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A palaeoenvironmental study of particle size-specific connectivity- new insights and implications from the West Sussex Rother Catchment, United Kingdom

Running title: Particle size-specific connectivity

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Abstract

Connectivity has become an important conceptual and practical framework for understanding and managing sediment transfers across hillslopes, between hillslopes and rivers and between rivers and other compartments along the river corridor (e.g. reservoirs, channel substrate, floodplain). Conventionally, connectivity focuses on the quantity of sediment transferred but here we also consider the size of the finer sediment (typically particles < 500 μm diameter). We examine the role of small rapidly silting reservoirs in the River Rother on storing sediment and disrupting downstream sediment transfers. Spatial and temporal changes in the particle size characteristics of sediment deposited in one of the ponds is explored in detail. Downstream of this pond we collected sediment from the river on nine occasions over 17 months using two sampling methods at two locations; one immediately downstream of the pond and a second ~700 m further downstream but upstream of the confluence with the Rother. Results showed a significant depletion in sand sized particles immediately downstream of the pond but the sand had been recovered from an in-channel source before the river reached the downstream sampling point.

KEYWORDS

Reservoirs, sediment dynamics, particle size, West Sussex River Rother

1. INTRODUCTION

In the UK, research into fluvial geomorphology is firmly rooted within physical geography and is concerned with interactions between process mechanics, channel dynamics and palaeohydrology (Petts, 1995). There are also key links between fluvial geomorphology, population ecology, community ecology and palaeoecology (see Figure 1 of Petts, 1995). A significant catalyst for linking river ecology to fluvial geomorphology emerged with ideas like the ‘river continuum’ concept (Vannote *et al*., 1980) that influenced fluvial geomorphologists’ understanding of longitudinal patterns in river behaviour and function and which were rapidly assimilated into fluvial research programmes. For example, Petts (1984a, p 21) demonstrated links between the river continuum concept and the fluvial geomorphological zones recognised by Schumm (1977), thereby providing an integrated framework for understanding the downstream variability of, and links between, river ecology and fluvial geomorphology.

Climate change and human intervention alter the quantity, calibre and chemical characteristics of sediment transported by rivers and here we focus on the less studied aspect of sediment calibre because sediment transfers are particle size specific. We also adopt a palaeoenvironmental approach to provide a longer-term perspective on the impact of river impoundments on sediment connectivity. Of particular importance ovr the last 1000 years or so isthe increasing number of impoundments constructed on river systems (e.g. Petts 1984 a; b; Petts & Wood 1988; Petts *et al.*, 1989; Foster 2010). The sediments accumulating behind these impoundments can provide long-term perspectives on fluvial processes and ecosystem response (e.g. Oldfield, 1977; Foster & Greenwood, 2016). Like the continuum concept, this framework was assimilated into studies of fluvial sediment dynamics and first introduced into a textbook on fluvial geomorphology by Petts and Foster (1985). More modern texts on fluvial sediment dynamics frequently incorporate research that is underpinned by this longer-term palaeohydrological framework (e.g. Foster, 2010).

Interactions and exchanges of water and sediment between hillslopes and river channels are controlled by weather conditions and land utilisation in the short term (years to decades) and climate change and soil degradation in the long term (decades to millennia). Exchanges of sediment and associated contaminants occur between rivers and their floodplains and rivers and their substrates at a range of spatial and temporal scales (e.g. Petts *et al.*, 1991; Gurnell *et al.*, 2008; Pulley *et al.*, 2015). These exchanges have been a major focus of fluvial geomorphology for many years and are now underpinned by unifying conceptual models of connectivity (e.g. Fryirs *et al.*, 2007). Such conceptualisations can often be used to justify sampling frameworks for sediment-associated contaminant assessment (e.g. Mokwe-Ozonzeadi *et al.*, 2019) or management interventions that either improve or reduce both structural and / or functional connectivity (e.g. Boardman *et al.*, 2019). The conceptual model in Figure 1 illustrates those factors that could boost or form barriers to sediment transfer at the catchment / landscape scale and identify natural and anthropogenic factors that might exist in a typical lowland UK catchment. Lateral transfers occur between hillslopes and the river and between the channel and its substrate and floodplain. Longitudinal transfers occur along the channel, but major reservoirs and in-stream weirs will disrupt longitudinal connectivity especially in relation to sand-sized and coarser particles. An important issue often not emphasised in conceptual models or measurements of connectivity is that sediment transfers are particle size-specific, although several studies have demonstrated the selectivity of fluvial sediment transport (e.g. Walling & Moorhead, 1989; Slattery & Burt, 1997). Here we attempt to address this gap by examining changes to the particle size distribution of sediment trapped within, and released downstream, of impoundments.

Downstream impacts on sediment transfer at the global and regional scale are well documented (e.g. Syvitski *et al*., 2005; Boardman and Foster, 2011), but here we make use of case studies using reservoir sediments to provide a longer term paleoenvironmental perspective on particle size. We present data for two north bank tributaries of the Rother where mediaeval age and more recent small reservoirs exist. The older reservoirs, locally called ponds, were constructed either to mill flour or drive hammers to crush ore for the Wealdon iron industry (Straker, 1931). We examine recent sedimentation rates in four reservoirs in the two catchments and then use one of them to explore its impact on stored and downstream particle size characteristics.

2. RESEARCH CATCHMENTS

The River Rother (~350 km^2) and specifically the two sub-catchments (the Hammer – 25 km^2 and Lod – 54 km^2 streams) discussed herein are shown in Figure 2A & B. The main river is 52 km long from its source to its confluence with the River Arun. Elevations in the whole Rother catchment range from ~240 m to ~0.4 m asl. The two sub-catchments were investigated as part of several recent projects including those reported by Collins *et al*. (2012) and Evans (2019).

Average annual (1881-2016) rainfall for the catchment, from the Petworth Park record, is ~863 mm, with highest mean monthly falls in December (102 mm) and November (100 mm). Occasional extreme rainfalls occur, with the highest for the 20th Century (over 100 mm) recorded at

Petworth in one day in 1945. Burt *et al*. (2015), from an analysis of part (1907-2014) of the dataset, showed statistically significant declines in the average summer rainfall, in the number of summer rain days and in the annual number of rain days. By contrast, the amount of rain per rain day in the autumn data set showed a statistically significant increase.

Land use in the Rother as a whole has seen a decrease in grassland and an increase in arable land since the 1930s (Table 1A) and the two sub-catchments have significantly more woodland and less arable land and grassland than the Rother catchment as a whole (c.f. Table 1B and 1A). Soils in both sub-catchments are dominated by the Wickham and Shirrell Heath (1 or 2) associations. The former is a slowly permeable and seasonally waterlogged fine silty soil underlain by Cretaceous age clays and mudstones; reported by Evans (1990) to be at low risk of erosion. The Shirrell Heath associations are well-drained acidic sandy soils overlying Cretaceous age sandstones (Greensand) (Soil Survey of England and Wales, nd). These soil associations are reported to be at moderate risk of erosion (Evans, 1990).

3. FIELD SAMPLING

Reference cores for estimating the local ^{137}Cs fallout inventory were taken in two areas of undisturbed open parkland to the west and south of Petworth (Figure 2) using a manual percussion corer to a depth of ~70 cm. These provide a baseline against which to compare reservoir sediment inventories as eroded topsoil generally increases the reservoir inventory as it brings ^{137}Cs bearing topsoil into the basin (e.g. Pulley *et al*, 2018).

The four ponds (Figure 2B) were surveyed using a Trimble® GPS and SonarMite® echo sounder. Bathymetric maps were constructed to estimate water volume to the level of the spillways and calculate total water holding capacity. Trap efficiency estimates used the capacity:inflow method of Brune (1953). All ponds were cored at approximately the deepest location using a mini-Mackereth corer (1.2 m long) (Furnace, Hammer and Inholms Ponds) or a Russian corer operated from the de-watered reservoir surface following a dam breach in December 2013 (Lurgashall). The coring location on the Hammer Pond is shown in Figure 2C along with the location of five surface Ekman grab samples collected to evaluate spatial variability in particle size and other characteristics. Isobaths in Figure 2C were obtained from the bathymetric survey.

Time-integrating tube samplers (Phillips *et al.*, 2000) were deployed on the Hammer stream at two locations; one about 50 m downstream of the outflow and the second ~700m further downstream at a footbridge (Figure 2B). This location was far enough upstream of the Rother confluence to avoid backflow effects. Tube samplers were used to provide a representative suspended sediment sample over a range of flow conditions and to trap a sufficiently representative range of particle sizes for fine sediment investigation (Russell *et al.*, 2000) although Smith and Owens (2014) have recently suggested that some very small particles may not be trapped if they are not transported as aggregates.

The bed disturbance method of Lambert and Walling (1988), and evaluated in detail by Duerdoth *et al*. (2015), was used to estimate the quantity of sediment stored on and within (upper ~5 cm) the river bed at both locations. Bed disturbance was undertaken when tube samplers were removed for emptying approximately every 2 months between January 2015 and May 2016.

Topsoil (upper 5 cm) from major soil associations was sampled using a non-metallic trowel. Each sample was a composite of five sub-samples collected from within a ~15 m radius of a randomly selected sampling point to increase the representativeness of the source sampling (Collins *et al.*, 2010). Channel bank material was collected from the upper and lower banks along the Hammer stream at 5 locations including a heavily poached bank adjacent to the stream. Samples were composites from at least 5 locations at each site.

4. LABORATORY METHODS

Reference cores were sub-sampled at 1 cm intervals and prepared for the analysis of ^{137}Cs in the same way as the Mackereth cores which were extruded vertically in the laboratory at 1, 1.5 or 2 cm intervals depending on the depth of core retrieved. Russian cores taken from Lurgashall were subsampled horizontally at 2 cm intervals. In Lurgashall, we found ~5.2 m of sediment had accumulated since construction (Table 2) but the analysis reported here focuses only on the upper ~1.5 m of the core which covered the period of sediment accumulation since around the beginning of the 20th Century when significant increases in erosion have been well documented across Europe (e.g. Rose *et al*., 2011). Dry bulk density (DBD) was calculated for each slice after drying a known volume of wet sediment.

Loss on ignition (LOI) was measured using a muffle furnace following the methods of Heiri *et al*. (2001), while particle size analysis used a Malvern® Instruments laser granulometer with a Hydro-2000 unit. Samples were pre-treated overnight with hydrogen peroxide to remove organic matter and were subsequently suspended in ultrapure water and ultrasonically dispersed before analysis. Sodium hexametaphosphate (Calgon) was also added to ensure full dispersal of samples prior to measurement (Pye & Blott, 2004). A range of particle size properties were used to describe particle size in addition to the full distribution. These included diameters of the 10th, 50th and 90th percentiles of the particle size distribution (D_{10}, D_{50} and D_{90}) in units of μm, and the specific surface area (SSA) of each sample in units of $m^2\ g^{-1}$; see Walling & Foster (2016).

Dating was undertaken using two gamma-emitting radionuclides (^{137}Cs and ^{210}Pb) measured on each slice of the sediment cores in Ametek® hyper-pure Ge detectors in a well configuration (11 mm diameter; 40 mm active depth). Count times were typically over 180,000s. Details of the analytical methods are given in Collins *et al*. (2012) and Walling & Foster (2016). Dates from the ^{137}Cs analysis were derived from pattern matching with atmospheric fallout records. While a number of models using ^{210}Pb can be employed for dating the sediment profile we used the 'c-crs' model developed by Appleby (2001) and discussed in detail by Walling and Foster (2016).

5. RESULTS AND DISCUSSION

5.1 The ponds

With the exception of Inholms, all ponds were very shallow with an average depth << 0.5 m. In consequence, calculated trap efficiencies were extremely low and had often declined significantly since the beginning of nuclear weapons fallout in 1954 (Table2). The average inventory for the ^{137}Cs reference cores (Table 2) is not significantly different from that of Inholms pond where sedimentation rates are low in this small, largely forested catchment. Depths to ^{137}Cs in the other cores are some of the highest reported for the UK (see Rose *et al*., 2011; Pulley *et al*., 2018) despite the very low trap efficiencies.

5.1.1 Dating the Hammer Pond sediments

The ^{137}Cs profile of the Hammer Pond is shown in Figure 3A and has a pattern typical of Furnace and Lurgashall Mill pond and of other lowland UK lakes receiving sustained inputs of ^{137}Cs-bearing topsoil (Foster, 2006; Pulley *et al*., 2018). The c-crs model ^{210}Pb depth-age curve is plotted in Figure 3B. The bottom of the core contained a relatively coarse sand but only a small amount of this was recovered. From the 'c-crs' ^{210}Pb dating model, fine tuned to the 1963 ^{137}Cs peak, this was predicted to have occurred between the late 1930s and mid to late 1940s. The Petworth rainfall record showed that July 1945 was the wettest July on record (190 mm; 1880-2016). Of the monthly total, 106.7 mm fell on the 14th July following another intense daily rainfall of 45.7 mm on 10th July. It seems likely that this extreme rainfall delivered to a very wet catchment could transport sand-sized sediment even to the deepest point of the pond – a feature similar to that described in South African farm dams by Foster *et al*. (2007). (In January 2013 we observed notably large amounts of sand and silt had reached the pond directly from a large gully in an adjacent field after very heavy rain creating a small (~10m^2 area) delta at the northern side of the lake. This was triggered either by rainfall in early or mid- November when 50.4 mm was recorded at Petworth between the 1st and 4th November and 88.4 mm was recorded between the 26th and 29th November before a site visit on 3rd December). Additional erosion undoubtedly occurred in January 2013 when 133 mm of rain was recorded between the 14th and 26th of the month). Sediment accumulation rates were calculated for three periods from the ^{137}Cs and ^{210}Pb chronology and appear to confirm the decline in trap efficiency (c.f. Table 2 & Figure 3C).

5.1.2 Bulk density, loss on ignition and particle size

Downcore trends in DBD and LOI in the Hammer pond core are given in Figure 4A. In general, LOI increases quite rapidly from ~9% to ~13% between 1945 and 1960 and increases more slowly to over 14% by 2011. The initial increase is probably due to post-WW2 increases in nutrient loads from agriculture increasing lake productivity, although we recognise that the organic matter deposited in the lake sediment will have both autochthonous and allochthonous origins. Dry bulk density generally declines up-core. and there is a statistically significant negative correlation (R = 0.79, $p << 0.05$ Pearson Correlation) between DBD and LOI but not between DBD or LOI and any of the particle size characteristics measured on the core, two of which are shown in Figure 4B. Since 1940, there have been major changes in the particle size distribution of the sediment and three distributions from the depths given in Figure 4C are plotted to show the change that occurs from samples with a very low Specific Surface Area (SSA; at 31.5 cm depth) to a very high SSA (75 cm depth). For the 31.5 cm sample, it is also evident that a small amount of sand can reach the deepest parts of the pond producing a trimodal distribution. The distribution from an ‘average’ SSA on Figure 4B (70.5 cm depth) loses the coarser mode and becomes bimodal while the sample with the highest SSA is unimodal with a dominant mode at < 10 µm (fine silt). Upcore of ~1990, there appears to be a general decline in SSA and an increase in the D_{90}; a pattern that would be expected as the trap efficiency declines over time. However, the wide scatter in the two data sets produces a statistically insignificant correlation.

Particle size distributions for the surface samples (Figure 4D) shows spatial variability across the Hammer Pond surface. The two deep-water grab samples (EG4 and EG5) are similar to each other with peak D_{50} at 30 µm and the three shallow water samples (EG 1-3) are also similar to each other with peak D_{50} between 34 and 39 µm. The deep-water samples also show an increase in fine sediment between 1 and 10 µm in diameter.

5.2 Hammer Stream Sediments

5.2.1 Bed sediment storage

Over the monitoring period, the amount of fine sediment (mainly < 500 μm diameter) stored in the river gravels as determined by bed disturbance at the Hammer outflow was significantly lower than that of the downstream footbridge samples (note; data are plotted on a logarithmic Y axis in Figure 5). The average for the period at the outflow was ~287 (+/- 143) g m^{-2} whereas the downstream site was over an order of magnitude higher and much more variable at ~3803 (+/- 2113) g m^{-2}. The footbridge values lie in the upper 90th percentile of those published for a number of British rivers while the outflow values lie in the lowest 10th percentile of data analysed by Naden *et al.* (2016).

Weak seasonal trends appear in the pond outflow data set but are less apparent in the footbridge data shown in Figure 5. Average bed storage at the footbridge is the highest of 9 locations measured during the wider Rother sampling programme (Evans, 2019) suggesting a local source of coarse sediment replenishment.

5.2.2 Particle size distributions in bed disturbace and tube samplers

The August and December 2015 particle size distributions, representing an end of summer and mid-winter sampling period for the tube sampler and bed disturbance data at both river sites, are plotted for comparison (Figure 6). Particle size summary statistics are given in Table 3. In Figures 6A and 6B, the coarser mode in the footbridge tube sampler does not appear in the outflow tube. The August footbridge coarse mode is slightly finer (170 μm; fine sand) than that of the December mode (195 μm; fine sand). Distributions at the finer end of the particle size fractions (< 10 μm; fine silt) appear to be reasonably similar at both locations for both time periods but these differences cannot be tested statistically. Figures 6C and D compare the tube sampler and disturbance data for August and December, respectively. For August, the distributions are slightly different with a peak mode(8.15 μm) in the disturbance data being a slightly coarser fine silt than the tube sampler (5.8 μm). Minor peaks are found at ~100 (very fine sand) and 450 μm (medium sand) in both plots. The differences in the December data for the comparison between disturbance and tube sampler distributions are more evident. The coarsest mode is 224 µm for the disturbance data but only 195 µm for the tube sampler although both are classed on the Wentworth scale as fine sand. The 6 µm modal peak in the tube data is barely visible in the disturbance data although a very minor peak exists at ~28 µm. The footbridge sample is dominated by the coarsest mode, where over 94 % of the distribution lies between 90 µm (very fine sand) and 500 µm (medium sand). What is not known for these samples is their residence time in the substrate and the extent to which they have been exchanged or replaced between sampling periods. However, it is evident that there is a source of available fine sand in the short distance between the outflow and the footbridge to satisfy the "hungry waters" described for sediment-starved rivers below dams by Kondolf (1997).

5.2.3 Potential sediment sources

A walkover survey between the two river sampling sites undertaken in July 2016 showed no streams, ditches or drains entering the river but there were areas heavily poached by horses and sections of channel bank up to 2 m high that had freshly collapsed. Both were sampled, along with local soil associations (see sampling methodology). Representative particle size data for these two potential sources and the two dominant soil associations in the catchment area are plotted for comparison (Figure 7). The Wickham association has a finer dominant modal peak (~80 µm; coarse silt) than the other three sources as the modal peaks of the poached area, channel banks and Shirrell 2 association are much coarser. The secondary mode in these three plots (28 µm) is less dominant in the poached sample than in the other samples except the Wickham association. While it is not possible to discriminate between specific sources using particle size alone, it seems unlikely that the Shirrell Heath association is contributing significantly to the fine sand in the footbridge disturbance samples. Unmixing modelling on the >125 µm particle size fraction undertaken by Evans (2019) on the tube sampler data from the footbridge location suggested that these sediments were derived predominantly from channel banks over the sampling period whereas the finer sediment fraction (<38 µm) was derived from a number of sources including arable & pasture land and woodland.

6. CONCLUSIONS

The four ponds have a wide range of sedimentation rates. Inholms has the lowest rate but its trap efficiency is the highest. The fact that it is largely forested and has a ^{137}Cs inventory indistinguishable from the local reference inventory also suggests that erosion and transport of ^{137}Cs with topsoil or other near surface sources labelled with this radionuclide is not important here. The three remaining sites evidence some of the highest sedimentation rates in the UK (c.f. Rose *et al*., 2011; Pulley *et al*., 2018) despite their low trap efficiencies, but there is no correlation between the inventory and sediment accumulation rate as demonstrated by the data in Table 2. The high ^{137}Cs inventories suggest significant amounts of sediment in all three derives from surface or near surface sources. These three ponds also show declining sedimentation rates in recent years as illustrated by the Hammer pond data (Figure 3C). This is unlikely to reflect decreasing sediment yields but is more likely to reflect a rapidly declining trap efficiency. The post 1990 particle size data appear to support this argument as sediments deposited in the Hammer pond have become slightly coarser towards the surface. Sediments within the pond exhibit a wide range of particle sizes and distributions and even sand size sediment is found in the core taken from near the deepest point. The coarse sediment in the core base helped to confirm the radionuclide chronology as it was probably associated with the highest daily rainfall in the 136-year record.

Clearly these small ponds disrupt longitudinal connectivity in river corridors, but their effect diminishes as they decrease in depth and reduce their trap efficiency. However, even with significantly reduced trap efficiencies, the coarser sediment (fine sand) remains within, or may even be deposited upstream, of the pond and is not delivered to the downstream receiving water course. The sediments immediately downstream are dominated by the fine silt and clay fraction which is not retained in the pond. Recovery of the coarse fraction in the Hammer stream appears to take place rapidly as there is sufficient sediment available (probably channel banks) to replenish it. In hindsight it would have been valuable to have included a tube sampler upstream of the Hammer Pond in order to compare with downstream samplers and this is recognised as a limitation which should be addressed in future research projects examining the particle size impacts of impoundments.

Our observations have several broad implications. First, they demonstrate that connectivity is not only particle size dependent but is also likely to be dependent on the magnitude of runoff delivering sediment to the ponds as reflected in the downcore particle size distribution of what has been trapped in the past. Secondly, sedimentation rates in the ponds decreases with decreasing trap efficiency and therefore likely increases both the amount and size of the sediment moving downstream over time. In extreme cases, where dams breach, this ultimately leads to the reconnection of the upper catchment with the lower reaches of a river channel over a broad range of particle sizes and potentially contributes to increased sediment transport as the pond sediment is evacuated if dams remain unrepaired (e.g. Boardman and Foster, 2011). Thirdly, the differences in the particle size distribution between the outflow and downstream samples demonstrate that rivers can restore their sediment supply over a relatively short longitudinal distance, probably from close-proximity locations. Fourthly, the fact that there does not seem to be a major loss of fine sediment in the tube samplers in comparison with the particle size distribution of the most likely contributing soils (Figure 7) also suggests that they retain a representative sample of sediment moving through the Rother catchment and confirms the suitability of this sampling method used here. Fifthly, big differences exist between the particle size of sediment from tube samplers and disturbance experiments suggesting that significant thought needs to be given to the choice of sampling compartment when collecting sediment for contaminant analysis because of the well-documented particle size control on contaminant concentration. Using our understanding of particle size dependent connectivity for managing sediment delivery opens up new opportunities to explore different strategies. A detailed discussion regarding management strategies is beyond the scope of the present paper but a range of strategies for the River Rother have recently been explored by Boardman *et al*. (2019).

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, IDLF, upon reasonable request.

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Figure Underlines

1. Conceptual model of major barriers (decreasing) and boosters (increasing) connectivity at the catchment / landscape scale identifying both natural and anthropogenic factors and those that are also used as potential mitigation options.
2. Location of the Rother catchment (A) with ^{137}Cs reference coring locations, the two study tributaries (Hammer and Lod streams) and four sampled ponds on the Hammer (Inholms and Hammer) and Lod (Furnace and Lurgashall Mill Ponds) sampling locations a and b relate to the outflow and footbridge sampling points respectively (B); bathmetry and sampling locations on the Hammer Pond (C).
3. A Downcore ^{137}Cs distribution in the Hammer pond Mackereth core.
   B The ^{210}Pb depth-age curve showing depths to the ^{137}Cs peak 1963 (arrow a) and likely first occurrence in 1954 (arrow b).
   C Predicted ^{210}Pb sediment accumulation rate in 3 time periods since 1945.
4. Characteristics of the Hammer Pond sediments
   A Downcore LOI and DBD in the Mackereth core
   B Downcore D_{90} and Specific Surface Area (SSA) of sediments in the Mackereth core
   C Particle size distributions of three sediment samples with low, average and high SSAs
   D Particle size distributions of the five Ekman surface grab samples
5. Bed sediment storage (< 500 μm dia.) in the gravels of the river bed at the Hammer outflow and downstream (footbridge) sampling location at approximately 2-monthly intervals (January 2015 to May 2016).
6. Particle size distributions for the bed disturbance and tube samplers at the Hammer Pond outflow and footbridge sampled in August 2015 (A) and December 2015 (B) with comparisons between the two sampling methods for the same sites and months shown in B and C.
7. Average (n=5) particle size distributions of dominant catchment soil types (Shirrell Heath 2; SH2 and Wickham; Wick Av) and average channel bank and poached bank samples (n = 5) taken from the Hammer stream between the Hammer pond outflow and the footbridge.

Table 1 **Land use in the River Rother catchment (A; From Evans, 2019; 1930s data are from the Dudley Stamp Land Utilisation Surveys) and B; in the Hammer and Lod streams (data from Collins *et al.*, 2012)**

A

Land Use	Area at 2010 (%)	1930s (%)
Grassland	36	49
Arable & horticulture	27	13
Woodland	30	20
Urban / misc.	5	3
Shrub heath	2	0
Other	2	15

B

Catchment	Urban (%)	Water (%)	Woodland (%)	Rough Grazing (%)	Improved Grazing (%)	Arable (%)
Hammer	5.7	0.8	42.4	2.1	26.9	22.1
Lod	4.9	0.9	41.8	3.9	29.8	18.6

Table 2 Characteristics of the ponds with depths to key ^{137}Cs time markers and pond and reference site inventories.

	Approx. Age	Average & (Maximum) Depth (m)	Capacity (m^3)	Trap Efficiency at 2016 survey (%)	Trap Efficiency at 1954 (%)	Depth to first ^{137}Cs Occurrence (cm)	Depth to ^{137}Cs 1963 Peak (cm)	^{137}Cs Inventory (mBq cm^{-2})
Reference Inventory (mean of 4 cores)								150.2 +/- 19.8
Inholms Pond	~1900	0.83 (3.4)	22301	83	85	42	30	153.3 +- 10.6
Hammer Pond	Early C16th*	0.37 (1.35)	9901	<5	<5	78	66	543.2 +/- 19.8
Furnace Pond	Mid C18th	0.35 (1.47)	6484	5	23	83	76	357.7 +- 25.1
Lurgashall Mill Pond	Early C16th	0.30 (1.55)	19765	<5	26	142	123	514.1 +-54.4

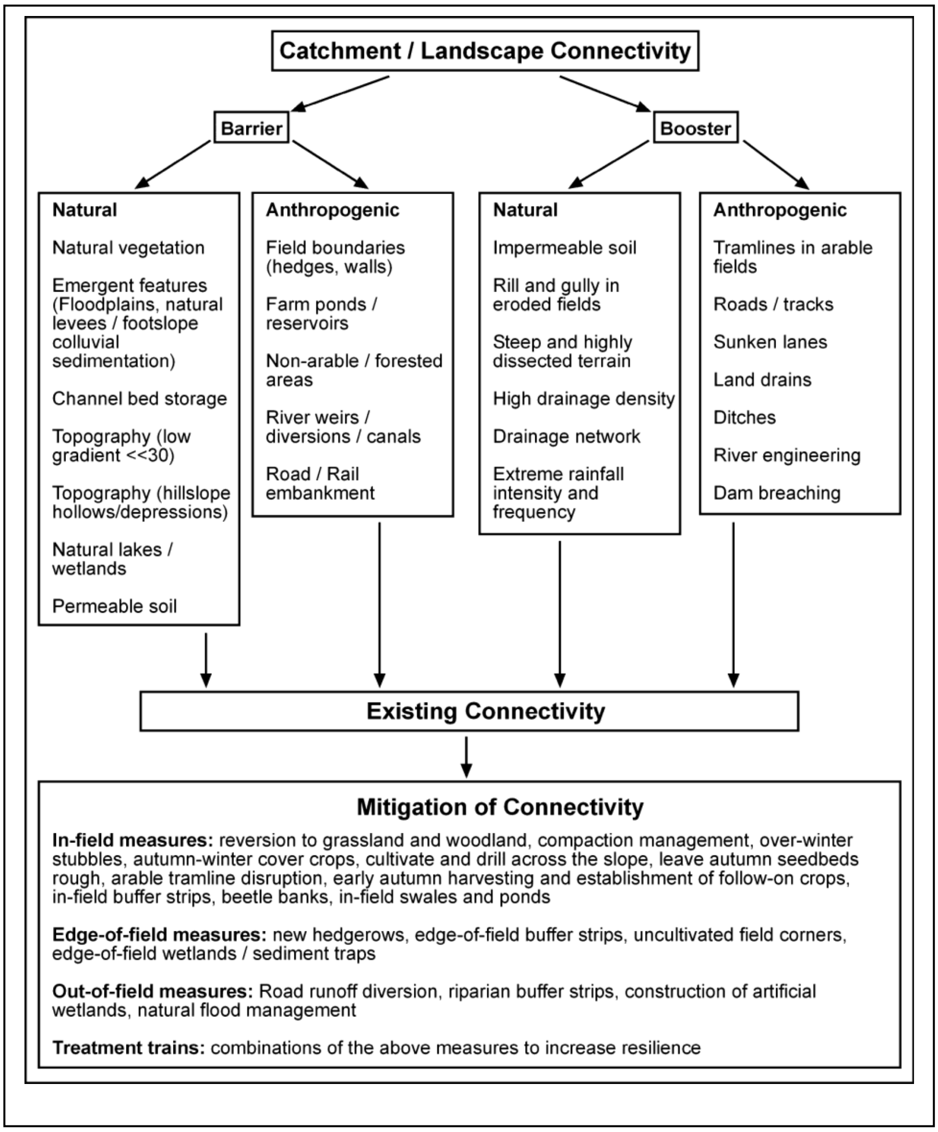
*Evans (1991) gives an uncalibrated ^{14}C date of 400 +/- 65 BP for the basal sediments (3.2 m depth). This gives a calibrated date of between 1424 and 1640 AD at +/- 2SD (Collins *et al.*, 2012).

Table 3 **Particle size characteristics of the surface sediment collected from the Hammer Pond, in tube samplers and from bed disturbance samples from the Hammer Pond outflow and Hammer stream footbridge (see Figure 2 for sampling sites).**

Source	**SSA (m^2 g^{-1})**	**D_{10} (μm)**	**D_{50} (μm)**	**D_{90} (μm)**
Surface Ekman grab samples (Hammer pond)	0.95 +/- 0.14	2.95 +/- 0.38	16.9 +/- 3.36	51.43 +/- 5.45
Outflow Tube (n = 9)	1.77 +/- 0.15	1.50 +/- 0.09	6.17 +/- 1.35	25.5 +/- 7.9
Footbridge Tube (n=9)	1.26 +/- 0.23	1.8 +/- 0.26	21.0 +/- 32.3	213 +/- 52
Outflow Disturbance (n = 9)	1.27 +/- 0.24	1.85 +/- 0.94	12.3 +/- 5.7	161 +/- 98
Footbridge Disturbance (n=9)	0.28 + - 0.09	24.5 +/- 10.5	26.2 +/- 34.7	174 +/- 15

Figures

Figure 1



In-field measures: reversion to grassland and woodland, compaction management, over-winter stubbles, autumn-winter cover crops, cultivate and drill across the slope, leave autumn seedbeds rough, arable tramline disruption, early autumn harvesting and establishment of follow-on crops, in-field buffer strips, beetle banks, in-field swales and ponds

Edge-of-field measures: new hedgerows, edge-of-field buffer strips, uncultivated field corners, edge-of-field wetlands / sediment traps

Out-of-field measures: Road runoff diversion, riparian buffer strips, construction of artificial wetlands, natural flood management

Treatment trains: combinations of the above measures to increase resilience

Figure 2

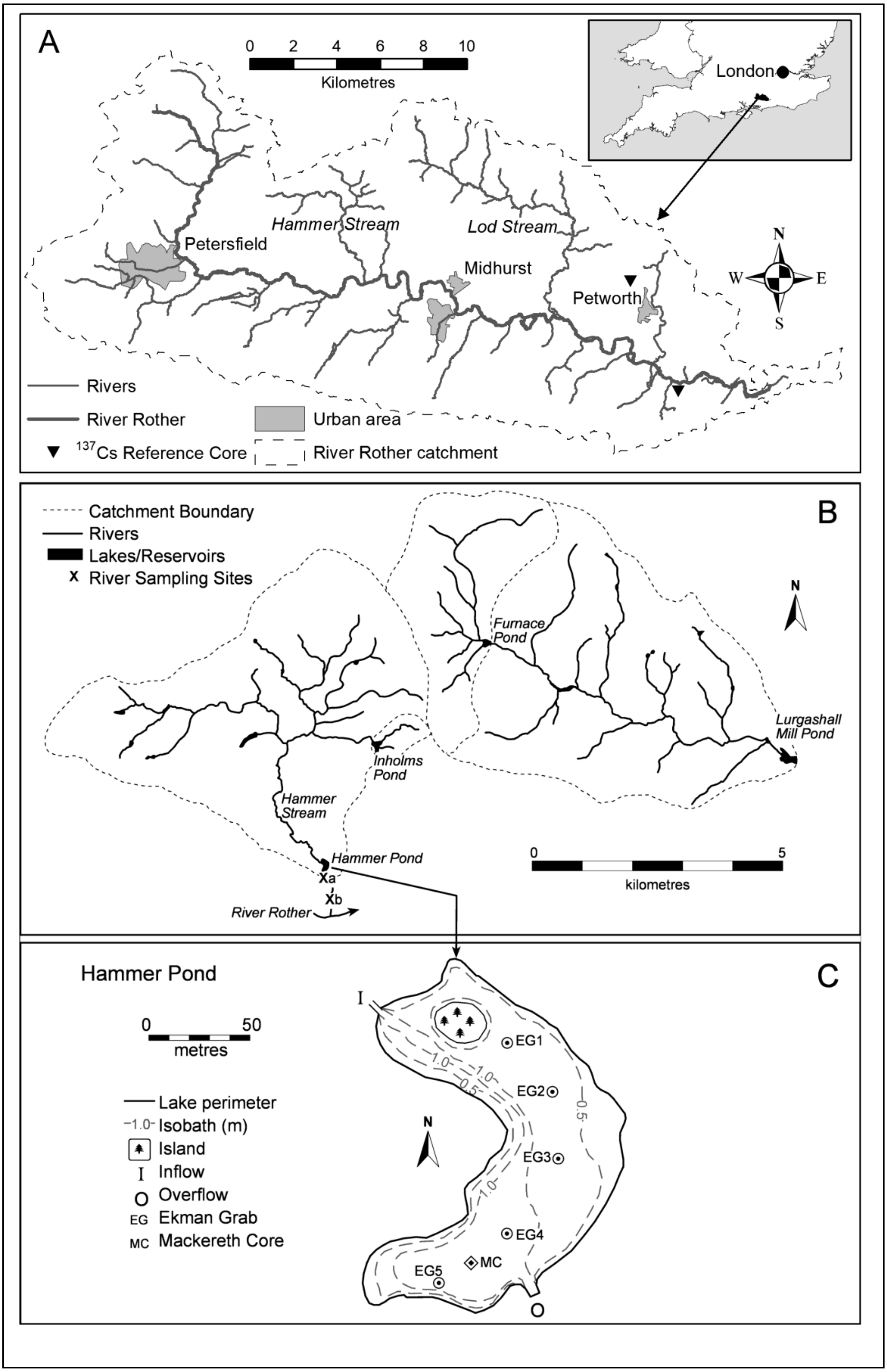

A
0 2 4 6 8 10
Kilometres
London
Petersfield
Hammer Stream
Lod Stream
Midhurst
Petworth
N
W
E
S
Rivers
River Rother
Urban area
^{137}Cs Reference Core
River Rother catchment
B
Catchment Boundary
Rivers
Lakes/Reservoirs
X River Sampling Sites
N
Furnace Pond
Lurgashall Mill Pond
Inholms Pond
Hammer Stream
Hammer Pond
Xa
Xb
River Rother
0 5
kilometres
C
Hammer Pond
0 50
metres
Lake perimeter
-1.0- Isobath (m)
Island
I Inflow
O Overflow
EG Ekman Grab
MC Mackereth Core
N
I
1.0
1.0
0.5
0.5
1.0
EG1
EG2
EG3
EG4
EG5
MC
O

Figure 3

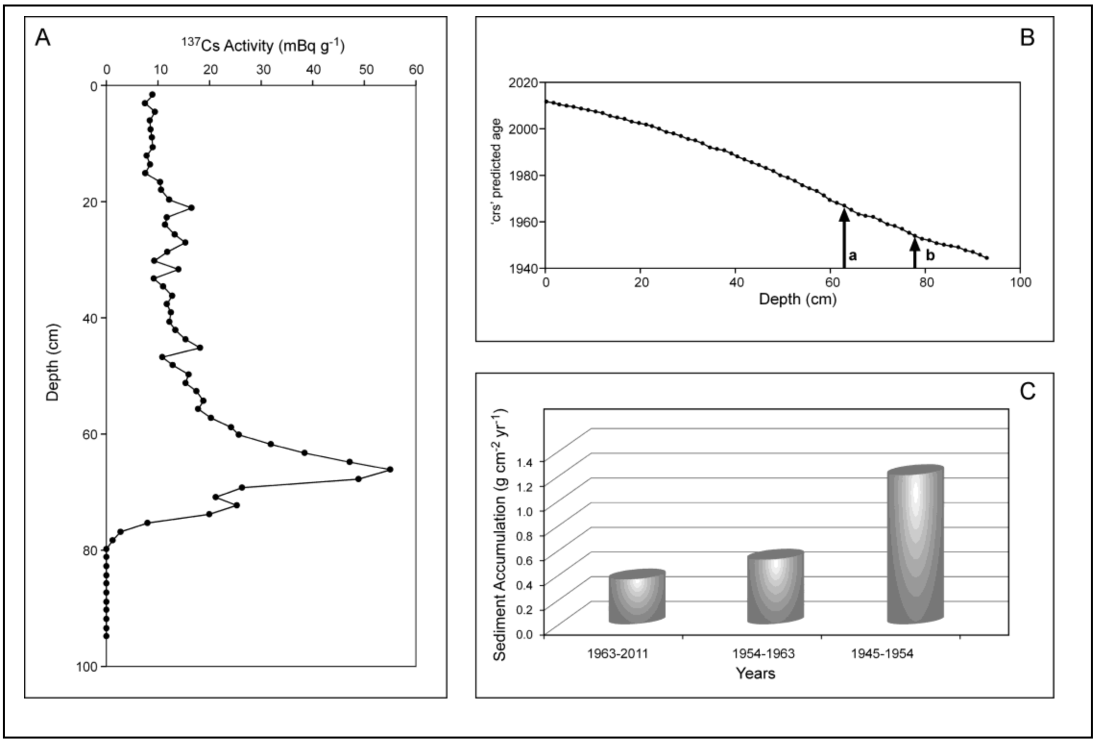


Figure 4

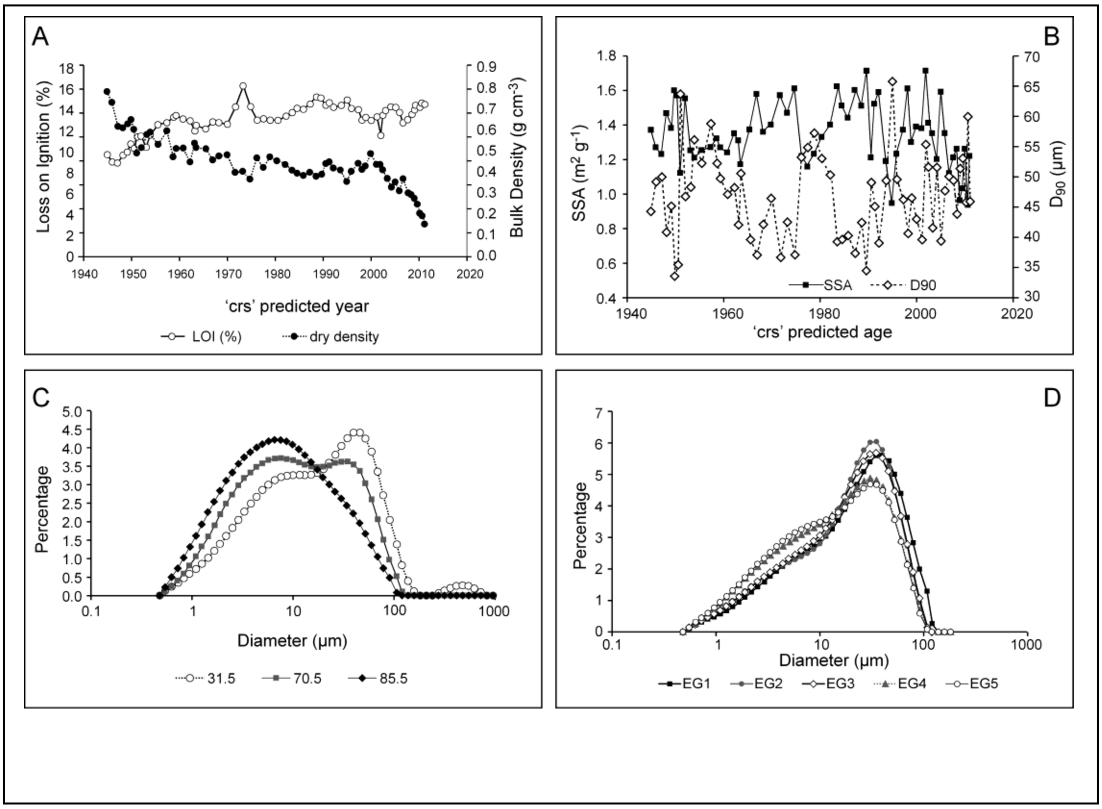


Figure 5

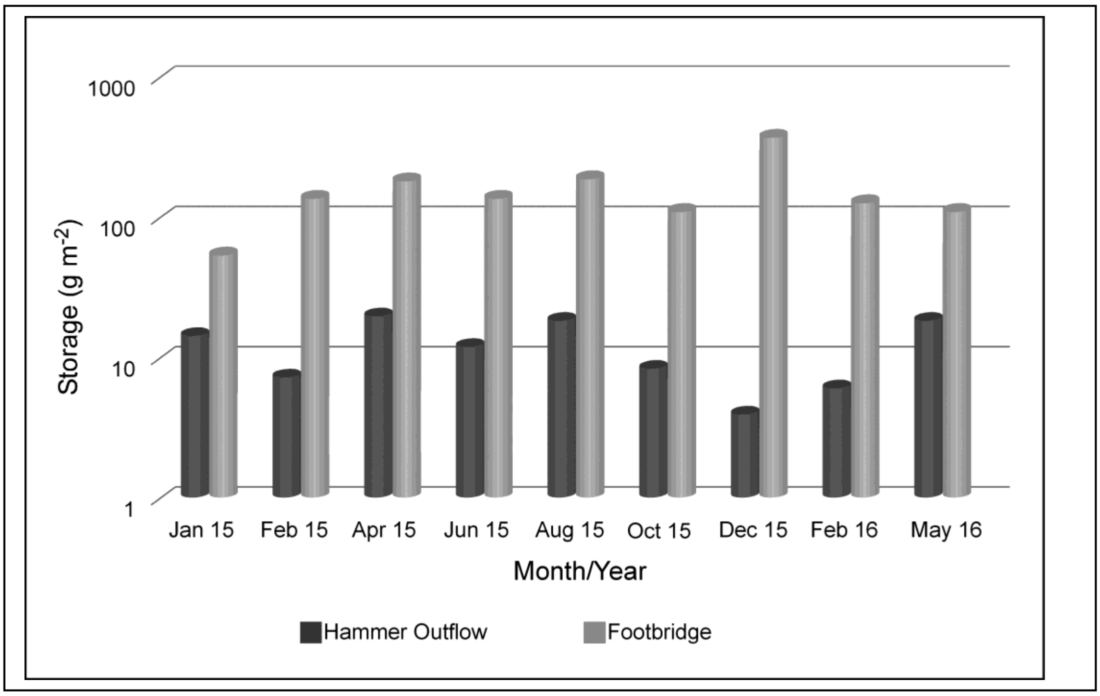


Figure 6

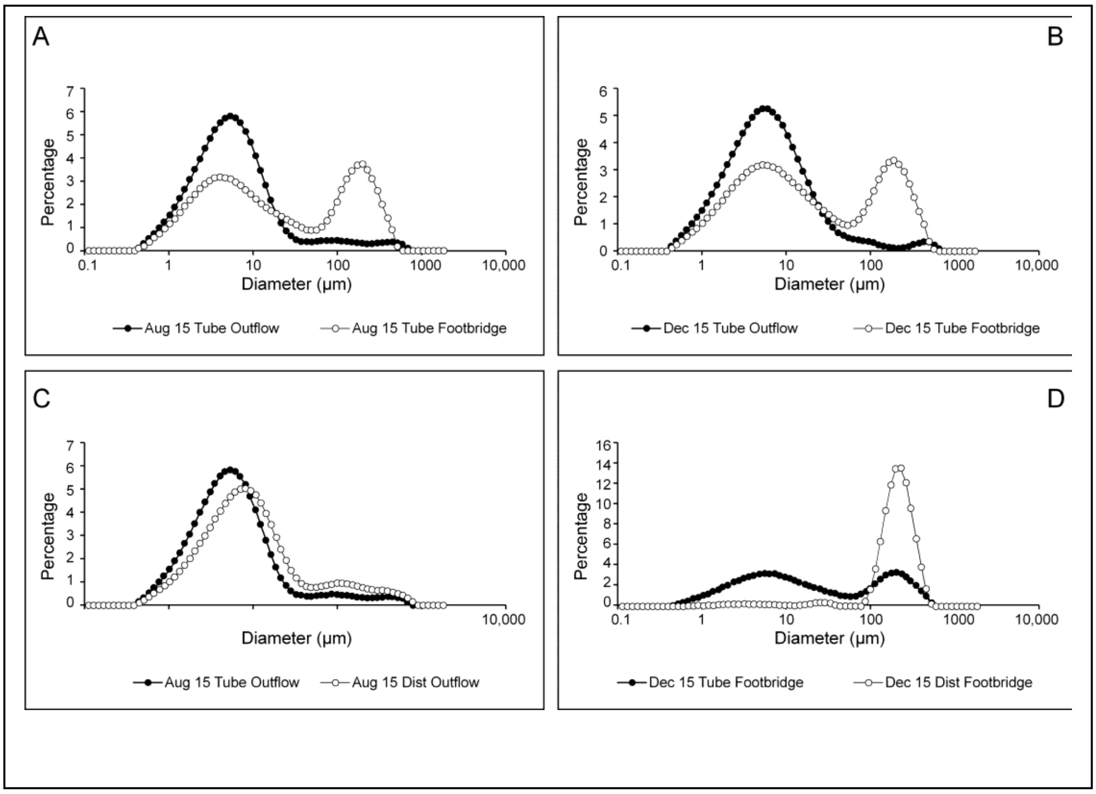
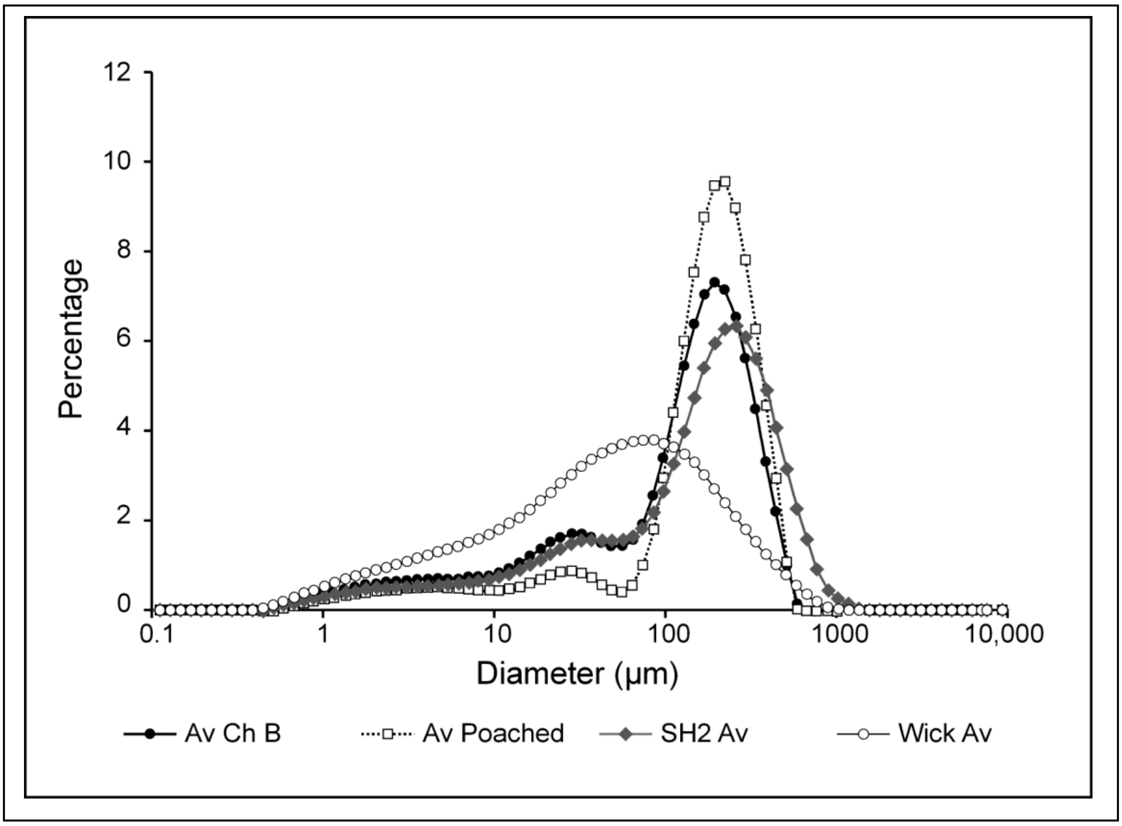


Figure 7



12
10
8
6
4
2
0
Percentage
0.1
1
10
100
1000
10,000
Diameter (µm)
Av Ch B
Av Poached
SH2 Av
Wick Av