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Can channel banks be the dominant source of fine sediment in a UK river?: an example using ^{137}Cs to interpret sediment yield and sediment source.

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Keywords: Fine sediment, channel banks, sediment yield, sediment sources.

Highlights:

- Channel banks contribute 60 – 100% of sediment to the River Nene
- Sediment yields are low at 11.2 – 11.9 t km^{-2} yr^{-1}
- Sediment yields have not increased between the 1906 – 1963 to post 1963 periods
- Low soil erodibility and poor connectivity limit sediment inputs from topsoils
- The topsoil sediment starved river has greater capacity to erode channel banks

Abstract

Cultivated fields have been shown to be the dominant sources of sediment in almost all investigated UK catchments, typically contributing 85 to 95% of sediment inputs. As a result, most catchment management strategies are directed towards mitigating these sediment inputs. However, in many regions of the UK such as the Nene basin there is a paucity of sediment provenance data. This study used the ^{137}Cs inventories of lake and floodplain cores as well as the ^{137}Cs activities of present day sediment to determine sediment provenance. Sediment yields were also reconstructed in a small lake catchment.

Low ^{137}Cs inventories were present in the lake and floodplain cores in comparison to the reference inventory and inventories in cores from other UK catchments. ^{137}Cs activities in the present day sediments were low; falling close to those found in the channel bank catchment samples. It was estimated that 60 to 100% of the sediment in the Nene originated from channel banks.

Pre 1963 sediment yields were approximately 11.2 t km^{-2} yr^{-1} and post 1963 was approximately 11.9 t km^{-2} yr^{-1}. The lack of increased sediment yield post 1963 and low sediment yield is unusual for a UK catchment (where a yield of 28 to 51 t km^{-2} yr^{-1} is typical for a lowland agricultural catchment), but is explained by the low predicted contribution of sediment from agricultural topsoils. The high channel bank contribution is likely caused by the river being starved of sediment from topsoils, increasing its capacity to entrain bank material.

The good agreement between the results derived using cores and recently transported sediments, highlight the reliability of ^{137}Cs when tracing sediment sources. However, care should be taken to assess the potential impacts of sediment particle size, sediment focusing in lakes and the possible remobilisation of ^{137}Cs from sedimentary deposits.

Introduction

The Water Framework Directive (WFD) (2000/60/EC) requires European governments to achieve a 'good' chemical and ecological status of water bodies. While not explicitly addressed in the WFD the key role of sediments in overall water quality and compliance with the WFD has been highlighted (White, 2008; Tueros et al., 2009; Foster & Greenwood, 2016). Excess fine sediment has been shown to be a major cause of environmental degradation, causing harm to aquatic life and a reduction in biodiversity (Newlon and Rabe, 1977; Quinn et al., 1992; Wood and Armitage, 1997; Acornley and Sear, 1999; Clarke and Wharton, 2001). Many anthropogenic changes to the environment have been shown to increase the supply of fine sediment to river systems (Chambers et al., 2000; Carter et al., 2003; Slaymaker, 2003; Foster et al., 2012). Channel bank erosion at natural rates can be desirable creating habitat diversity (Florsheim et al., 2008). However, human alterations to the environment, such as changes in hydrology associated with land use changes and poaching by livestock, can increase rates of bank erosion (Foster & Walling 1994; Moscrip and Montgomery, 1997; Booth and Jackson, 1997) creating sediment pressures on aquatic ecosystems.

Surface erosion from agricultural land has been shown to be a dominant source of sediment in almost all investigated UK catchments, typically contributing 85 to 95% of sediment inputs (Walling et al., 2007). Channel banks are normally a minor sediment source typically contributing 5 to 15% of the sediment to most catchments (Walling et al., 2007). A review by Walling and Collins (2005) indicated that, of the UK catchments investigated at the time of publication, only two had contributions of sediment from channel banks exceeding 50%. These were in the highly urbanised River Aire, Yorkshire (55% from banks) (Carter et al.,

2003) and the rural River Worm, Herefordshire (55% from banks) (Walling et al., unpublished). Additionally, Owens et al (1999) suggested that there was a greater than 50% contribution from channel banks to some floodplain sediment deposits in the rivers Ouse and Wharf in North East England. It was also identified by Walling and Collins (2005)that there was a clear trend of channel banks having a greater relative importance as a sediment source in the northern and western parts of the UK (typically above 30%) (Walling and Collins, 2005). This was attributed to a greater channel density, storm runoff and channel mobility, as well as the lack of cultivated areas, thinner soils and less disturbed vegetation cover in these upland areas (Walling and Collins, 2005). Collins and Anthony (2008) suggested that only in the west of the UK were channel banks likely to typically contribute an annual sediment yield of more than 0.99 t km^{-2} yr^{-1}. For the UK as a whole, mean annual sediment yields from channel banks were suggested to be approximately 2.6 t km^{-2} yr^{-1} (Collins and Anthony, 2008).

In contrast to the UK, channel banks and subsurface sources such as gullies have been shown to be a much more important sediment sources in many catchments worldwide. The European colonisation of Australia has been shown to be associated with extensive gully erosion resulting in up to 90% of sediment originating from subsurface sources (Olley and Wasson 2003; Caitcheon et al., 2012). Gully erosion is also extensive in many parts of South Africa (Boardman and Foster, 2008; Boardman et al., 2015). Additionally, a review of literature by Bull and Kirkby (2002) identified that subsurface erosion has been shown to be a major or dominant source of sediment in drylands in Algeria, Southern France, Northern Morocco, Romania, Spain and Tunisia.

The assumption that topsoil from agricultural land is the dominant source of sediment in UK catchments is a driver of many research and catchment management strategies. For example, Collins et al., (2010b) constrained contributions from channel banks in a fingerprinting investigation to a maximum of 50% on the basis that it was considered unlikely that channel banks would contribute a greater proportion of sediment than this. The loss of field boundaries has led to the loss of traditional sites of sediment deposition and an increase in the risk of sediment export from farm land to rivers as a result of increased connectivity (Boardman and Vandaele, 2015); as a result, remediation work has frequently been directed at restoring these boundaries. Other management strategies directed at mitigating sediment inputs from surface sources involves ploughing around slope contours (Deasy et al., 2008; Deasy et al., 2009a) and the management of tramlines on cultivated fields (Silgram et al., 2010). Riparian fencing is commonly used to prevent poaching by livestock representing one mitigation that is aimed at channel bank inputs (Parkyn, 2004; Collins et al., 2010). However, livestock rearing is perceived to be the driver for the observed erosion rather than the fluvial erosion of banks per se. Given the strong evidence that cultivated land is most often the dominant sediment source in UK catchments, these mitigation methods seem appropriate. However, a review by Walling et al., (2007) showed that sediment yield and sediment provenance data has been obtained extensively in the north and west of the UK but there have been relatively few investigations performed outside of these regions. Therefore, current knowledge of sediment sources can be considered incomplete and the assumption that channel banks are a minor sediment source in almost all UK catchments may be incorrect.

The ^{137}Cs activity of sediment has been widely used to infer its provenance. ^{137}Cs was produced through nuclear fission during atomic weapons testing during the 1950s, 1960s and 1970s (Cambray et al., 1989) or, in some regions, during the 1980s after the Chernobyl nuclear power plant accident (Smith and Clark, 1989). Being a fallout radionuclide ^{137}Cs is delivered to the earth's surface from the atmosphere, primarily in association with rainfall (Davis, 1963; Longmore, 1982). Upon reaching the earth's surface ^{137}Cs is presumed to be rapidly adsorbed to soil and sediment particles (Tamura and Jacobs, 1960; Brisbin et al., 1974; Eyman and Kevern, 1975). ^{137}Cs has been suggested to be largely chemically immobile once associated with soil and sediment particles (Davis, 1963; Lomenick and Tamura, 1965) meaning that its primary means of redistribution around a catchment is when these particles are transported by wind or water. However, it has been identified by Parsons and Foster (2011) that ^{137}Cs mobility may be greater than initially suggested. Due to its nature as a fallout radionuclide large differences in ^{137}Cs activities would be expected in different potential sediment sources. In the case of vertical channel banks, which are not exposed to direct fallout, greatly reduced activities or activities below the limits of detection are usually expected (Walling, 2004). Grassland or woodland topsoils soils would be expected to have higher surface (0-5 cm) activities than cultivated land due a to lack of ploughing mixing the ^{137}Cs more deeply through the soil profile (Walling and Woodward, 1992). ^{137}Cs inventories in lake and floodplain sediments have been calculated to qualitatively interpret the amount of sediment originating from topsoils (He et al., 1996). The ^{137}Cs inventory is defined as the total ^{137}Cs activity per unit area (Bq m^{-2}) of an environment which has received atmospheric fallout that has been subject to radioactive decay but has neither lost nor gained ^{137}Cs as a result of erosion or deposition (Heit et al., 1984). A lake with a high contribution of ^{137} Cs enriched sediment from surface sources will have a significantly higher inventory than one with sediment inputs dominated by subsurface sources. However, care must be taken when interpreting ^{137}Cs inventories as total atmospheric fallout may have been different in different regions, especially when considering regional fallout from the Chernobyl accident (Walling and He 1992; Smith and Clark 1989). Sediment particle size also exerts a strong influence on its ^{137}Cs activity, with fine particles having higher activities due to its larger surface area available for absorption (Livens and Baxter 1988; He and Walling, 1996).

This paper aims to investigate the importance of channel banks as a sediment source in the Nene river basin, a typical river in the East Midlands of the UK. Local observations of this catchment have suggested that channel banks are likely to be a major sediment source, despite the Nene being a catchment primarily used for cultivation, and the lack of any observable gully erosion. ^{137}Cs activities are used to reconstruct sediment yields in a small representative lake catchment in the Nene basin and the ^{137}Cs activities and inventories in recently transported and historically deposited sediments are examined.

Study catchment

The Nene basin is located in the East Midlands region of the UK and has a total area of 1,634 km^2. The catchment has an average annual rainfall recorded at Althorp over the last 140 years of 638 mm (+/- 1 standard deviation of 67 mm). The basin is underlain by Jurassic marine sedimentary deposits mostly comprising silts and clays with some outcrops of ironstone and limestone. On hilltops these deposits are often overlain by Quaternary diamicton and, in valley bottoms, gravels, sands and silts are widely represented (British Geological Survey, 2011). The maximum elevation is 226m Above Ordnance Datum (AOD) decreasing to 40 m AOD at Stanwick. The hillslopes in the catchment have steep gradients (up to 52°) in the west and north of the catchment, hillslopes are generally poorly connected to the river channel due to the presence of wide flat valley bottoms.

The 2007 UK Land Cover Map indicates that land utilisation in the catchment is 56% cultivated land, 22% improved grassland and 9% urban, and the remaining 13% is composed of woodland, rough grassland and surface water (Morton et al., 2011). Land cover in the 1930s was approximately 50% pasture, 25% cultivated land, 3% urban, and the remaining 22% was composed of woodland, rough grassland and surface water (Stamp, 1932). The catchment contains the towns of Northampton, Wellingborough, Daventry, Kettering and Corby which are protected by flood defences that are found extensively along the rivers main channel. Locks are also present downstream of Northampton and produce a stretch of river to the sea which is navigable by boats. The Anglian region catchment management plan (Environment Agency, 2009) reports that only 47% of surface waters in the Nene basin currently achieve good ecological and chemical status; of the reasons stated for poor water quality, fine sediment is suggested to be prominent, however insufficient standards and data are currently available to determine where fine sediment concentrations are excessive. No evidence of rill or gully erosion contributing sediment to the river was observed during the study period.

Sediment yield reconstruction was conducted in the catchment of Sywell Reservoir. The characteristics of this catchment are shown in Table 1. The land use in the catchment is 3% urban areas, 80% agricultural land and 17% woodland; the geology is composed of Jurassic oordial ironstone and mudstone and Quaternary diamicton.

Materials and methods

Sediment sampling

Sywell reservoir was chosen as a representative lake catchment for sediment yield reconstruction on the basis of its comparable land utilisation and geology to the central part of the Nene basin, and the fact that it has had a continuous 105 years undisturbed record of sediment deposition since its construction in 1906 (Figure 1). Historical changes in sediment yield were reconstructed by determining the mass of sediment accumulated in the reservoir, using sediment coring to determine the depth and density of accumulated sediment, and a bathymetric survey to determine the area of sedimentation.

A total of seven sediment cores were retrieved from the reservoir using a ‘mini-Mackereth’ pneumatic corer (Mackereth, 1969). The cores were collected in Perspex tubes of ~ 5 cm internal diameter and 1 m length using the methods described by Foster and Walling (1994) and Foster (2010). The bathymetric survey of the reservoir was performed using echo sounding and a differential GPS in a series of nine transects. Recorded depths were corrected to the maximum reservoir volume at the spill weir, and were extrapolated to produce a bathymetric map of the reservoir using ARC GIS 10 and the “topo to raster” function, based upon the methods described by Hutchinson and Dowling (1991).

Four floodplain cores were retrieved to determine total ^{137}Cs inventories in deposited sediments throughout the Nene basin at a distance of ~ 10 m from the main channel (Figure 1). The cores were retrieved using a steel percussion corer of ~6 cm internal diameter and 75 cm length. The corer was driven into the floodplain using a sledge hammer and recovered using a tripod mounted chain hoist.

Suspended and recently deposited overbank sediment samples were collected between September 2011 and March 2013 to compare their ^{137}Cs activities with samples of potential surface and subsurface sediment sources (sampling locations are shown in Figure 1). Suspended sediment was collected using time-integrated samplers based upon the design of Philips et al., (2000). These have been shown to provide a representative sample of suspended sediment over a range of flow conditions. The traps were installed at 60% of the water depth during the time of installation which was a period of drought. Traps were emptied monthly between September 2011 and March 2013. Samples of sediment recently deposited overbank in the riparian zone of the river were collected after four overbank events in April, July October and November 2012. The samples were washed from the leaves of Comfrey (*Symphytum officinale)* and Stinging Nettle (*Urtica dioica)* within 24 hours of flood waters receding.

Samples of potential sediment sources were collected throughout the Nene basin from cultivated land (173 samples), improved grassland (74 samples), urban road dusts (21 samples) and channel banks (90 samples). Samples from cultivated land and pasture were collected from the top 2 cm of the soil using a non-metallic trowel. Channel bank samples were retrieved from visibly eroding channel banks using a non-metallic trowel. Urban street dust samples were collected from the edges of major roads using a plastic dustpan and brush. Each sample consisted of an amalgamation of five subsamples collected from within a 15 m radius of the sampling point.

Laboratory analysis

The lake cores were sectioned into 1 cm slices and the floodplain cores into 2 cm slices. Each core section, source and recently transported sediment sample was oven dried at 40°C. After drying the density of each slice of sediment core was recorded. Sediment source samples were then sieved to <63 µm to approximately match the particle size of the sediment samples.

The ^{137}Cs activity of the samples was measured using Gamma spectroscopy with an Ortec EG&G hyper-pure Ge gamma detector in a well configuration using the methods of Foster et al., (2007). Approximately 3 g of sample was packed to a depth of 4 cm in PTFE sample pots. The samples were measured for a minimum of two days (>172,800s) and source samples for a minimum of one day (>86,400s). The 1963 peak in ^{137}Cs activity was determined for a master Sywell reservoir core (activities were not measured for the other six cores retrieved from the reservoir) and each floodplain core.

Low frequency magnetic susceptibility (χlf) was measured for each slice of the seven Sywell Reservoir cores for the purpose of transferring the depth of the 1963 ^{137}Cs peak in the measured master cored to the other six cores. χlf was measured using 5 – 10 g of sediment tightly packed into 10 ml sample pots placed into a Bartington Instruments MS2B magnetic susceptibility meter.

The particle size of each source and sediment sample was determined using a Malvern Mastersizer 2000 laser granulometer with a Malvern 2000 MU wet sample dispersal unit. Approximately 0.2 g of sample was dispersed using Hydrogen Peroxide at room temperature for 24 hours and at 80 °C for a further 4 hours. Samples were then treated with 5 ml of 3% sodium hexametaphosphate and 2 minutes of ultrasonic dispersal. D50 (median) particle size was calculated to represent sample particle size.

The organic matter content of the samples was determined using loss on ignition (LOI) at 450°C for 4 hours in a Carbolite muffle furnace following the methods laid out by Grimshaw et al. (1989).

Results

Sediment yield reconstruction in Sywell Reservoir

The peak in ^{137}Cs activity at 22 cm in the master Sywell Reservoir core was tentatively identified as the year of maximum fallout in 1963 (Figure 2). The depth of 1963 in the master core was transferred to the other cores using a core correlation of χlf where possible or at a proportional depth to 22 cm where peaks in χlf were not clear. The basal date of the reservoir sediments at 1906 was also known and so was assigned to the base of each core. Using these date markers it was calculated that between 1906 and 1963 a mean depth of 17 cm of sediment accumulated in 57 years with a mass of 5.20 g cm^{-2}; equating to a sediment accumulation rate of 0.091 g cm^{-2} yr^{-1}. Between 1963 and 2010 a mean of 16 cm of sediment accumulated in 48 years with a mass of 4.64 g cm^{-2}; equating to an accumulation rate of 0.097 g cm^{-2} yr^{-1}. The area of sedimentation in the reservoir was identified as lying at the 3.9 m isobath as no sediment was found in cores retrieved from shallower water (Figure 3). Using the area of sedimentation (107,000 m^2), and a catchment area of 8.68 km^2, sediment yields of 11.2 t km^2 yr^{-1} from 1906 – 1963 and 11.9 t km^2 yr^{-1} from 1963 – 2010 were calculated. These estimates lie within the expected error margins of sediment yield reconstruction suggesting that sediment yields over the last ~ 100 years have remained relatively constant. The sediment yield was calculated as the total yield with no subtraction of the quantities of organic material in the sediment. The mean organic content of the core sediments pre 1963 was 8.23% and post 1963 was 9.57%.

^{137}Cs inventories in lake and floodplain cores

The ^{137}Cs in the recently deposited (0 to 5 cm) reservoir sediments (Figure 2) are high compared to activities in contemporary catchment source samples screened to < 63µm (see Table 3). Additionally, the total ^{137}Cs inventory is high in comparison to the local reference inventory (Table 2). This finding may indicate delayed inputs of ^{137}Cs from the catchment associated with a change in sediment source as there is no recorded evidence of Chernobyl fallout in this region of the UK (Smith and Beresford, 2005). However, the activities in the reservoir sediments are well in excess of those measured in the grassland and cultivated land catchment samples taken from surface sources and measured in the same detectors (Table 3). An alternative explanation is that the steep sides of the reservoir may have caused sediment focusing and extension of the

^{137}Cs peak. The sedimentation limit of the reservoir is between 50% and 60% of the lake area, suggesting that ^{137}Cs would be focused into a smaller area of the lake raising the calculated inventory and elongating the 1963 peak. Correcting the total inventory for sediment focusing suggests that the total inventory is only slightly higher than the reference inventory (1032 – 1239 compared to 840 Bq m^{-2}). Given that the mean ^{137}Cs activity of channel bank samples collected in the Sywell catchment is 2.5 mBq g^{-1} (standard deviation = 2.90, n=25), and that the particle size of the sediment in the reservoir is very fine (Mean D50 = 7.55 µm) it seems unlikely that significant quantities of sediment in the reservoir could have originated from topsoil.

The total ^{137}Cs inventories of the floodplain cores from the Nene catchment are variable with the low inventory of the Kingsthorpe core suggesting very low inputs of topsoil derived sediment. The inventories in the Upton, Earls Barton and Stanwick floodplain cores are higher, suggesting inputs of greater amounts of topsoil-derived sediments. The fine particle size of these cores does however suggest that the high inventories may be a result of the selective deposition of very fine sediments which are likely to have high ^{137}Cs activities due to their larger surface area.

The total ^{137}Cs inventories of the cores retrieved from the Nene basin were compared to those published for other UK lakes and floodplains. A total of 41 previously published inventories were found and decay corrected to 2011, the year that the cores were retrieved from the Nene basin, a map of these inventories is shown in (Figure 7). The 0^{th} through to the 100^{th} percentile ^{137}Cs inventories were calculated for the total ^{137}Cs inventory dataset (excluding the cores retrieved in the Nene basin) (Figure 4). A wide range of values was found for the previously published inventories with some inventories being in excess of 10,000 Bq m^{-2}. The high inventories found in Chew valley lake, Furnace pond B, Groby pool, Turton and

Entwhistle Reservoir and Barnes Loch may be explained by some Chernobyl fallout (Smith and Beresford, 2005). However, many high inventories are found in areas not documented to have experienced high Chernobyl fallout (e.g. Boltby Reservoir). These data suggest that sediment provenance, particle size and sediment accumulation rates are highly variable in UK catchments. This is especially evident in Gormire, Boltby Reservoir and Elleron Lake where very different inventories are found in lakes in close physical proximity to each other.

Comparing the cores retrieved from the Nene basin to the inventories for other UK lakes shows that the Sywell core (when uncorrected for sediment focusing) falls well below the 20th percentile ^{137}Cs inventory of previously sampled UK cores; the Stanwick and Upton cores fall close to the 10th percentile and the Earls Barton and Kingsthorpe inventories are below the 10th percentile. Therefore, the Nene basin would be expected to have a much smaller contribution of sediment from surface agricultural sources than ~90% of other investigated lake and floodplain sites in the UK for which published data are available.

Mapping the ^{137}Cs inventories for the Nene cores and previously published inventories shows that, with the exception of Groby pool Leicestershire which may have received some Chernobyl fallout (Smith and Beresford, 2005), the Nene cores are found in a central region of the UK with low ^{137}Cs inventories. The highest inventories are found in the north and west of the UK, however, inventories are highly variable with many low inventories in these regions and some higher inventories in the south east.

^{137}Cs activities in recently transported and deposited sediments

An examination of ^{137}Cs activities in the suspended sediment samples retrieved from the Nene shows that they are very close to those found in the sieved channel banks and urban street dust source samples (Figure 5). Only in the Dodford site is the mean activity of the suspended sediment close to that found in cultivated land or grassland. As only a small proportion (9%) of the Nene basin is covered by urban areas and research by Pulley et al. (2015b) showed little evidence of urban pollutants (Pb, Cu, and Zn) outside of a small reach of the river close to the town of Northampton suggesting minimal sediment inputs from urban areas; these results suggest that channel banks are the source of almost all of the suspended sediment present in the Nene.

As with the current suspended sediment samples, ^{137}Cs activities in the recently deposited overbank sediment are very low and suggest that almost all sediment in the catchment originates from channel banks (Figure 6). In the Dodford site the high ^{137}Cs activities found in the suspended sediment are not present in the overbank sediment suggesting that during very high flows, topsoils are a relatively minor sediment source. The low observed activities in both suspended and overbank sediment (Figure 5 and 6) suggest that up to 100% of sediment could originate from channel banks, with most sites suggesting that at least 60% of sediment originates from channel banks.

As sediment particle size has been shown to be strongly correlated with ^{137}Cs activity the particle size of the sediment samples was compared to the source samples. The D50 particle size of the suspended sediment samples is generally finer than that of the source samples, suggesting that some enrichment of the ^{137}Cs activity of the sediment would be expected (Table 3). Therefore, contributions of sediment from channel banks are likely to be even higher than suggested by Figure 5. The mean D50 in the overbank sediment is generally coarser than the source samples, partially explaining the very low ^{137}Cs activities found which were often lower than in most channel bank source samples. However, the mean D50 of the overbank sediments is not substantially coarser than the sieved source samples suggesting that most of the overbank sediment does originate from channel banks, as Figure 6 suggests. A plot of sediment and source sample D50 against ^{137}Cs activity (see online supplementary material) does however show that there is no significant relationship between the two factors suggesting particle size does not exert a large influence on ^{137}Cs activity in the Nene basin.

It is also of note that the mean D50 particle size of the sediment in the Sywell, Upton, Earls Barton and Stanwick cores (Table 2) are finer than almost all of the source and present day sediment samples, adding further evidence that their low inventories represent small contributions of sediment from surface sources.

Discussion

Sediment yields in UK catchments have been shown to range from 1 to 286 t km^{-2} yr^{-1} (Walling et al., 2007). The Nene represents a lowland agricultural catchment with a total area of between 1000 and 10,000 km^2, where a sediment yield of between 28 and 51 t km^{-2} yr^{-1} would be expected (Walling et al., 2007). The sediment yields of 11.9 t km^{-2} yr^{-1} (1963-2010) and 11.2 t km^{-2} yr^{-1} (1906-1963) for the pre and post 1963 period in Sywell reservoir are therefore substantially lower than would be expected. Pulley (2014) measured present day sediment yields in the Whilton arm (Dodford) of the Nene at 13 t km^2 yr^{-1} and in the Brampton arm (St Georges Avenue) at 19 t km^{-2} yr^{-1} using a suspended sediment : turbidity calibration and gauged flow records provided by the UK Environment Agency at their gauging stations. These values are comparable to those reconstructed at Sywell reservoir. A 1967 - 1978 study of the Nene published by Wilmot and Collins (1981) measured a lower sediment yield of 5 t km^{-2} yr^{-1} to 10 t km^{-2} yr^{-1}. However, this research was conducted close to the mouth of the Nene, downstream of floodplains where sediment deposition and long term storage would be expected to reduce downstream sediment yields from a much larger catchment with a likely lower sediment delivery ratio.

The findings of Rose et al., (2011) showed that in over 200 investigated European lakes, a significant increase in sediment accumulation rate occurred after 1950. This increase has been attributed to post Second World War agricultural intensification as reported by Foster and Walling (1994) and Foster et al., (2011). The lack of a significant increase in sediment yield observed in Sywell Reservoir after 1963 is therefore highly unusual in comparison to other European catchments. This finding is also highly unusual considering that the increase in the percentage of the Nene basin utilised as cultivated land rose from 25% in the 1930s (Stamp, 1932) to 56% in 2007 (Morton et al., 2011).

That channel banks are the dominant sediment source in the Nene is also highly unusual for a UK catchment. A general range of contributions from sediment sources in UK catchments is 85-95% from surface sources and 5-15% from channel bank /subsurface sources (Walling et al., 2007).

The suggested low contributions of sediment from surface sources (suggested to be close 0% in many samples) may be explained by the very limited connectivity which was observed during sampling and from aerial photographs of the catchment. Well maintained buffer strips are extensive either side of the channel for ~ 5 m width on each side of the smaller tributaries and ~ 10 m wide on each side of the main channel. There were few bridging points present which reduce road to river connectivity and connections to remote parts of the catchment via the road network. The valley bottoms of the catchment are generally flat and wide, thereby reducing lateral connectivity and disrupting hillslope to channel linkages. The low erodibility of the soils within the basin are also likely to be a significant factor causing the low contribution of sediment from cultivated land. (Table 4; Evans, 1990).

The finding that channel banks are the dominant sediment source does, however, explain the low observed sediment yields. The increased amount of cultivated land in the catchment after the 1930s does not appear to be contributing significant amounts of sediment to the river. A similar dominance of subsurface sources was found by Neal and Anders (2015) in the Wildcat Slough in central Illinois which, like the Nene basin, is a low-gradient agricultural watershed. As in the Nene basin the result was attributed to disconnectivity between agricultural uplands and the rivers channel, reflecting the low relief of the uplands.

Total sediment yields originating from channel banks in the Nene are estimated to be in the range of 6.72 to 11.9 t km^2 yr^{-1} which was calculated using a total sediment yield of 11.9 t km^{-2} yr^{-1} (1963-2010) and 11.2 t km^{-2} yr^{-1} (1906-1963) with 60 – 100% of the sediment originating from channel banks. This may be higher in other parts of the Nene as Pulley (2014) measured a sediment yield of up to 19 t km^{-2} yr^{-1} in the Brampton arm of the Nene. These values are significantly higher than the mean sediment yield of 2.6 t km^{-2} yr^{-1} estimated to originate from channel banks in UK catchments by Collins and Anthony (2008). However, these values are not outside of the sediment yield from channel banks expected in upland catchments with high total sediment yields (27-111 t km^{-2} yr^{-1}) where only a low percentage contribution of sediment from channel banks would be required to exceed the yield from channel banks found in the Nene. Therefore, the sediment yield from channel banks in the Nene basin is high but not atypical for a UK catchment.

The reason for these high contributions from channel banks in the Nene basin is uncertain. Bank retreat was observed during the study period especially after large flood events. Fresh bank material was exposed after the events rather than the surface drapes of sediment present before the events and where sediment traps were installed banks became noticeably further away from the traps.

The poaching of banks by livestock was only observed in one isolated field within the basin, discounting this as a major reason for bank instability. It was also observed that there was almost no connectivity between agricultural land and the river due to the widespread presence of riparian fencing and buffer strips. It is therefore likely that the low contributions of sediment originating from agricultural land is starving the river of sediment and resulting in the enhanced entrainment of available bed and bank material (Williams and Wolman, 1984). The lack of a significant change in sediment yield suggests that this has been the condition of the river since the early 20th Century and represents the semi-natural condition of the Nene basin.

The effects of particle size in this study appear to have been accounted for reasonably simply due to the generally fine particle size of the sediment and the low ^{137}Cs activities and inventories. A fine particle size would be expected to increase ^{137}Cs activities and inventories, therefore, the fact that they were low suggested an even greater contribution of sediment from channel banks. The effects of the post-depositional mobilisation of ^{137}Cs on floodplain cores is less easily accounted for. Pulley et al., (2015) suggested that some floodplain cores in the Nene were affected by the dissolution of iron oxides. As a result the

^{137}Cs adsorbed to these minerals could have been lost to solution. Therefore, care must be taken when interpreting floodplain inventories. In the example of this investigation the good agreement between the floodplain and lake cores and the present day sediment suggest that dissolution is not causing a major change in the interpretation of floodplain ^{137}Cs inventories.

Conclusions

The results of this study have shown that, unlike most UK catchments, anthropogenic changes to the Nene basin have not resulted in increased sediment yields and increased sediment inputs from agricultural land. The low erodibility of the catchment soils, fairly flat topography and the widespread presence of riparian fencing and buffer strips explained the lack of sediment inputs from agricultural land. As a result, channel banks are the dominant sediment source contributing close to 100% of sediment inputs to the river Nene. The lack of surface sediment inputs resulted in a low sediment yield of only 11.2 to 11.9 t km^2 yr^{-1}.

The use of ^{137}Cs in this study highlights the good agreement between the inventories in floodplain and lake cores and activities in present day suspended and recently deposited sediments.; providing additional validation to the reliability of this widely used environmental tracer.

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Figures and Tables

Table 1: Characteristics of the Sywell Catchment and Reservoir

Catchment Area (witrh reservoir) (ha)	896
Catchment Area (Excluding Reservoir) (ha)	868
Reservoir Area (ha)	28
Reservoir Volume (m^3)	1.2 x 10^6
Reservoir Capacity : Inflow Ratio (%)	0.8
Reservoir Trap Efficiency (Brune 1953)*	>95% (present day volume)
Catchment:Lake Area Ratio (Dimensionless)	31:1
Maximum Altitude (m)	139
Minimum Altitude (m)	79
Relative Relief (m)	60

*Based on the capacity:inflow ratio. Runoff was calculated using flow data from the Nene Catchment in Northampton. Volume was estimated from a bathymetric survey.

Table 2: Total ^{137}Cs inventories and D50 particle size in the cores collected in the Nene and background value from Eyebrook Reservoir (20 km north of the Nene basin with an average annual rainfall of 608 mm) Foster et al. (2008 unpublished); values are decay corrected to 2011.

Sampling location	Total inventory (Bq m^{-2})	D50 (µm)	D50 standard deviation
Background	840 (+/- 90)	28.5	4.01
Sywell reservoir	2065 (1032- 1239*)	7.55	2.03
Upton Floodplain	1603	7.13	1.87
Kingsthorpe Floodplain	910	36.18	9.76
Earls Barton Floodplain	1400	10.13	11.29
Stanwick Floodplain	1623	7.97	0.90

* corrected for sediment focusing.

Table 3: Mean and standard deviation D50 and ^{137}Cs activities in source and suspended sediment samples retrieved from the Nene basin.

	D50 (µm)	^{137}Cs activity (mBq g^{-1})

Cultivated	**Mean**	**14.63**	**2.85**
	Standard deviation	3.75	1.67
Grassland	**Mean**	**17.18**	**4.12**
	Standard deviation	4.12	3.06
Channel Bank	**Mean**	**14.38**	**1.59**
	Standard deviation	4.20	3.20
Urban street dusts	**Mean**	**21.82**	**0.78**
	Standard deviation	5.77	0.68

T1	**Mean**	**14.37**	**0.95**
	Standard deviation	6.89	0.70
T2	**Mean**	**12.54**	**0.89**
	Standard deviation	3.22	0.58
Dodford	**Mean**	**9.05**	**2.28**
	Standard deviation	0.79	0.61
Heyford	**Mean**	**12.29**	**1.15**
	Standard deviation	3.46	1.25
Kislingbury	**Mean**	**10.30**	**1.50**
	Standard deviation	1.52	0.53
Northampton	**Mean**	**8.50**	**1.55**
	Standard deviation	1.25	0.98
Wellingborough	**Mean**	**12.47**	**0.75**
	Standard deviation	2.73	0.44
Knuston	**Mean**	**12.70**	**1.04**
	Standard deviation	3.67	0.86

Table 4: Classification of soils and their water erosion risk in the Sywell Catchment.

Soil Assoc' Code	Soil Type	Soil Association	Water Erosion Risk (based on Evans, 1990 5 point scale; very small, small, moderate, high, very high)
712g	Pelo-stagnogley	Ragdale	very small
411d	Calcareous pelosol	Hanslope	small
511b	Brown calcareous earth	Moreton	moderate
544	Ferritic brown earth	Banbury	moderate
712b	Pelo-stagnogley	Denchworth	very small

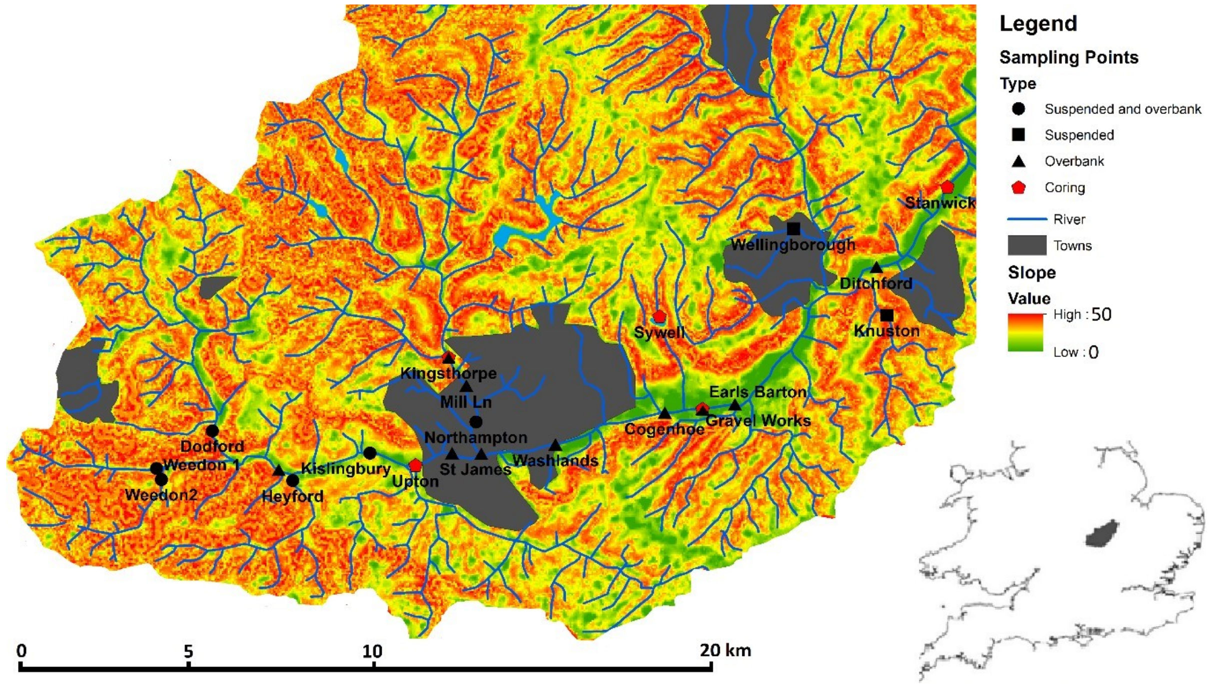


Figure 1: Sediment sampling locations, river channels and slope angle of the Nene basin.

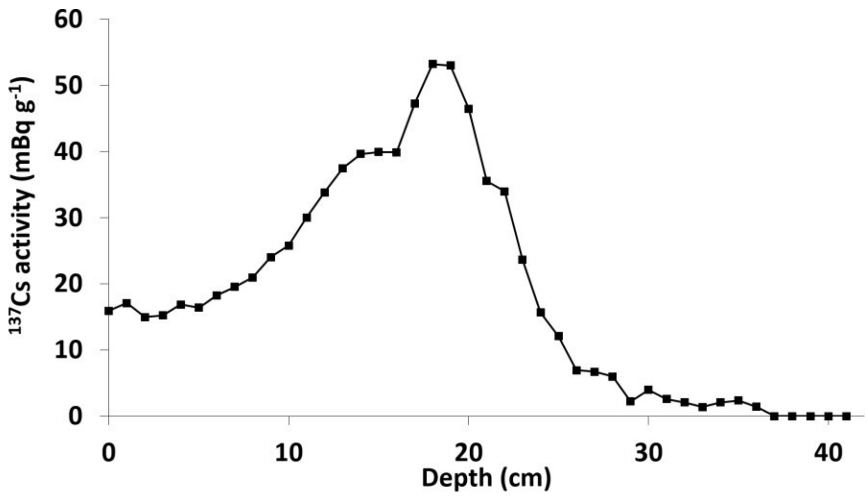


Figure 2: Down-core variations in ^{137}Cs activity in Sywell reservoir.

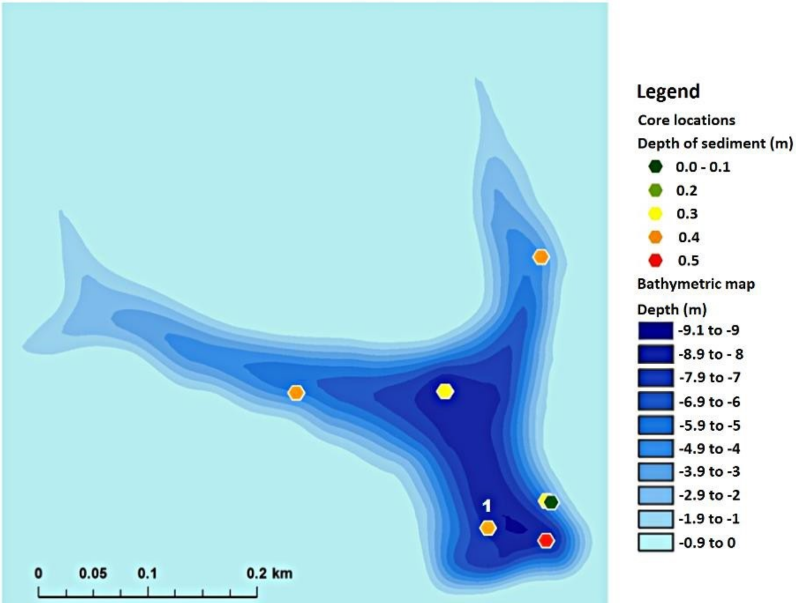
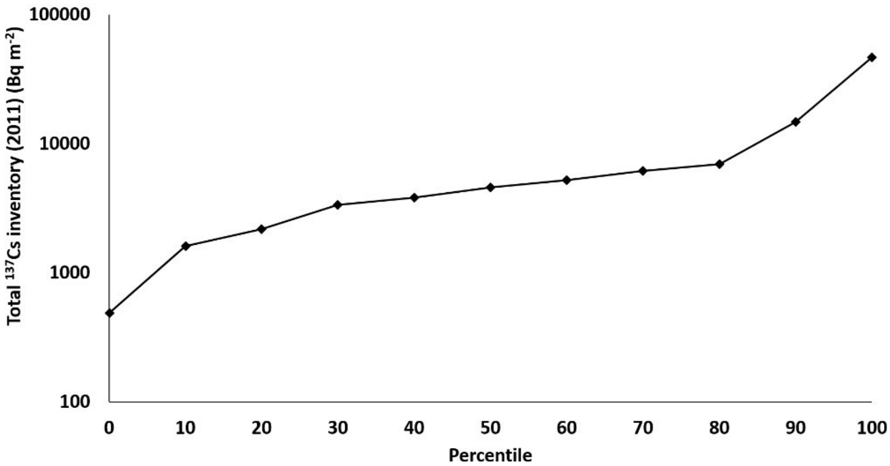


Figure 3: Bathymetric map, coring locations and depth of sediment in collected cores in Sywell reservoir.



Percentile	Total inventory (2011) (Bq m^{-2})
0	488
10	1610
20	2176
30	3363
40	3812
50	4570
60	5224
70	6137
80	6963
90	14738
100	46547

Figure 4: Total ^{137}Cs inventories in UK lake and floodplain cores for 41 sites not including those in the Nene.

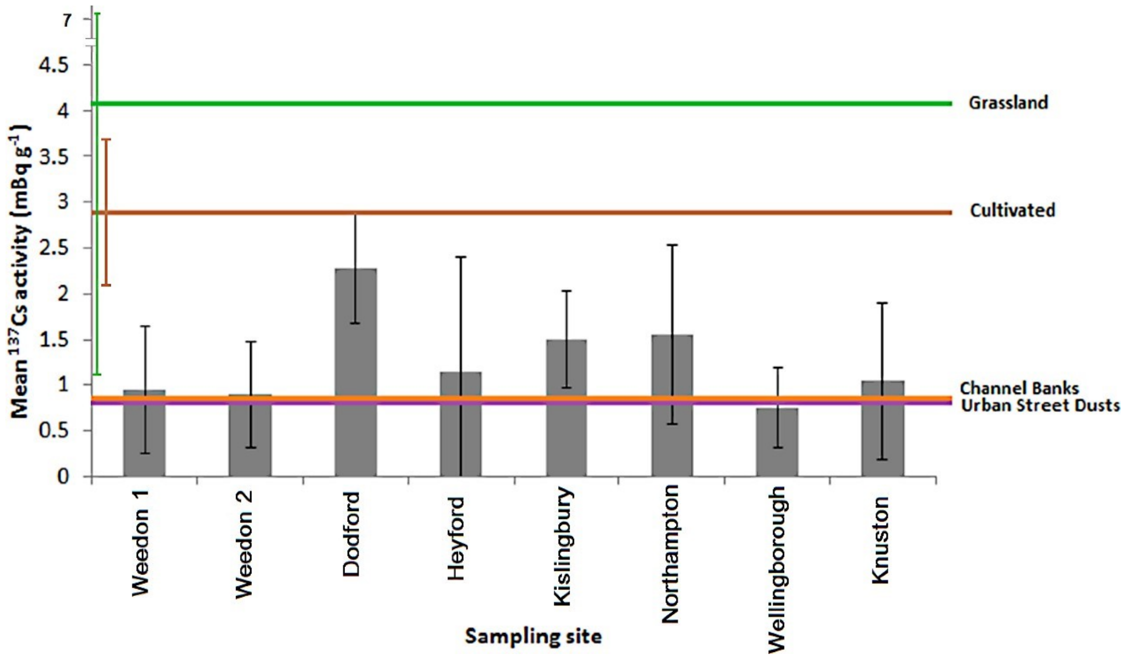


Figure 5: Mean ^{137}Cs concentrations in suspended sediment and potential sediment sources, with standard deviation.

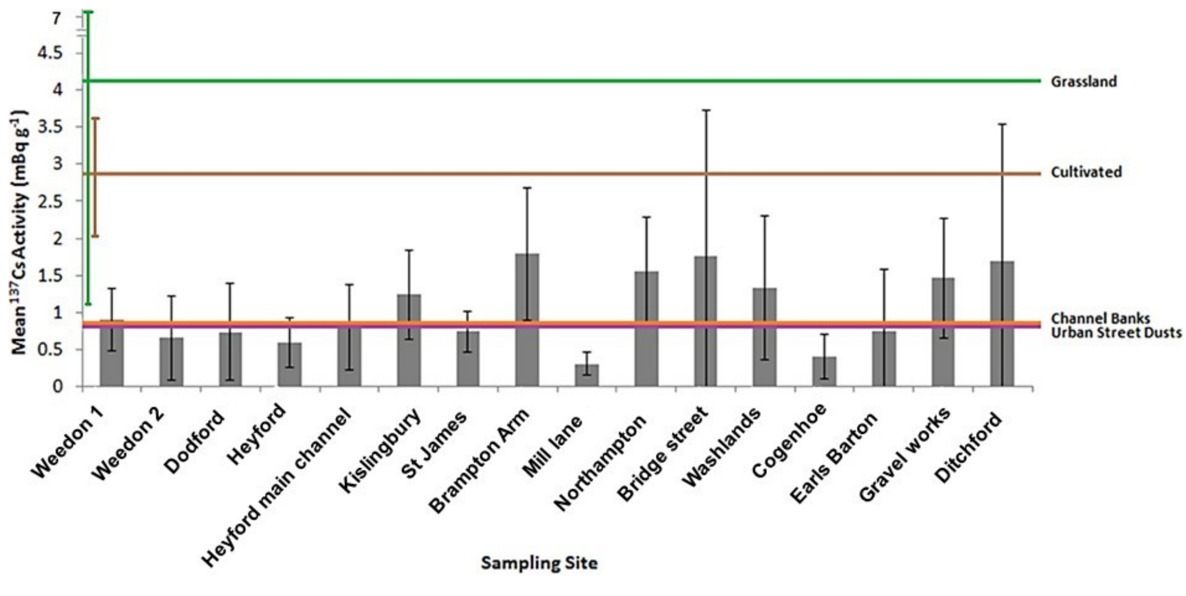


Figure 6: Mean ^{137}Cs concentrations in recently deposited overbank sediment and potential sediment sources, with standard deviation.

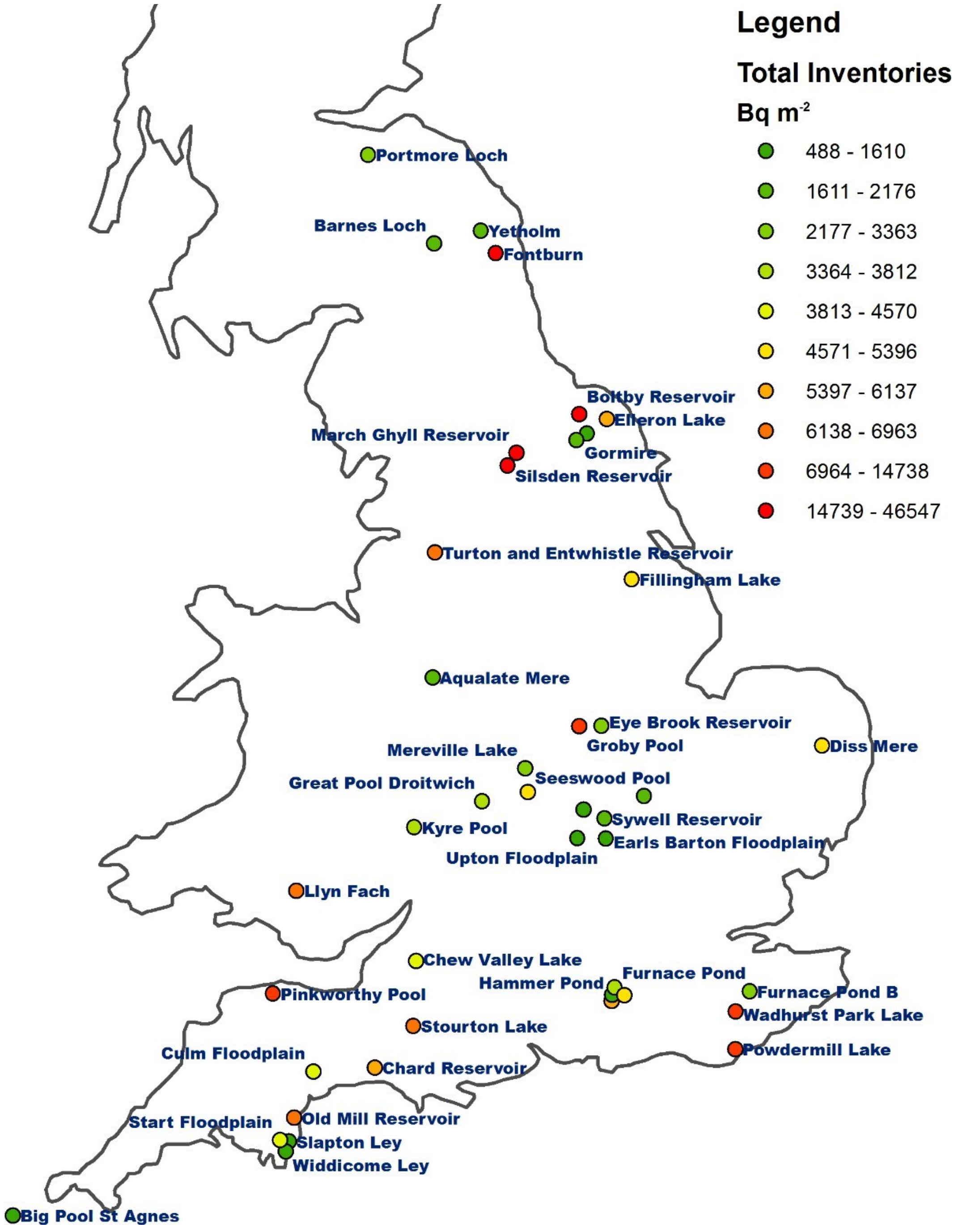


Figure 7: Total ^{137}Cs inventories in UK lake and floodplain cores. Gormire, Llyn Fach, Great Pool Droitwich, Groby Pool, Pinkworthy Pool, Portmore Loch, Powdermill Lake, Turton & Entwistle (calculated using the data presented by Yang and Rose, 2005); Furnace pond B, Chard Reservoir, Wadhurst Park Lake, Stourton Lake He et al., (1996); Culm Floodplain, Start Floodplain (Walling and He, 1993); Barnes, Boltby, Elleron, Fillingham, Fontburn, March Ghyll, Newburgh, Slapton Ley, Yetholm (Foster

and Lees, 1999); Chew Valley, Eye Brook (Foster et al 2008 unpublished); Merevale, Seeswood Pool (Foster et al., 1990); Old Mill (Foster and Walling, 1994). Aqualate Mere (Pittam et al., 2009) Hammer Pond, Lurgashall, Inholms Copse Pond, Furnace Pond (Evans et al., unpublished data); Big Pool St Agnes, Widdicombe (Foster et al., 2006), Kyre (Foster et al., (2003), Silsden (Foster & Lees 1999).