positioned downstream of the River Chess entry point to the lake and before the confluence with the Colne/Gade, although two additional traps at upstream locations were sampled from January 2023 onwards.

The largest mass of sediment retrieved at any site was from the Little Chess at Bois Mill and on the Main Chess at the Loudwater estate, and the individual sampling period with the most sediment trapped was August 2022 (Figure 8). Samples of sediment deposited on the channel bed were retrieved as grab samples from the suspended sediment sampling sites in August 2022 and February 2023.

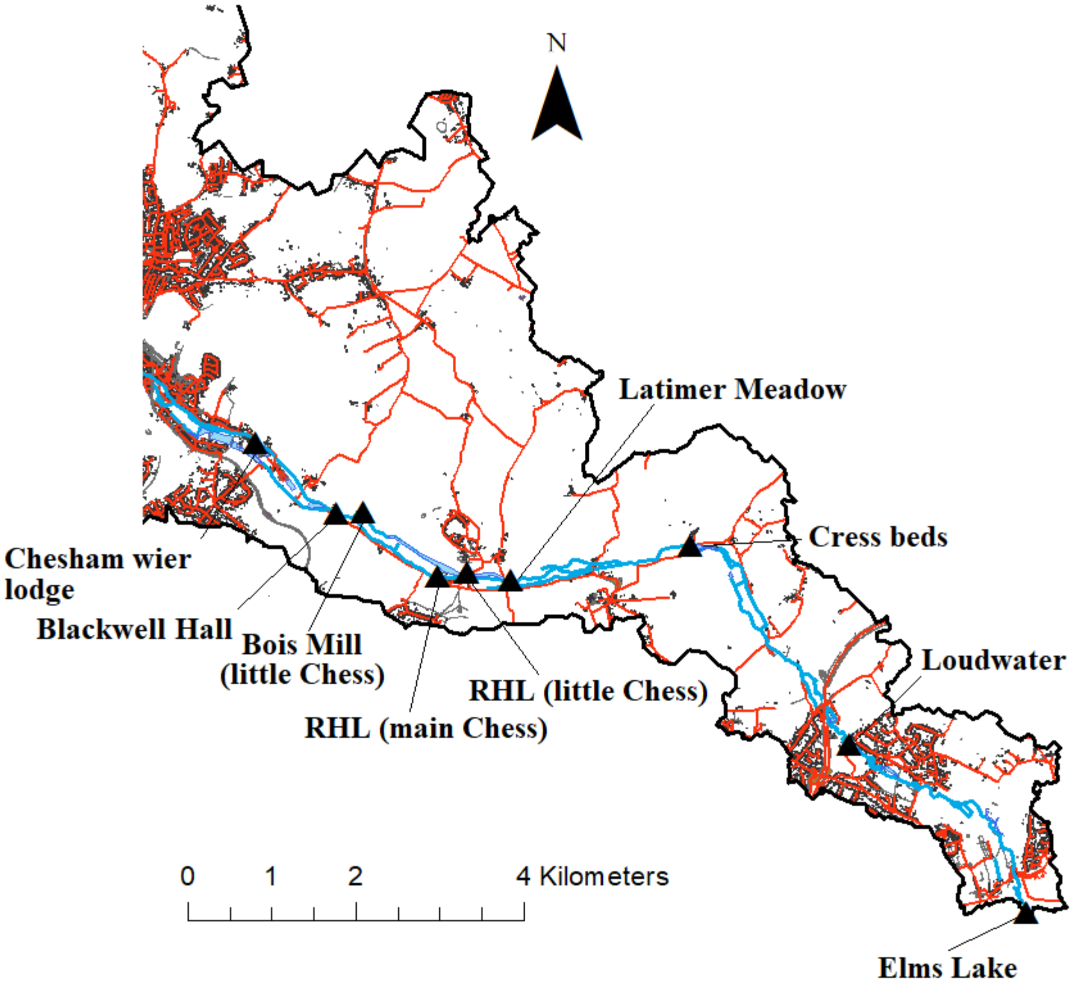
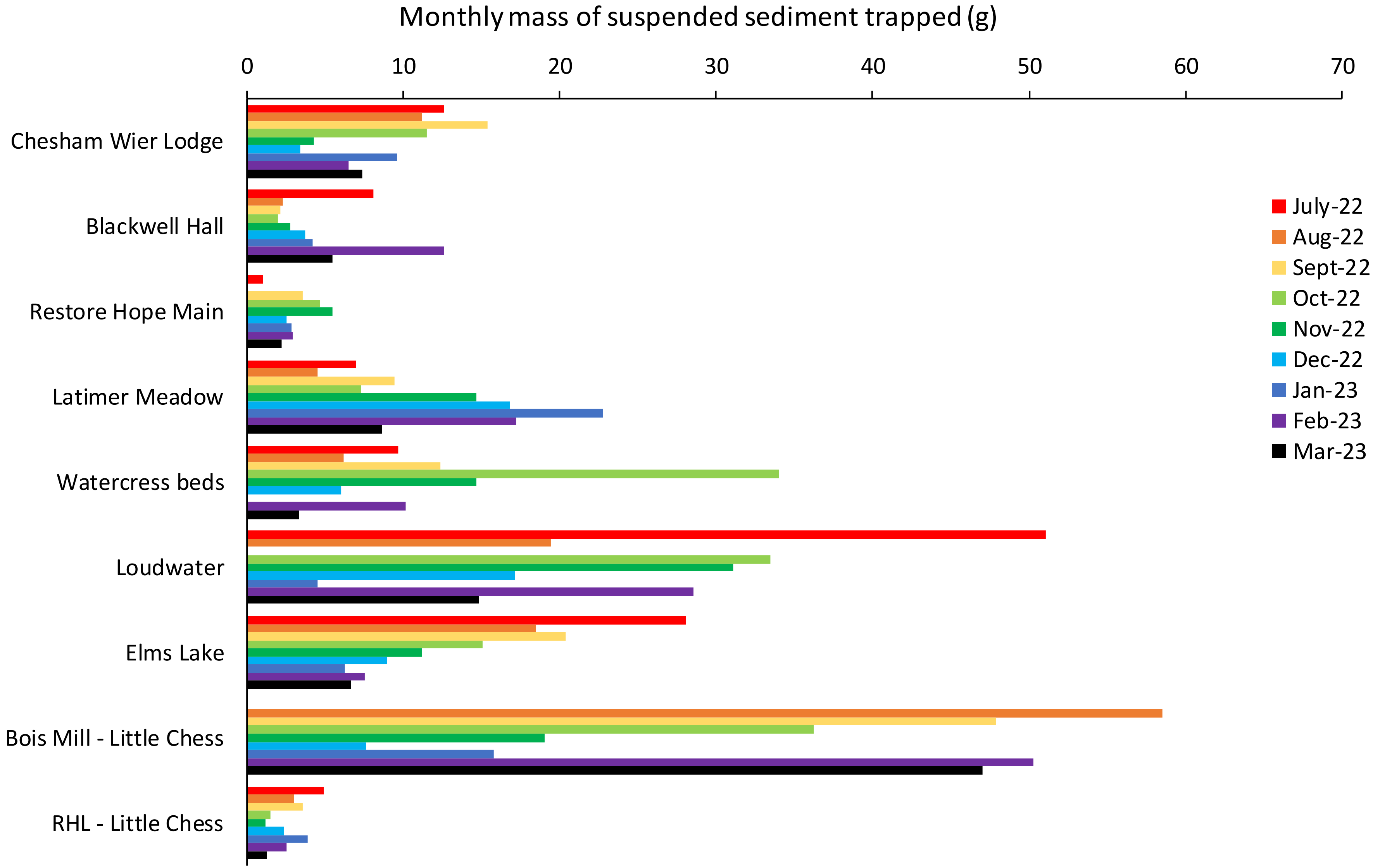


Figure 7: Sediment sampling locations along the River Chess.

Figure 8: Mass of sediment retrieved in the time-integrating suspended sediment traps each month from July 2022 to March 2023.



117 samples were retrieved from potential sediment sources, comprising all major land uses as well as channel banks, with the aim to sample all parts of the study catchment and all major geologies representatively (Figure 9; Table 1). Samples of cultivated, woodland and grassland topsoils were collected from the top 2 cm of the soil profile using a steel knife, as this is the depth to which erosion processes are expected to operate in the UK (Evans et al. 2016). Channel bank samples were collected from the bottom two-thirds of unvegetated banks which could be subject to fluvial erosion to avoid contamination from surface material and ensure maximum source discrimination. Road verge and urban samples were retrieved by scooping up lose material deposited on rural and urban roads by hand.

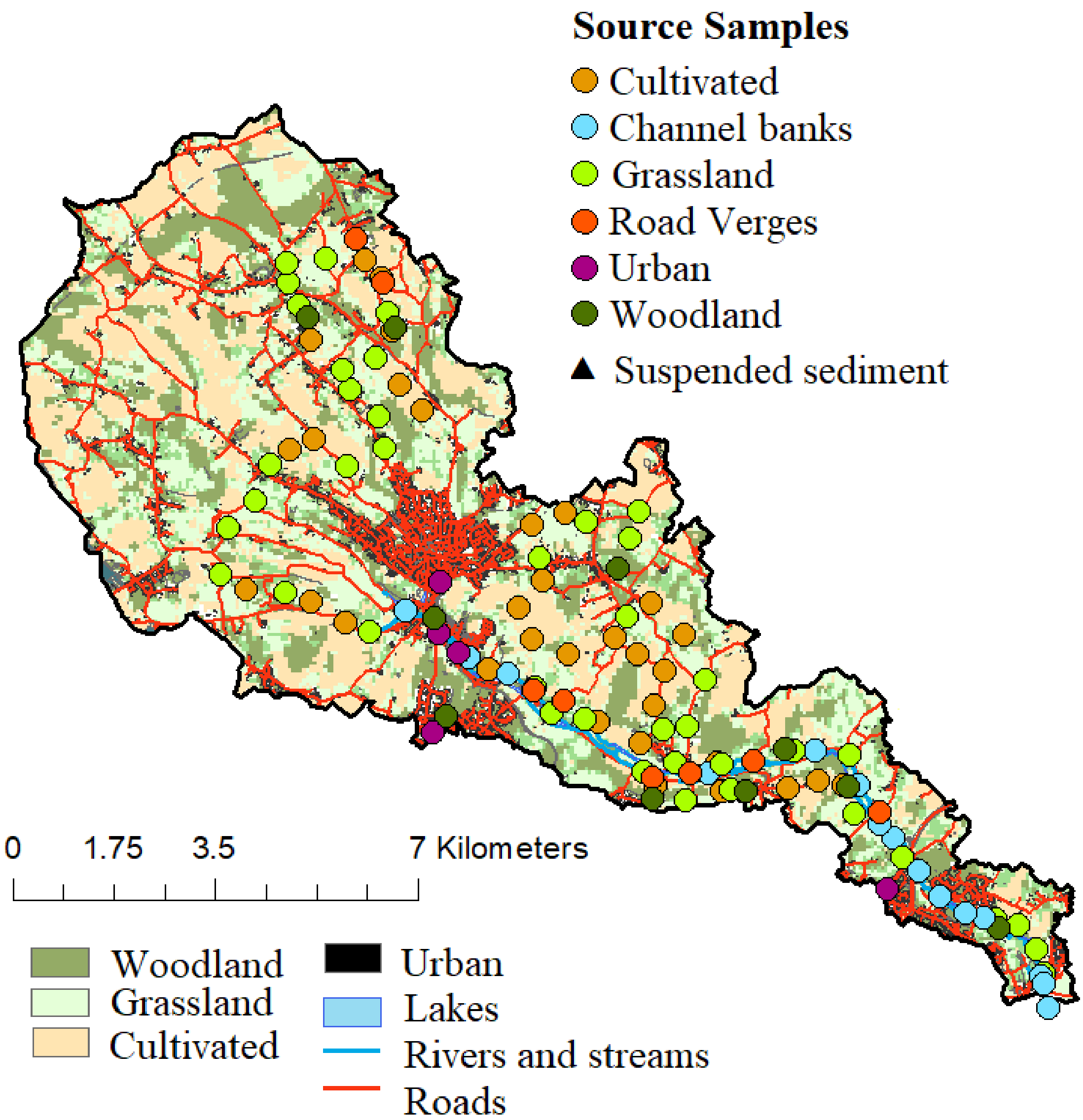


Figure 9: Source sampling locations in the River Chess catchment.

Table 1: The number of source samples retrieved, classified by land use.

Source	Number of samples
Cultivated	32
Channel banks	19
Grassland	42
Road verges	8
Urban	5
Woodland	11

3.2. Sample preparation and analysis

The source and sediment samples were fractionated through a 25 µm stainless steel mesh whilst still wet from the field. The samples were placed into a beaker with ~100 ml of deionised water and disaggregated using a metal spatula, before being rubbed through the sieve by hand with additional water applied as needed. The <25 µm fraction was selected for analysis to minimise the potential for particle size associated uncertainties and to maintain consistency with the other catchments investigated using the colour tracing method (Pulley and Rowntree, 2016; Laceby et al. 2017; Pulley and Collins, 2021b). The fractionated samples were then oven dried at 105ºC and manually disaggregated using a pestle and mortar.

The prepared samples were then treated using hydrogen peroxide to remove any organic matter associated with the soil and sediment and potentially allow for improved source discrimination based upon catchment geology (Pulley et al. 2018). Here, approximately 0.2g of each sample was placed into a 50 ml plastic centrifuge tube and 8 ml of 30% hydrogen peroxide was added. The samples were left to stand overnight before being heated at 80°C in a hotplate until dry. The dried samples were disaggregated by hand, using a pestle and mortar, and packed into transparent polythene bags. Images of the samples were captured using a Ricoh MP office document scanner. The values of reflected red, green and blue light in the RGB colourspace (0-255) were extracted using the Gimp 2 open-source image editing software (Krein et al. 2003; Pulley and Rowntree, 2016; Pulley and Collins, 2021b). Sediment provenance was determined using a scatter plot of red and blue with each source sample group colour coded and sediment sample labelled. Separate plots are provided for each suspended sediment sampling month as well as for the two channel bed sediment sampling campaigns.

3.3. Suspended sediment load measurement

Suspended sediment loads and yields were calculated using turbidity and flow measurements at six sites along the River Chess (Chesham Wier lodge, Blackwell Hall, Latimer Park, Sarratt Cress beds, Loudwater Estate and Elms Lake). Turbidity was measured at 15-minute intervals using Eureka sondes at Willow Cottage and Sarratt Cress Beds, Proteus sondes at Blackwell Hall and Restore Hope Latimer and Xylem EXO sondes at Loudwater and Elm Lake. Measurements took place between 5/12/2022 – 10/10/2023 at Willow Cottage, 05/08/2022 - 16/10/2023 at Blackwell Hall, 05/08/2022 – 17/10/2023 at Latimer Park, 26/05/2019 – 11/10/2023 at Sarrat Cress Beds, 17/10/2022 – 15/10/2023 at Loudwater Estate, and 21/10/2022 – 13/10/2023 at Elms Lake. The turbidity data was found to be extremely noisy, likely due to the fouling of sensors by organic matter. As such, any anomalous readings in the data were removed manually. Flow data was used from the River Chess at Rickmansworth Environment Agency gauging station number 39088.

Turbidity was converted to suspended sediment concentration using a calibration with water samples retrieved during high flow events. ISCO autosamplers were positioned at Willow Cottage, Latimer Park, Elms Lake and Blackwell Hall. The samplers were triggered on the 13th October 2023 at 15:34 for Willow Cottage, 16:19 Blackwell Hall, 15:59 Latimer Park, and 16:55 Elms Lake and retrieved a ~800ml sample at 30 minute intervals for a total of 24 samples collected over 12 hours. A second storm was sampled on the 18th October 2023 at three of the sites which were triggered at 14:06 at Latimer Park, 14:52 at Blackwell Hall and 15:13 at Elms Lake. It was found that the samples from the first event sampled were contaminated with insect parts and organic debris. For this reason, only the samples for the second flood were used for the three sites it was collected at. For Willow Cottage, where samples were only collected in the first flood, only those free of contamination were analysed. All samples were vacuum filtered through pre-weighed glass fibre filter papers and the mass of suspended sediment was recorded. The relationship between measured turbidity and suspended sediment concentration (SSC) was calculated to generate a 15-minute record of SSC (Figure 10). Suspended sediment yield was calculated by multiplying the discharge of the river in each 15-minute interval by its suspended sediment concentration. Yield was first calculated using the discharge at the catchment outlet at all sites and corrected values were estimated by reducing the discharge at each site by the proportion of the catchment area downstream of it and the flow monitoring point at Rickmansworth.

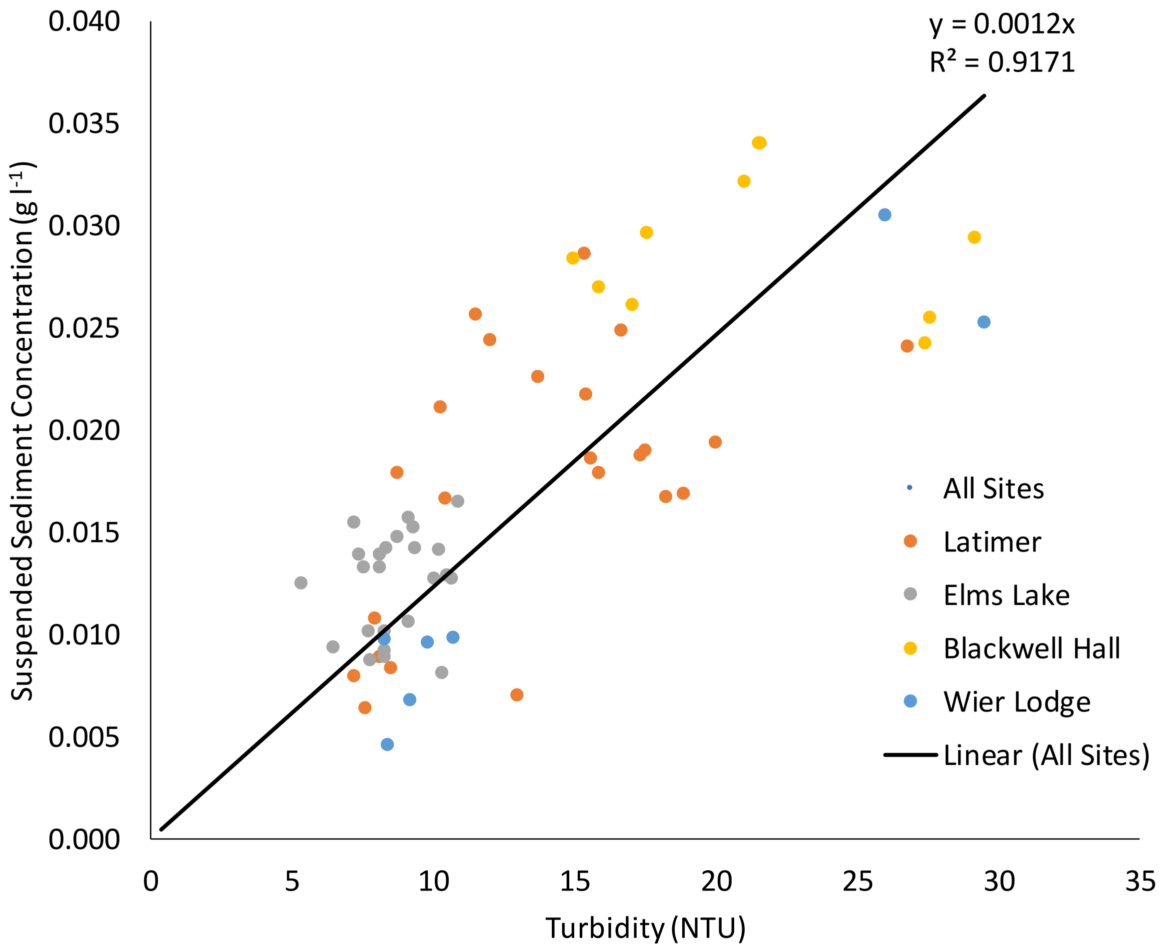


Figure 10: Calibration between measured turbidity and suspended sediment concentration.

4. Results

4.1. Sediment sources

Colour was able to discriminate between most sampled sediment sources well (Figure 11). Urban road samples had the lowest reflected red and blue values, caused by dark materials from sources including vehicle exhaust emissions and tyre wear. Rural road verge material has a lighter colour but still darker than other sources likely indicating a greater dilution of darker anthropogenically-derived materials with subsurface material forming the road cuts and verges. In four of the road verge samples, there was a lower blue value in relation to red than in urban samples providing some discrimination between these sources. This likely reflects the presence of some topsoil material on the road. Channel bank samples have high blue and red values separating them from other sources. The woodland, cultivated, and grassland topsoils all have a low blue value in relation to red when compared to the road and channel bank samples. There is little discrimination between these three topsoil sources after the samples have been treated using hydrogen peroxide. However, all but one of the cultivated source samples have a low blue:red ratio whilst some woodland and grassland samples have a higher ratio which overlaps with the channel bank samples. Three channel bank samples have a red:blue ratio comparable to topsoils, suggesting that the banks here are composed of displaced surface material. Four other bank samples may be a mixture of subsurface and topsoil material.

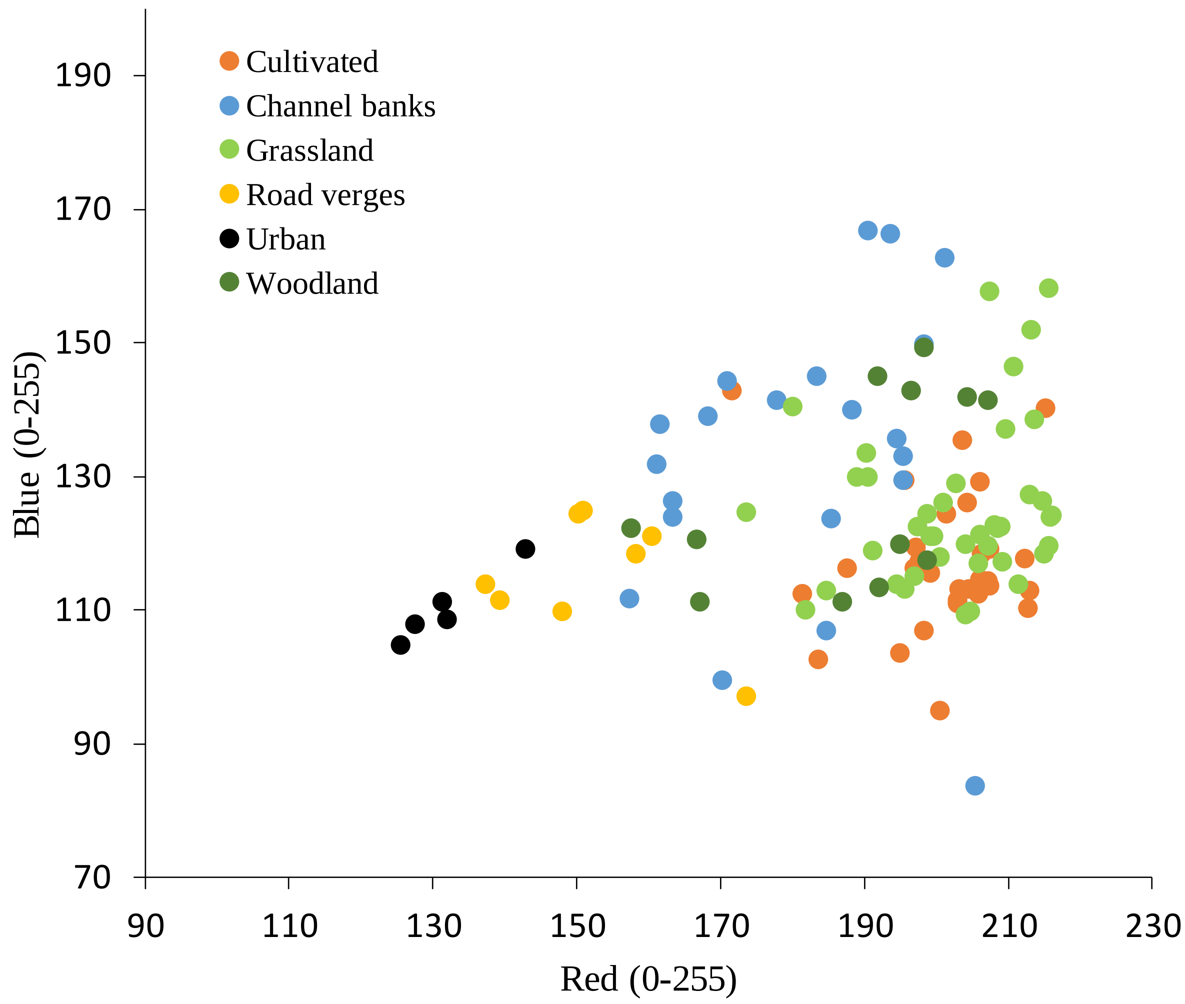


Figure 11: Hydrogen peroxide treated source sample red and blue.

The colour of all suspended sediment and channel bed sediment fell between the urban road dust and channel bank sources (Figures 12 – 15). There is also possibly some input of sediment from rural road verges; however, this contribution is likely small due to the limited spatial extent of this source and small mass of material in verges susceptible to erosion. There is a general trend in all suspended and bed sediment samples of their colour being darker in the Chesham Wier Lodge, Blackwell Hall and RHL Main Chess sites, suggesting a mixed urban and channel bank sediment provenance (Figure 14). Downstream of these three sites on the main channel and at the RHL Little Chess sampling site, sediment colour is comparable to the channel bank source samples suggesting that the sediment originates primarily from this source. The blue value of the sediment is higher in relation to red in the sediment samples than in the woodland, grassland and cultivated sources suggesting no significant contributions from topsoils to any sediment sample, apart from the outlier of RHL Little Chess in July 2022. The reason for this outlier is unclear although could be related to local activities such as farming within the catchment.

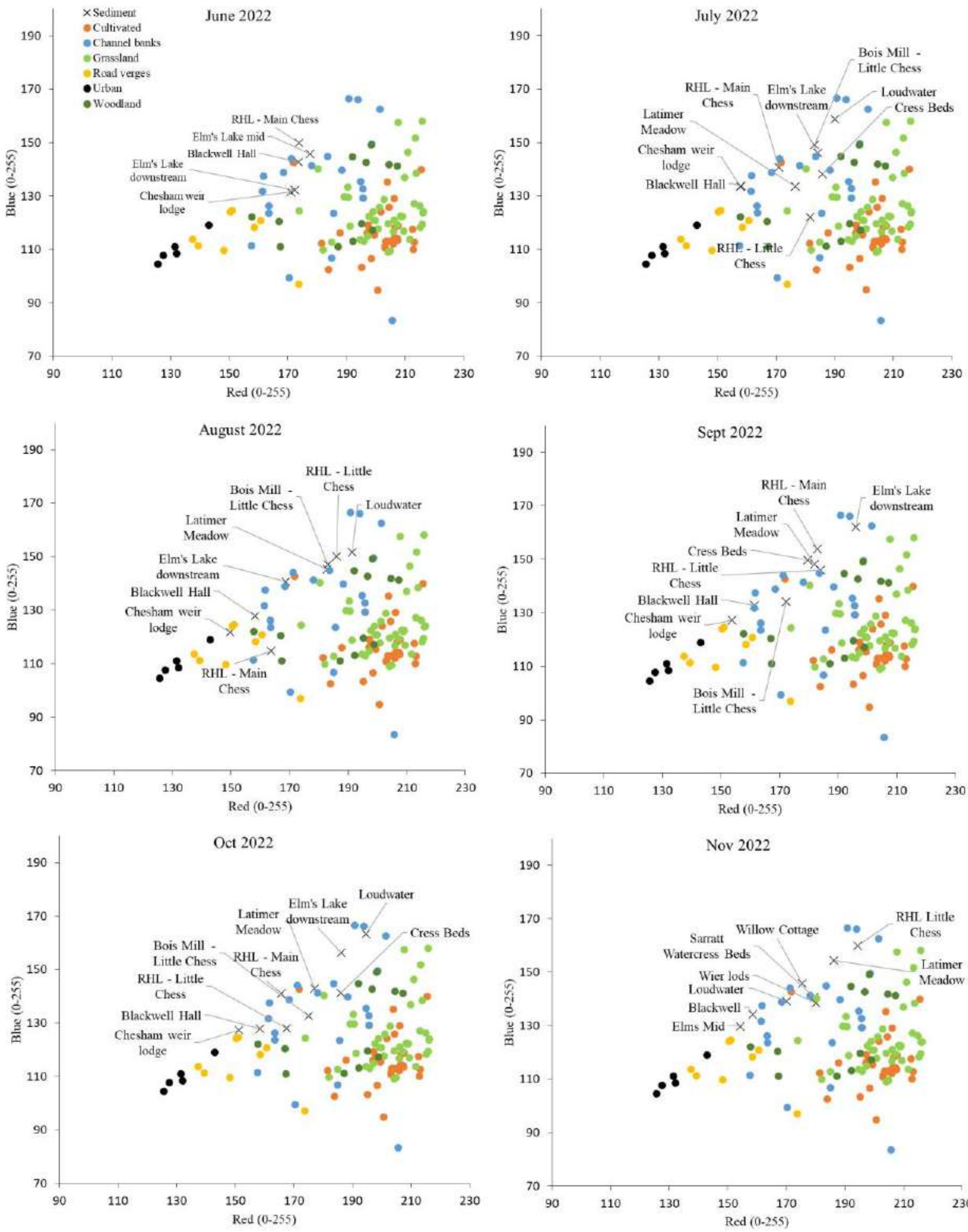


Figure 12: Hydrogen peroxide treated source and sediment sample red and blue from June to November 2022.

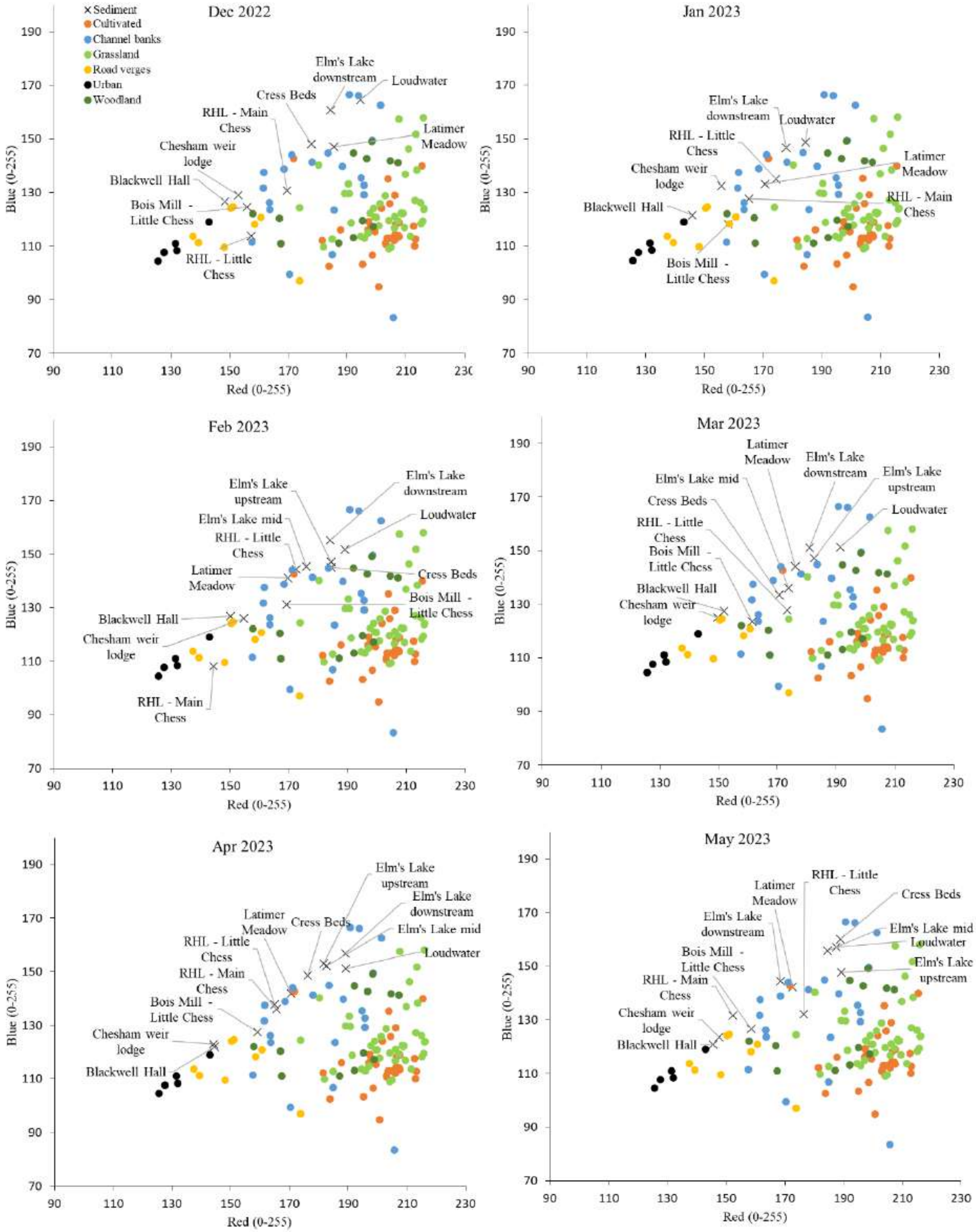


Figure 13: Hydrogen peroxide treated source and sediment sample red and blue from December 2022 to May 2023.

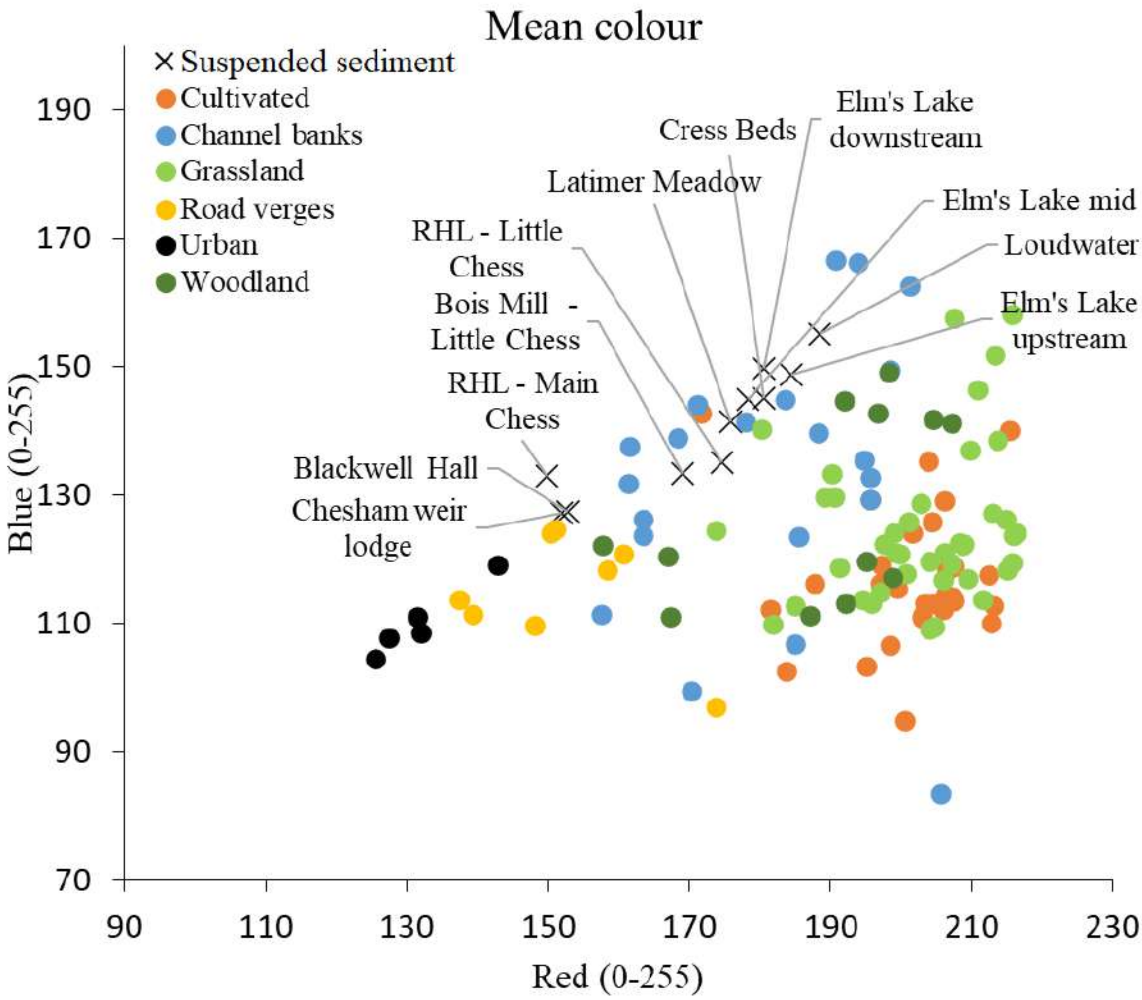


Figure 14: Hydrogen peroxide treated source sample and mean suspended sediment sample red and blue from June 2022 to May 2023.

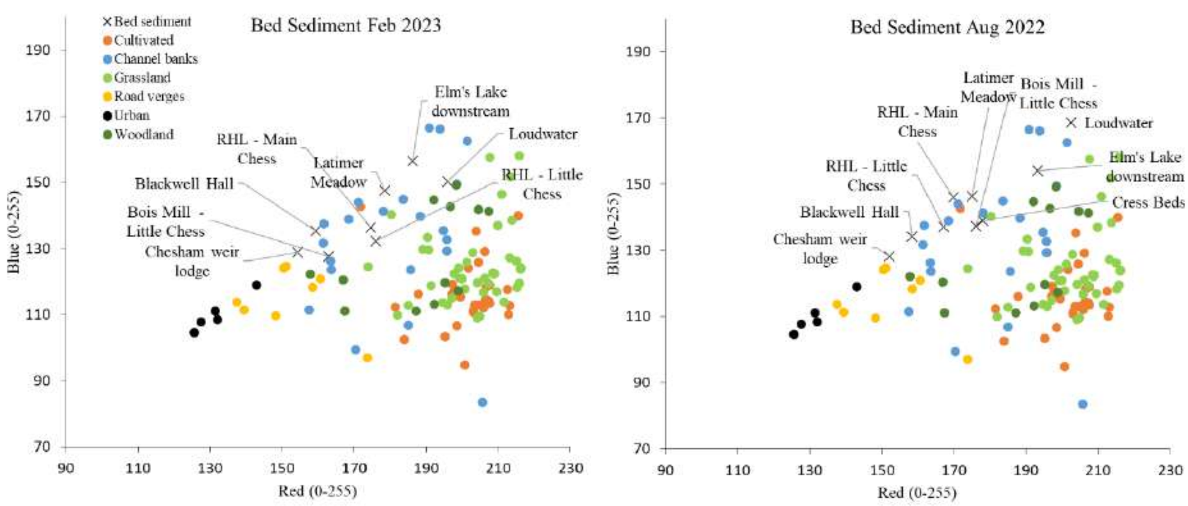


Figure 15: Hydrogen peroxide treated source sample and channel bed sediment sample red and blue.

Loss-on-ignition measurements on the sediment, prior to fractionation to 25 µm, show it has organic matter contents of between 11 and 33%, indicating large amounts of organic matter transported in association with the fine-grained sediment (Table 2). As the channel bank source has a highly organic appearance where floodplain deposits are being eroded, organic matter likely originates from this source. There may also be the preferential transport of organic matter from sources such as riparian woodland adjacent to the river channel.

Table 2: Loss-on-ignition (4 hours at 450°C) of samples retrieved in August 2022 prior to fractionation to <25µm.

Sampling site	LOI (%)
Blackwater Hall	26.70%
Bois Mill	35.70%
Latimer Meadow	30.10%
RHL Little Chess	28.50%
Sarrat Cress Beds	32.80%
Loudwater Estate	10.90%
Elms Lake Upstream	22.50%

4.1. Suspended sediment loads and yields

There is generally a poor correlation between turbidity and flow at all sampling sites with many high flow events not being associated with a rise in turbidity and some rises in turbidity not being associated with a rise in flow (**Error! Reference source not found.**s 16;17; Supplementary Figure 1). Responses of turbidity to high flow are most clear at the most upstream sites (Latimer Park, Blackwell Hall and Bois Mill). Large fragments of organic matter were found in the suspended sediment samples which may have contributed to the noisy turbidity datasets at all sites. Turbidity measurements at Latimer Park are significantly higher than at the other sites; however, rises in turbidity are often not associated with rises in flow and therefore may represent fouling of the sensor.

Suspended sediment yields were calculated to range from 0.23 - 1.21t km^2 yr^{-1}, using flow recorded at the catchment outlet, or 0.15 - 1.16 t km^2 yr^{-1} reducing measured flow in proportion with catchment area downstream of each monitoring site (Table 3). The suspended sediment yield at Latimer Park was higher at 7.23 t km^2 yr^{-1} (5.90 t km^2 yr^{-1} with flow corrected). However, due to the very noisy turbidity data this is likely a significant overestimate of the actual suspended sediment yield. When compared to the suspended sediment yields of other UK catchments, all are extremely low and therefore these small differences in yield between the six sites are difficult to interpret given the significant measurement uncertainties likely present. These measurement uncertainties are primarily a result of the low amounts of sediment being transported through the stream and therefore the low turbidity signal available to be captured. In this context, noise in the datasets caused by the fouling of sensors or other similar processes becomes extremely significant.

Concentration duration curves show that in most sites sediment concentrations only rise on a small proportion of days with high flow (<5%) (Figure 18). In the most upstream Blackwell hall site elevated sediment concentrations occur during a greater proportion of days likely due to the impermeable urban land surface upstream and the absence of in-line ponds to buffer flows. At Elms Lake and Loudwater, suspended sediment concentrations are higher during low flow conditions which may reflect a greater presence of organic matter within the river water.

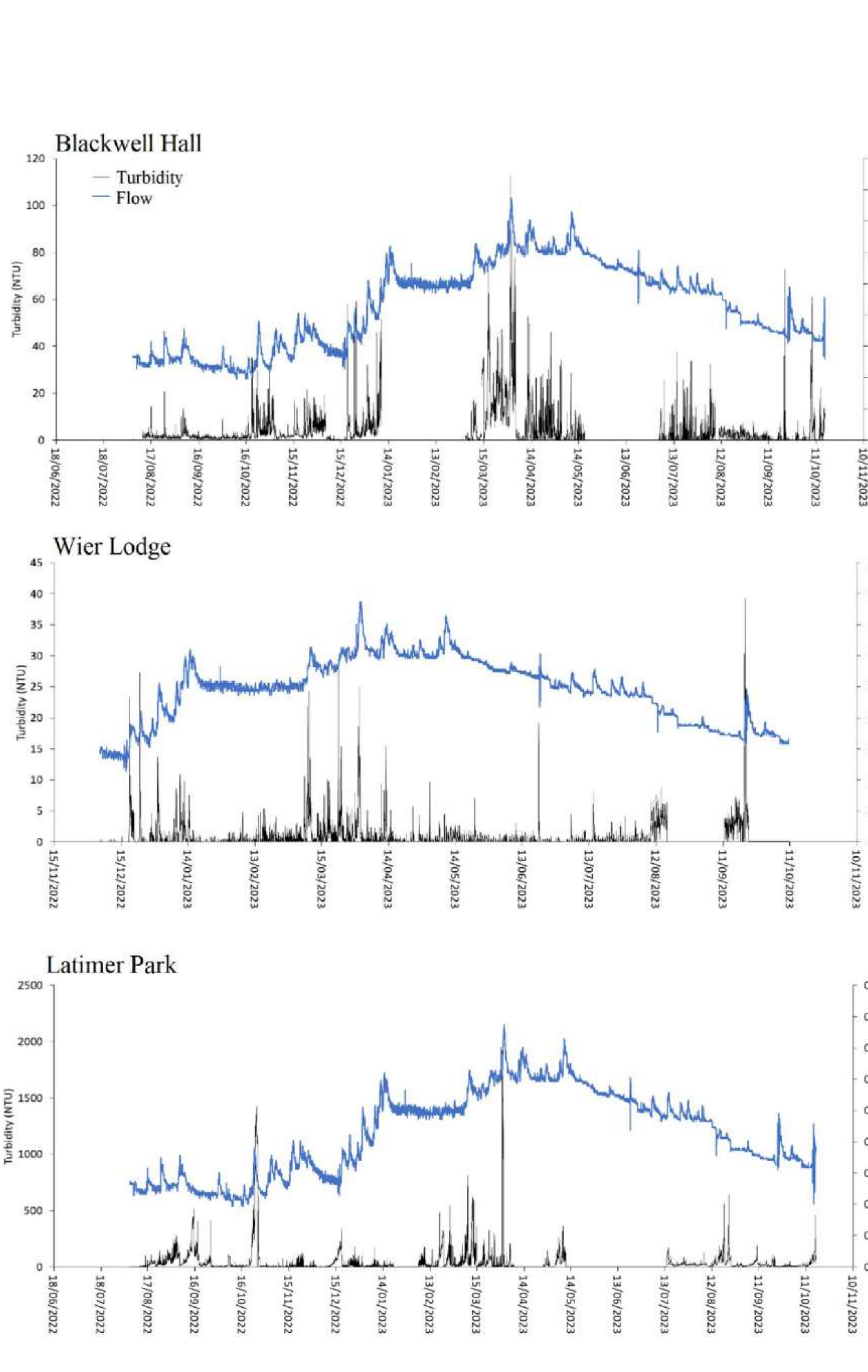


Figure 16: Timeseries of flow and turbidity for the Blackwell Hall, Wier Lodge and Latimer Park monitoring sites. Flow from the Chess at Rickmansworth (39088) gauging station. https://environment.data.gov.uk/hydrology/station/b0a28c3c-b5dc-4a94-a661-2ef0639049c7

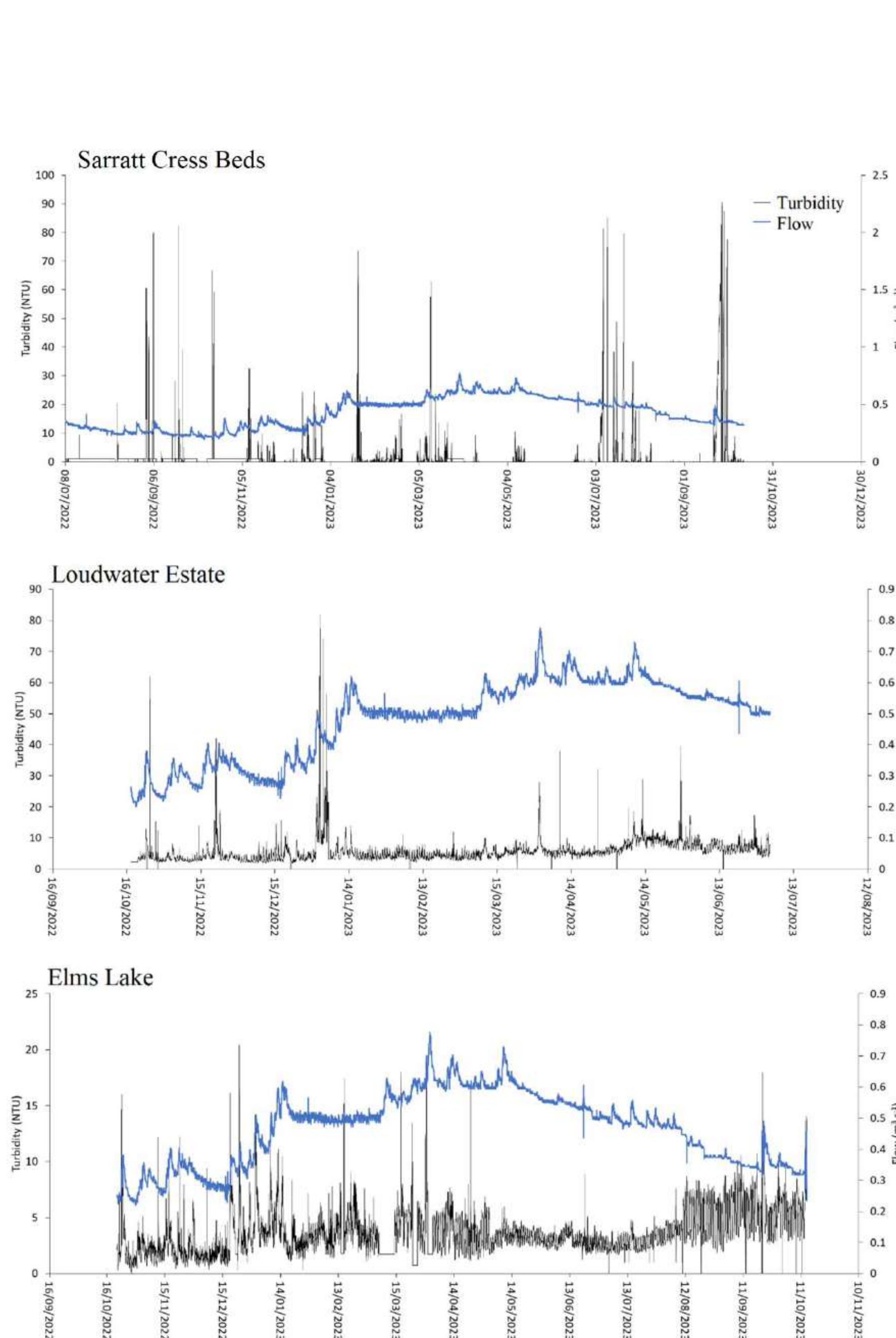


Figure 17: Timeseries of flow and turbidity for the Sarratt Cress Beds, Loudwater Estate and Elms Lake monitoring sites. Flow from the Chess at Rickmansworth (39088) gauging station. https://environment.data.gov.uk/hydrology/station/b0a28c3c-b5dc-4a94-a661-2ef0639049c7

Table 3: Estimated suspended sediment yields at the six monitoring sites.

Site	Suspended sediment load (tonnes)	Years of monitoring	Upstream catchment area (km^2)	Suspended sediment yield (t km^2 yr^{-1})	Yield with flow reduced in proportion to catchment area (t km^2 yr^{-1})
Blackwell Hall	79.11	1.2	69.15	0.96	0.69
Bois Mill	11.8	0.85	60.97	0.23	0.15
Latimer Park	683.9	1.2	78.85	7.23	5.9
Sarrat cress Beds	146.49	4.38	85.02	0.39	0.34
Loudwater Estate	111.21	0.99	92.33	1.21	1.16
Elms Lake	70.15	0.98	96.6	0.74	0.74

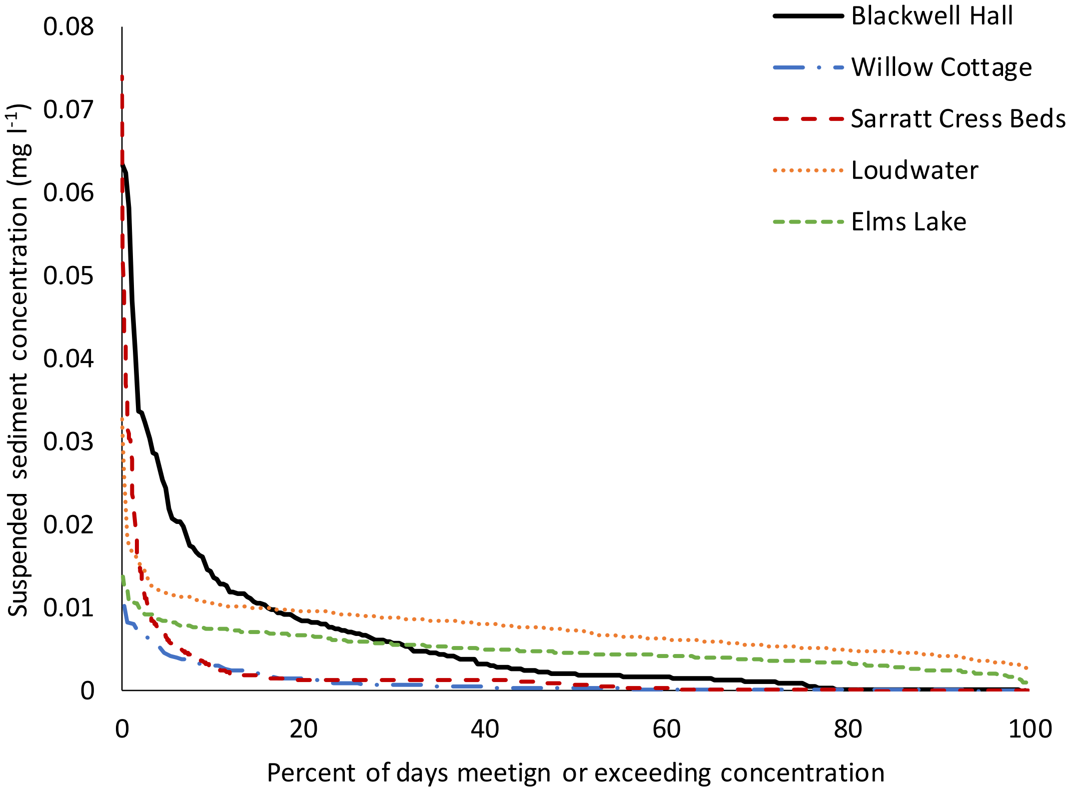


Figure 18: Suspended sediment concentration duration curves for the Blackwell Hall, Willow Cottage, Sarratt Cress Beds, Loudwater and Elms Lake sampling sites.

5. Discussion – sediment source tracing results

It was found that almost all sampled sediment in the River Chess originated from channel bank erosion, with no indication of substantial sediment inputs from topsoil sources. This was combined with an extremely low suspended sediment yield of <1.21t km^2 yr^{-1} for the river when compared to an average of 44 t km^2 yr^{-1} for all UK catchments (Walling et al. 2008). Regardless, this yield for the Chess is comparable to those reported for other chalk streams, such as the Hampshire Avon (1.4 to 12.5 t km^{-2} yr^{-1};Heywood and Walling, 2003). A similarly high contribution of sediment from channel banks has been found in other UK catchments using older sediment tracing methodologies (Collins et al. 1997a,b; Owens et al. 2000; Russel et al. 2001; Walling et al. 2008; Pulley and Foster, 2017). Using the colour-based tracing method presented herein, sediment has been traced in fifteen other catchments and, in only two of them, were high erosion risk arable fields identified as the most important sediment source (Figure 19; Table 4). Instead, channel bank erosion was the most important source in most of the catchments.

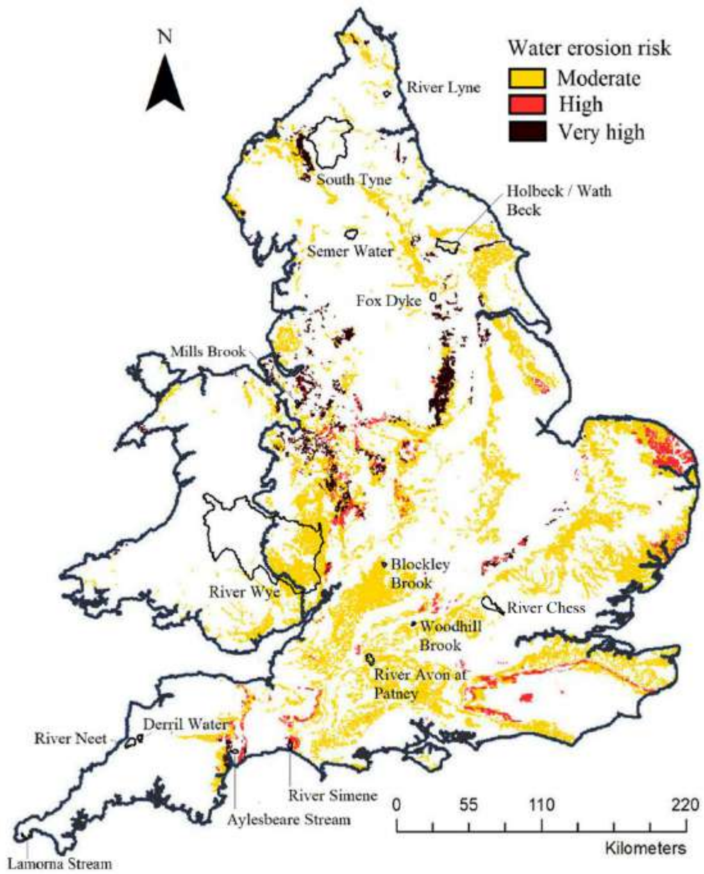


Figure 19: The locations of catchments studied using the colour-based tracing method overlain over a soil erosion risk by water map produced by Evans et al. (1990).

Table 4: Summarised dominant sediment sources and notable characteristics of the catchments previously studied using the colour-based tracing method.

Site	Dominant sediment source	Notable catchment characteristics
Derril Water	Channel bank erosion	Grassland dominated catchment
River Neet	Channel bank erosion	Grassland dominated catchment
Aylesbeare Stream	Channel bank erosion	Mixed arable and grassland land use
Lamorna Stream	Channel bank erosion	Mixed arable and grassland land use
Woodhill Brook	Channel bed erosion	Arable dominated catchment
River Simene	Arable topsoils and likely some bank erosion	Mixed arable and grassland land use
River Wye	Lower catchment dominated by arable fields but likely with a significant channel bank contribution	Grassland dominated upper catchment and arable dominated lower catchment
River South Tyne	Channel bank erosion	Grassland dominated catchment
Semer Water	Combined grassland topsoils, landslips and subsurface sources	Grassland dominated catchment
Mills Brook	Grassland topsoils	Low importance of a small number of visibly eroding arable fields
River Avon at Patney*	Flat valley floor area	Low importance of sloped arable fields
Holbeck / Wath Beck	Flat valley floor area	Low importance of sloped arable fields
River Lyne	Woodland and channel bank erosion	Low importance of agricultural topsoils
Blockley Brook	Channel bank erosion	Low importance of agricultural topsoils
Fox Dyke	Topsoil and subsurface sediment transport through field drains	Extremely flat arable dominated catchment

- Chalk streams

The absence of sediment from topsoil sources entering the River Chess can be explained by a low stream density resulting in little agricultural land being directly adjacent to a watercourse. Therefore, given the lack of a flashy hydrology generating significant overland flows, there are likely minimal sediment surface transport pathways to the river. The land which is next to a stream channel is also generally flat and consists of grassland, trees or semi-natural vegetation. Except for infrequent areas of livestock poaching, this land is generally of very low erosion risk.Therefore, low source – stream connectivity is likely the key driver of sediment sources and the low suspended sediment yield within the study catchment. A similar result was found using the colour-based tracing method in the Hampshire Avon at Patney on the North Wessex downs which is also a partially chalk dominated catchment (Pulley and Collins, 2022). Here, higher erosion risk arable fields on chalk hillslopes contributed less sediment than the flat ungrazed grassland adjacent to the stream channels. Similarly, in Woodhill Brook and Blockley Brook studied in a similar region of the country, but with a surface flow dominated hydrology, channel bank and bed erosion, respectively, were identified as the dominant sources of fine-grained sediment.

Low soil erosion rates are also likely a driver of small contributions of topsoil derived sediment to the study river. On the North Wyke Farm Platform at Rothamsted Research, sediment yields from grassland fields have been measured at ~23 t km^{-2} yr^{-1} which is roughly in line with the yield which would be expected in a river draining fairly flat grassland (Walling et al. 2008; Pulley and Collins, 2019). Rill and gully erosion rates in the UK have been previously measured in the SSEW (Soil Survey of England and Wales) monitoring project (1982-1987; Evans, 2005). Evans (2013) used data from the SSEW project to calculate landscape scale rill and gully 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). This estimate does not, however, include 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). As the average sediment yield of a UK river is only 44 t km^{-2} yr^{-1}, soil erosion rates are unlikely to be able to account for most of this yield given that most of the eroded sediment is likely to be retained within a field or between a field and a river due to intermediate storage. Given this general national picture, it is not unexpected to find the same in the River Chess, albeit with proportionally lower soil erosion rates, connectivity and suspended sediment yields on account of the local permeable geology.

In contrast, channel bank erosion can account for a significant proportion of the annual sediment yield of a UK river. A lower mean rate of 27 km^{-2} yr^{-1} (3-44 t km^{-2} yr^{-1}) was calculated by Janes et al. (2018) who compared the mapped historic locations of river channels in eight river catchments in England. However, channel banks in the River Chess are low and highly organic in composition and are therefore likely to have low erosion rates which is reflected by the low suspended sediment yield of the river. High flows through the river are also of low magnitude due to the subsurface flow driven hydrology of chalk stream rivers and the inline lakes buffer flows which are further likely to lower erosion rates.

Signal crayfish have been shown to potentially increase rates of channel bank erosion. Sanders et al. (2021) found in two UK rivers that bank retreat was increased by 253% in heavily burrowed banks compared to banks without burrows. Burrowing directly released 0.2% and 0.6% of total sediment at the reach studied, but bank collapse caused by burrows contributed

12.2% and 29.8%. Combined here these processes increased sediment supply to the river by up to 25.4 t km^{-1} yr^{-1}. The rivers studied had higher and more erodible banks than in the River Chess and extremely high crayfish burrow densities of 6.9 burrows m^{-1} so the rates of bank collapse are unlikely to be as high in the Chess with its often shallow banks. Using the calculated suspended sediment yield of the River Chess, the theoretical burrow density required to account for a significant proportion of the sediment load can be estimated.

Sanders et al. (2021) measured an average crayfish burrow volume of 516.1 cm^3. If assuming a density of bank material of 1.6 g cm^{-3} one burrow releases 825 g of sediment. To increase the annual sediment load at Elms Lake by 5% would require 3.5 tonnes of sediment which would equate to 4,242 crayfish burrows in the river, which is a density of 0.23 burrows per meter of channel or approximate one burrow every 4 m. If the burrows are causing bank collapse then the burrow density required would be lower. Future visual surveys of the river banks could determine if this density of burrows or greater is plausible and if the financial costs of crayfish removal are likely to deliver good cost-benefit for sediment management.

Whilst there is a high contribution of sediment from urban sources in the upper reaches of the River Chess, these are rapidly diluted and become insignificant moving in a downstream direction. It is likely that almost all the sediment from urban areas originates from local sources within the urban landscape, rather than originating from agricultural land entering roads and then being altered to have an urban signature. During storms, runoff down the road will be extremely rapid and will enter the river without sufficient time to be altered. As there was no indication of fresh agricultural sediment within the river, it is highly unlikely that eroded sediment can be deposited on the same roads for a long period of time and then transported to the river. In some UK rivers, such as the River Aire, urban areas have been indicated to be important sediment sources (Carter et al. 2003). Contributions from urban sources are diluted more quickly in the Little Chess, which is likely due to the presence of ponds here in which the urban sediment from upstream is deposited. Therefore, mitigating sediment losses from urban runoff may provide very localised benefits, especially when considering the pollutants transported in association with the sediment, but are unlikely to have a significant impact on the River Chess as a whole.

Sediment originating from agricultural topsoils has been observed to be transported along roads by local citizen scientists in the river Chess catchment along Latimer Road from

Chesham to Chenies, upstream of the Sarratt Cress beds; however, this source and transport pathway was not identified in our new results to contribute substantially to the suspended sediment yield of the river given the observed lack of topsoil contributions. Despite the low suspended sediment yield of the Chess, annually 70 tonnes of suspended sediment were found to be transported through it at the Elms Lake site. Therefore, for cultivated topsoils to even contribute 5% of this suspended sediment yield, would require 3.5 tonnes of sediment to be delivered to the river via roads annually given the lack of other transport pathways, which is an implausibly large amount and would require extremely high soil erosion rates from the areas of agricultural land draining onto roads.

There was no significant change in sediment source between the different months of sampling and their different flow conditions. The same finding was reported by Pulley and Collins (2021a) who showed that changes in sediment sources rarely occurred even with the extreme wet winter of 2019–2020 in most of the eight catchments studied at the time for the CSF initiative. Similarly, the relatively smooth down-stream change in sediment source found in the River Chess with the dilution of urban sediment has also been found elsewhere. For example, in the River Wye there is a smooth transition of sediment sources in a down-stream direction (Pulley and Collins 2023). In the River Chess it was previously unclear if the inline ponds would cause more localised differences in sediment source; however, from our results herein, there is little local variability. This is likely due to a lack of sediment transport pathways between topsoils and the river channels along the entire length of the study river.

6. Mitigating the fine-grained sediment problem

Two issues need to be considered carefully in devising a sediment mitigation strategy for the River Chess. These comprise the key sediment sources, as indicated by the new work reported herein, and the high propensity for sediment storage on the channel bed. The former issue is important since source control will help to reduce the sediment problem, especially in the future. The second issue is also important since without addressing current sediment sequestration on the channel bed, sediment-driven degradation of water quality and ecological status will continue given the absence of flushing flows. Addressing both issues in combination will deliver both short- and longer-term sediment mitigation.

On the basis of the sediment source tracing work, river bank erosion sediment sources need to be targeted by mitigation measures in the River Chess catchment. Assuming an absence of substantial capital resources, alternative so-called ‘green’ or ‘green-grey’ measures warrant consideration. The former measures are founded 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 eroding river banks. For 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 eroding river bank face. Bank stakes are used to protect eroding channel bank toes from fluvial scour. Faggots comprise bundles of untreated brushwood such as willow or hazel, bundled together using biodegradable fibres. Willow spiling is based on the insertion of willow fencing to provide physical protection to the eroding river bank face. Coarse woody material is used to deflect eroding river flows away from the river bank and can comprise complete trees or just the trunks thereof. ‘Green-grey’ measures include, amongst others, vegetated rock rolls, reinforced mattresses, ripraps, gabions or concrete blocks. Rock rolls are netting filled with cobbles and established vegetation. These are commonly used to protect the toes of eroding river banks. Reinforced mattresses are flexible mats made from natural or synthetic materials which are used to protect the eroding 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 for reducing erosion. These can be used to protect just the river bank toe, or stacked up to protect the entire bank face from erosive fluvial scour. Concrete blocks are typically vegetated using grass plugs or the insertion of live cuttings. Where river bank erosion is assessed to be especially problematic, the above measures can be applied in combination to maximise reductions in erosion. Although recommended by various organisations, including the River Restoration Centre, it is important to recognise that these types of measures can fail and are expensive if applied at scale.

The accumulation and net storage of fine sediment within riverbeds is a function of three main mechanisms; bed load transport, infiltration and exfiltration (Figure 16). The interplay of these mechanisms is manifest in the channel bed sediment budget, which determines the amount of fine sediment accumulation and thereby the propensity for detrimental impacts on water quality and benthic aquatic organisms. The transport of fine sediment in the water column (Mechanism A, Figure 16), is controlled by inputs of sediment from the key catchment sediment sources (i.e., eroding channel banks in the case of the River Chess), channel bed material, and the stream power (transport capacity) of the river (Sear et al., 2008; Naden et al., 2016; Vercruysse et al., 2017). Upon being delivered to a river system, sediment is transported downstream as suspended or deposited sediment, dependant on particle density and the erosion/ transport capacity of the stream (Vercruysse et al., 2017; Wilkes et al., 2019). Transport capacity is largely determined by stream power, which is a function of channel hydromorphological characteristics including width/depth ratio, discharge, slope and channel roughness (Cooper et al., 2008; Naden et al., 2016). Alterations to the characteristics controlling Mechanism A, such as reduced discharge and increased channel width, reduce the system's stream power and transport capacity, promoting sediment deposition on the channel bed (Wohl, 2015; Vercruysse et al., 2017).

In turn, the transport capacity influences the second mechanism (Mechanism B in Figure 16) controlling the accumulation of fine sediment in riverbeds; infiltration or ingress (Casas-Mulet *et al.*, 2017). This mechanism is highly dependent on the gravel framework of the riverbed, which determines the amount of fine sediment it can sequester, dependant on the availability of framework pore space and ease of infiltration (Wooster *et al.*, 2008; Gibson *et al.*, 2009). The size ratio between the deposited fine sediment and bed framework directly affects the mechanism of fine sediment infiltration into the intra-gravel pores (Wooster *et al.*, 2008). When sufficient interstitial spaces are present, unimpeded percolation occurs whereby the infilling fine sediment infiltrates to an impermeable layer (Herrero and Berni, 2016). If the interstitial spaces are smaller than the infilling sediments, however, bridging occurs where the deposited sediment is trapped at the pore throats, creating a clogged layer at the surface (Gibson *et al.*, 2009; Herrero and Berni, 2016).

The final mechanism controlling the net accumulation of fine sediment in riverbeds is exfiltration (Mechanism C, Figure 16). The factors controlling this mechanism are strongly interrelated and, in some cases, are the same as those that control infiltration (Mechanism B). The occurrence of bed mobilising flows, intra-gravel flows and arrangement of bed sediments are the dominant factors controlling exfiltration (Casas-Mulet et al., 2017). The entrainment of fine sediment occurs when the shear-force exerted on sediment particles by flowing water exceeds the resisting forces of the particles (Turowski et al., 2011). The resisting forces are determined by particle mass and arrangement within the channel bed, including degree of protrusion and friction between other particles (Turowski et al., 2011; Hodge et al., 2013).

The combination of low stream power, relatively low connectivity arising from naturally low drainage density, and low sediment production from subdued topography in chalk catchments, including the River Chess, suggest that, theoretically, chalk streams should naturally experience low rates of fine sediment accumulation within the bed gravel framework. However, chalk streams typically manifest significantly higher fine sediment mass within their framework gravels compared with other gravel bed systems (Sear et al., 2008). Applying a sediment budget approach as described immediately above, therefore indicates that, for chalk streams, Mechanisms B and C must dominate relative to Mechanism A.

The stream power (transport capacity) of a system directly influences the extent of bed mobilising flows. Alterations to a system such as narrowing of the channel or increases in discharge during storm conditions increase stream power and thus increase the occurrence of bed mobilising flows and exfiltration of fine sediment from the bed (Wohl, 2015; Hauer et al., 2019). The infiltration depth of deposited sediment, a function of the ratio between pore size and sediment size, can also influence how readily sediment can be remobilised by flows (Franssen et al., 2014). Biological processes can also influence Mechanism C (Figure 3), for example, the secretion of EPS (extracellular polymeric substances) can increase adhesion between particles, decreasing exfiltration (Gerbersdorf et al., 2008; Gerbersdorf and Wieprecht, 2015). To deliver, short-term management of the sediment problem in the River Chess catchment, alterations to the channel system to increase stream power will be critical, since this will result in increased exfiltration of the bed sediment currently sequestered on the bed substrate.

Low stream power promotes low transport capacity within chalk stream channels (Sear et al., 1999), contributing to high rates of deposition of suspended sediment and low rates of sediment exfiltration from the gravel framework. As a result, the low transport capacity of chalk streams plays a significant role in the high rates of Mechanism B, fine sediment infiltration, and low rates of Mechanism C, fine sediment exfiltration, within the channel sediment budget of chalk streams. The surface 10 cm of chalk stream gravel beds has been identified to be the most ecologically-sensitive to elevated quantities of deposited fine sediment. Accordingly, improved management of fine sediment in chalk streams, including the River Chess, needs to focus on the removal of current excessive fine sediment from the surface 10 cm of the gravel bed, without the removal of the relict and naturally irreplaceable gravel framework which provides important benthic habitat for many species. Here, there is a need to identify the target for flushing flows to increase sediment exfiltration from the river bed.

Many flume studies have been made of the transportation, deposition and infiltration of fine sediment into immobile gravel beds (Beschta and Jackson, 1979; Gibson et al., 2009;

Dudill et al., 2017; Mooneyham and Strom, 2018). Critically, however, relatively few studies have investigated exfiltration of fine sediment from immobile gravel beds (e.g., Stradiotti et al., 2020; Trevisson and Eiff, 2022). Additionally, work on exfiltration generally fails to represent the natural conditions in chalk stream gravel beds, with few experiments using representative grain size distributions for either the gravel bed frameworks or the infiltrating fine sediment measured in chalk streams. Most studies have focused on fine sediment in the sand-sized fraction meaning that there are few examples where silt-clay sized sediment (<63 μm) was considered (e.g., Mooneyham and Strom, 2018; Stradiotti et al., 2020). Whilst some studies have considered such fine-grained sediment, these have done so within a framework consisting of only sand-sized particles (e.g., Fetzer et al., 2017; Du et al., 2018) meaning that such work is equally unrepresentative of natural conditions in chalk streams. Subsequently, this brings into question the reliability of previous experiments which, in turn, means that existing fine sediment models run a risk of failing to generate reliable results in terms of management targets focussed on flushing flows or bed shear stress. To address this shortcoming, new experimental work is needed to identify specific bed shear stress targets for the River Chess. The new experimental work could be performed in a flume with gravel bed and interstitial grain size distributions representative of the River Chess.

In the absence of resources for targeted experimental work designed specifically to inform revised sediment management for the River Chess, reach-scale restoration could be deployed to create localised areas of higher flows, that would increase shear velocities and bed shear stress. Here, the installation of woody material and management of instream macrophytes can create localised higher velocities, generating higher bed shear stresses and remobilisation of fine sediment (Gurnell et al., 2006; Osei et al., 2015; Parker et al., 2017). In addition, the removal of channel obstructions can increase localised flows (Lenders et al., 2016). Importantly, these restoration techniques are more self-sustaining than previous approaches such as manual gravel washing (Pander et al., 2015) as they restore hydrological and sedimentological processes instead of focusing on moving fine sediment from one place to another in the river channel system. The generation of heterogenous flow patterns by these restoration techniques, can also create heterogeneous habitats within the gravel bed. For example, instream macrophytes create regions of lower flow within their stands, promoting highly localised fine sediment deposits (Gurnell et al., 2006; Osei et al., 2015), which are critical for certain life-cycle stages of some chalk stream species.

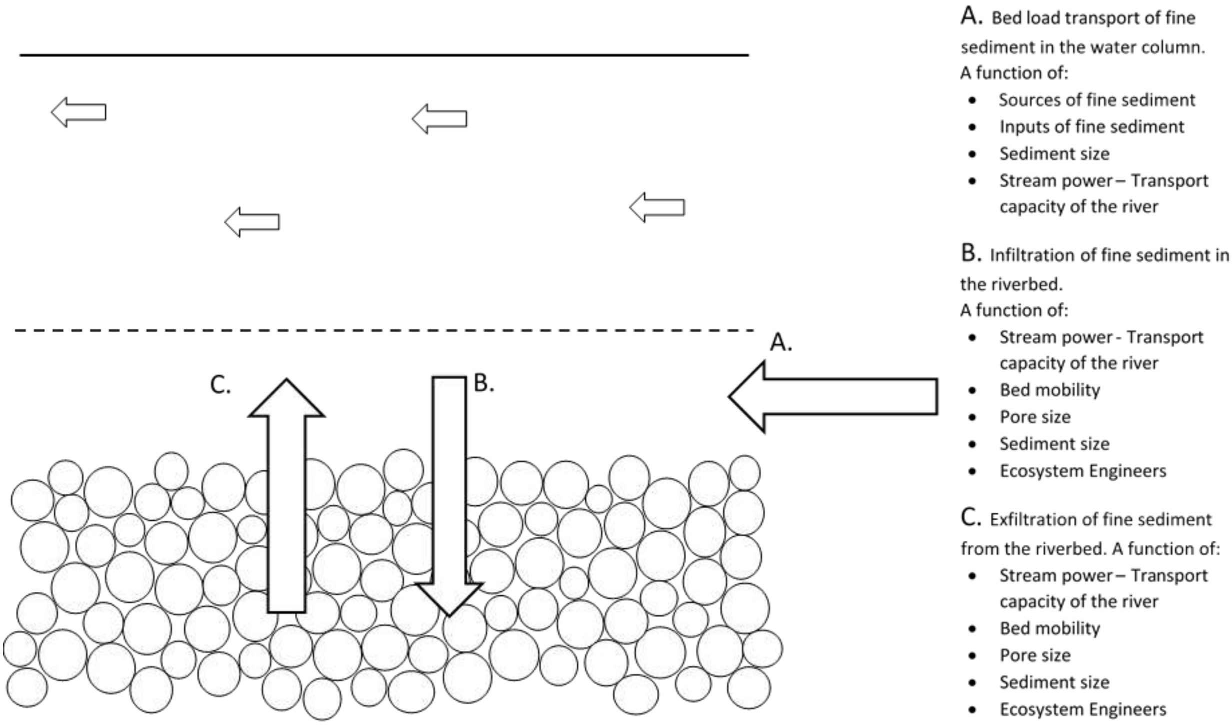


Figure 20: Conceptual model of the transportation, infiltration and exfiltration of fine sediment in a gravel river bed. The rate at which fine sediment accumulates is the net effect of the three interacting mechanisms: A. bed load transport of fine sediment in the water column delivered from key catchment sediment sources; B. infiltration of fine sediment into the riverbed, and; C. exfiltration of fine sediment from the gravel riverbed. From Mondon et al. (2021).

7. Conclusions

An absence of sediment inputs from topsoils to the River Chess suggests that the erosion of agricultural land is not a principal cause of its degraded water quality. Instead, most sediment originates from eroding channel banks. Given the low height of the channel banks and lack of stream power, the erosion rate of banks is low, which is reflected by the very low suspended sediment yield of the river, although poaching by livestock in some places can be observed to augment bank erosion. It is therefore likely that any sediment-related pressures on water quality in the River Chess are linked to its groundwater-fed hydrology and lack of high flows that can flush sediment from ecologically sensitive benthic habitats, as opposed to excess sediment inputs from any particular catchment source. Similar issues have been identified in other chalk stream catchments within the UK. Therefore, efforts to reduce sediment losses to the river are likely to deliver only small within-stream impact. Instead, options to target pollutants such as phosphate and nitrate from agriculture which may be delivered through groundwater pathways may deliver more benefit where evidence suggests that they are needed. The sediment in the River Chess is highly organic which likely results in a high oxygen demand and low dissolved oxygen in channel bed gravels which are important habitats for aquatic life and specific key life stages. Therefore, the removal of existing sediment deposits would likely be of greatest benefit for improving the ecological status of the river.

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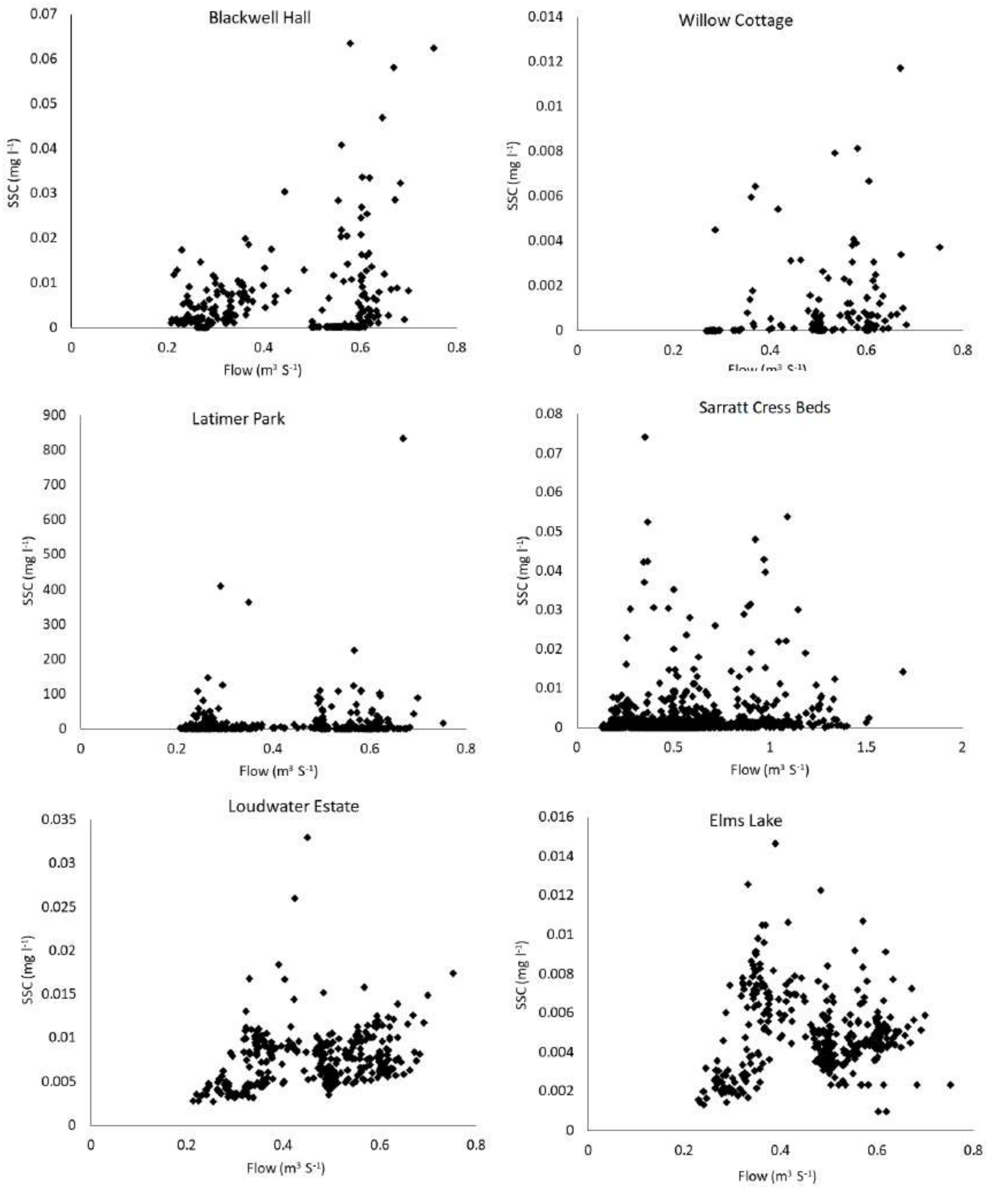
9. Appendix



Supplementary Figure 1: Sediment – Flow rating curves for the six monitoring sites.