

The fate of suspended sediment and particulate organic carbon in transit through the channels of a river catchment.

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Abstract

Particulate organic matter (POM) transiting through rivers could be lost to overbank storage, stored in-channel, added to by erosion or autochthonous production, or turned over to release greenhouse gases to the atmosphere (either while in the water column or while stored in the channel). In the UK a net loss of POM across catchments has been recorded and the aim here was to investigate the balances of processes acting on the POM. This study considered records of suspended sediment and POM flux in comparison to stream flow, velocity, stream power and residence time for the River Trent (English Midlands, 8231 km²). We show that for the lower two thirds (106 km) of the River Trent, 2 % is lost to overbank storage; 10% is lost to the atmosphere in the water column; and 31% is turned over while in temporary storage. Permanent in-channel storage is negligible and for the lower course of the river material stored in-channel will have a residence time of the order of hundreds of days between the last flood

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hydrograph of one winter and the first winter storm of the next winter (usually in the same calendar year). When considered at the scale of the UK, 1% POM in transit would be lost to overbank sedimentation; 5% turned over in the water column, and 14% turned over while in temporary storage. In the upper third of the study river channel there is insufficient stream power to transport sediment and so in-channel storage or in-channel turnover over to the atmosphere dominate. The in-channel processes of the River Trent do not conform to that expected for river channels as the headwaters are not eroding or transporting sediment. Therefore the source of sediment must be lower down the channel network.

Keywords: carbon, greenhouse gases, POC, POM.

1. Introduction

The flux of particulate organic matter (POM) from the terrestrial biosphere to the World's shelf seas and oceans has long been recognised as an important component of the fluvial carbon budget and indeed of the terrestrial biosphere (Meybeck, 1993; Ludwig et al., 1996). Furthermore, it has been argued that the erosion of soil organic carbon and subsequent storage of particulate organic carbon (POC) represents a sink of carbon with respect to the atmosphere (eg. Smith et al., 2005). However, at both the national and global scale the flux and fate of POC in the fluvial network is the least known component. At the global scale, initial estimates (Meybeck, 1993; Ludwig et al., 1996) were of the flux of carbon from rivers, at their tidal limit, to oceans, but they did not account for in-stream losses along the length of the river, between the carbon sources (e.g. soils) and the ocean. Cole et al. (2007) estimated that 1900 Mtonnes C/yr (estimated as all forms of carbon) enters rivers of which 800 Mtonnes C/yr (42% of the input) is returned to the atmosphere. Battin et al. (2009) considered the loss of dissolved organic carbon (DOC) from rivers at a global scale and suggested 21% removal of DOC in-

stream to the atmosphere implying that, in comparison to the values suggested by Cole et al. (2007), there must be considerable contributions from the loss of POC. Regnier et al. (2013) have estimated that the total carbon flux (inorganic and organic carbon, the latter including DOC and POC) into freshwaters was 2800 Mtonnes C/yr of which 1000 Mtonnes C/yr was exported from the tidal limit (a 64% removal rate). Battin et al. (2008) used a value of 180 Mtonnes C/yr for the global flux of POC from rivers to oceans based on values from Cauwet (2002). Syvitski et al. (2005) suggested that pre-human POC fluxes from rivers to the oceans were between 140 and 470 Mtonnes C/yr decreasing to between 126 and 380 Mtonnes C/yr in modern times with the difference being the role of reservoir storage outstripping the influence of increased soil erosion. Thus, there is a general realisation of the importance of rivers in transporting and processing terrestrial carbon and the potential that rivers will be sources of carbon to the atmosphere, but the potential for the processing of particulate organic matter, be that to convert it to atmospheric gases or into a dissolved form, has not been explicitly included in these global assessments and given the methodologies used would not have been included implicitly.

Worrall et al. (2014a) considered the flux, from land to sea, of particulate organic matter from 80 catchments across the UK and by comparing the flux between the 80 catchments, allowing for differences in soils and land use, meant it was possible to assess change in POC with increasing catchment size. By this approach it was possible to show that there was 20% loss of POM in transit through UK catchments. The 20% loss is 264 ktonnes C/yr which given the median C composition of POM (47.5%) means that the 20% loss represents a POM loss of 556 ktonnes/yr or 2.3 tonnes/km²/yr for every km² of the UK land surface. However, this 20% loss could be due to a number of processes and not just turnover of the organic matter to the atmosphere and indeed in Worrall et al. (2014a) the amount lost to permanent burial was given as unknown (Figure 1a). The loss of POM and suspended sediment through a catchment could

be due overbank sedimentation, in-channel storage or turnover to the atmosphere due to mineralisation, and therefore, the loss of 264 ktonnes C/yr given by Worrall et al. (2014a) should be considered the upper limit of the amount of POC lost to the atmosphere. Therefore, Figure 1b shows a more accurate concept of the possibilities for the processing of POM and POC in the fluvial network.

Walling et al. (1999) estimated overbank sedimentation for the rivers Yorkshire Ouse and Tweed and found values of between 23% and 29% of influent suspended sediment flux: at its maximum, the rate of overbank sedimentation was therefore 6 tonnes/km²/yr. Given the median values of POM and POC for the UK (median POC of UK suspended sediment = 15.8% - based upon Worrall et al. 2014a) the flux of POC to overbank sedimentation would represent 0.9 tonnes C/km²/yr. Other than overbank storage, the suspended sediment could be stored in the river channel itself. Collins and Walling (2007) gave values of in-channel storage as between 18% and 57% of the outlet flux of two UK lowland streams but they noted that most of this storage was transient, and Walling et al. (2002) noted that permanent in-channel storage was only between 1 and 3% of the catchment influent flux. Therefore, there is no evidence that there is sufficient in-catchment storage to explain the 20% loss calculated for POM.

It is commonly assumed that suspended sediment is conservative and most contemporary sediment budgets (e.g. Walling and Collins, 2008) do not include a component of loss due to carbon turnover. However, the average organic matter content of UK suspended sediment at Harmonised Monitoring Sites (HMS – Bellamy and Wilkinson, 2001) between 1974 to 2012 was 33.5% with a 5th percentile of 6% and a 95th percentile of 75% (Worrall et al., 2014a). Therefore, there is considerable potential for turnover and loss of particle mass in transit along a river channel.

The turnover or storage of POM is not only important for considering the impact of fluvial processes on the atmosphere but it has important implications for terrestrial processes.

In some environments the flux of POM can be the largest single component of the carbon budget (Worrall et al., 2011) and so, if such budgets are to be extended to consider greenhouse gases, then the fate of any POM flux needs to be known. Second, it has been argued that the erosion of particulate organic carbon (POC) from soils constitutes a global carbon sink because the eroded soil organic carbon lost to POC is replaced whilst the eroded POC is stored by downstream burial (Stallard, 1998; Harden et al., 1999; Smith et al., 2005). Van Oost et al. (2007) suggested a net carbon sink of 120 Mtonnes C/yr, based on a soil-erosion rate of between 470 and 610 Mtonnes C/yr from global agricultural land. However, Van Oost et al. (2007), like earlier studies, explicitly stated that their method made no allowance for in-stream loss of the POC to atmosphere once out of the immediate catchment area, or for the burial efficiency in marine waters; in effect, they assumed that, once outside of the immediate source area, the POC would be buried into a long-term store (e.g. alluvium). Van Oost et al. (2007) reported between 470 and 610 Mtonnes C/yr were lost globally due to soil erosion of which between 240 and 570 Mtonnes C/yr was retained in the immediate catchment, which meant between 30 and 220 Mtonnes C/yr were exported to streams and assumed to be buried (i.e. storage of up 93%). For England and Wales, Quinton et al. (2006) suggested POC flux to the fluvial network to be between 120 and 460 ktonnes C/yr and suggested that the rivers of England and Wales are either a small source of carbon to the atmosphere or possibly a net sink due to alluvium deposition. At a global scale, Regnier et al. (2013) have estimated a removal rate of 64% for export of TOC to the tidal limit. However, the least known term in their estimate was the global value of burial of organic matter in freshwater systems with estimates between 200 to 1600 Mtonnes C/yr (Cole et al., 2007, Tranvik et al., 2009, Smith et al., 2001, Aufdenkampe et al., 2011) – Regnier et al. (2013) took a median value of 600 Mtonnes C/yr (21% of the total carbon input).

Given, therefore, that a considerable portion of suspended sediment flux has the potential for being atmospherically active the question is what is the fate of POM and suspended sediment that it is a part of once it enters a river channel? Can the proportion of turnover vs storage be estimated? The estimates of net watershed loss of POM from studies such as Worrall et al. (2014a) cannot be interpreted in terms of atmospheric fluxes unless the other sources and sinks of suspended sediment such as in-channel storage are known.

In this study we considered a number of hypotheses concerning the fate of suspended sediment and particulate organic matter (POM) once in channel.

- 1) That, for overbank sediment storage to occur, then overbank flow must occur and the proportion of the annual sediment and POM flux that is lost to overbank storage will be that which occurs during days of overbank flow.
- 2) That change in suspended sediment rating curves (suspended sediment concentration vs. river discharge) along a channel would reflect the dominant process: transport, storage or erosion.
- 3) That, in a channel dominated by storage, transport distances will be small whilst in a channel dominated by transport the transport distances will mean that particles can travel through the length of the channel network in a single events.
- 4) That the regime of the channel (erosion, transport or deposition) can be assessed by reference to accepted models of river sediment dynamics in particular the Hjulström curve (Hjulström, 1939).

2. Approach & Methodology

To test the hypotheses listed above the sediment dynamics of the River Trent, English Midlands were considered (Figure 2). This catchment was chosen because, firstly, it is one of the nine

large catchments for which there was sufficient gauging station information to calculate longitudinal velocity profiles and in-stream residence times (Worrall et al., 2014b) and, of those nine catchments, it is the catchment with the most complete suspended sediment and POM data for the most individual sites (three on the main channel - Worrall et al., 2013a). Using the longitudinal velocity profiles; in-stream residence times; suspended sediment and POM concentration; and derived fluxes were used to test the hypotheses. Specifically for the hypotheses given above the following approaches were used:

- 1) Overbank sedimentation was estimated from bankfull discharges and from flow records for the gauging stations on the River Trent. The proportion of the calculated annual suspended sediment and POM fluxes was taken as the proportion of those fluxes lost on days of overbank flow.
- 2) Suspended sediment and POM rating curves were compared for each site along the main channel of the River Trent where POM had been sampled. It would be expected that rating curves would be the same if transport dominated between sites but that increases or decreases in the suspended sediment or POM concentration on a similar flow would reflect dominance of erosion or deposition between monitored sites.
- 3) The flow records for the River Trent were used to calculate the travel length of particles along the main channel of the River Trent. Travel lengths could then be used to define lengths of the main channel that are dominated by storage (i.e. short travel lengths) or dominated by transport as travel lengths become longer than the channel length.
- 4) Parameterise the Hjølström curve such that estimates of stream velocity derived from flow records for the River Trent can be used to estimate lengths where erosion, transport or deposition dominate for different particle sizes.

By being able to estimate the roles and proportions of erosion, transport, overbank sedimentation and in-channel storage means that it possible to know how much of the POC loss through the catchment would be loss to the atmosphere.

2.1 Study site

The catchment characteristics of the River Trent are given in Table 1.

2.2 Flux calculation

The study used data from the Harmonised Monitoring Scheme (HMS - Bellamy and Wilkinson, 2001). Sites are selected for inclusion in the HMS if they are at the tidal limit or on a tributary with an average annual discharge $> 2 \text{ m}^3/\text{s}$. Within the database maintained as part of the HMS programme, three determinands were of particular interest to this study: suspended sediment concentration (mg/l); instantaneous river flow (m^3/s); and the ash content of the suspended sediment (mg/l). From these data the suspended sediment flux was estimated and, as the ash content represents the mineral proportion of the suspended sediment (particulate mineral matter concentration), it was possible to calculate the particulate organic matter (POM) concentration of each sample by difference. From the measured suspended sediment concentrations and the calculated POM concentrations and river flow data, it was then possible to calculate the suspended sediment and POM flux for three sites on the River Trent main channel. The flux calculations were performed using the method of Worrall et al. (2013b). Worrall et al. (2013a) showed that by examining a three-year long, high-frequency ($f = 1$ per hour) time series; with a range of extrapolation and interpolation methods; and by considering the sources of variation (Goodman, 1960) that the best method (Equation (i)) for calculating fluxes in sparsely sampled data (was a very simple method that had a very high precision ($\pm 8\%$ for $f = 1$ per month) compared to some previous methods and a high accuracy (-2% at $f = 1$ per month):

$$F = KE(C_i)Q_{total} \quad (i)$$

where: Q_{total} = the total flow in a year (m^3a^{-1}); $E(C_i)$ = the expected value of the sampled concentrations ($mg l^{-1}$); and K = unit conversion constant (0.000001 for flux in tonnes/yr). For the best results (highest precision and accuracy), the expected value of sampled concentration was based fitting a gamma distribution to the available concentration data and using the expected value of that fitted gamma distribution.

2.2 Overbank sedimentation

To calculate the proportion of the in-stream loss due to floodplain sedimentation, it is necessary to estimate the proportion of time that the discharge in any river is greater than bankfull discharge, and therefore the proportion of time in which there is flow and sediment delivery to the floodplain. Nixon (1959), using surveys of local water board engineers, found that 29 English rivers were at or exceeded their bankfull discharge between 0.1 and 2.9% of the time, i.e. overbank flow would be occurring between 1 day every 3 years and 11 days per year. These are only the days when discharge would be flowing from the channel to the floodplain and not the days of standing water on the floodplain and so these represent the only times when particle transfer from the channel to the floodplain would be possible. Nixon (1959) includes the River Trent in his study and shows that bankfull discharges occurred 1% of the time, i.e. 3.7 days per year.

Days of overbank sedimentation are likely to be days of high flow in the main channel and thus days of considerable sediment flux. Therefore, using the suspended sediment and POM flux data for the sites on the River Trent at Colwick (Worrall et al. 2013a, 2014a), we assumed the highest flows each year were overbank flows and that any sediment flux they

carried, including its POM fraction, would be lost to overbank storage. The number of days of flux lost to overbank sedimentation was varied from the lowest to the highest value as measured by Nixon (1959) (0.33 to 11 days per year) with the assumption that the first day of overbank sedimentation was the day with the highest flux of suspended sediment in that year and then, for each further day of the overbank sedimentation, it was assumed that these were days of second highest, third highest days of suspended sediment fluxes, and so on. In the cases studied here, the days of the highest suspended sediment flux were also days of the highest riverflows. It was then assumed that all the suspended sediment flux on days of overbank flow was lost to overbank sedimentation; this would tend to over-estimate loss to the floodplain since a river does not cease to flow along its main channel on days overbank flow nor does a river overbank to the floodplain uniformly along its length at any one time and while one reach of the river is at bankfull another reach may not be. The suspended sediment and POM flux lost each year to overbank sedimentation were expressed as a percentage of the total sediment or POM flux from the catchment for that year.

It should be noted that this approach to the estimation of overbank sedimentation will give a maximum value as some sediment taken over the river bank will eventually be carried back into the channel; also, some of the suspended sediment will remain in the channel and be transported from the catchment.

2.3 Flow characteristics

Key to this study's approach is the calculation of the velocity and stream power profiles of the main channel and the in-stream residence times.

The velocity profile of the River Trent was calculated using the approach of Worrall et al. (2014b). The mean velocity of a river at any point in sub-critical conditions (Froude number < 1) can be estimated from the Manning equation (Manning, 1891):

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$$v = \left(\frac{1}{n}\right) \left(\frac{a_{cross}}{p}\right)^{\frac{2}{3}} s^{\frac{1}{2}} \quad (ii)$$

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249 where: a_{cross} = cross-sectional area of the river at point x; p = the wetted perimeter; s = the water
250 surface slope; and n = the Manning coefficient. It is common for the longitudinal slope profile
251 of a river to be expressed as an exponential function of river length (Putzinger 1919):

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253
$$S_x = S_0 e^{-\phi x} \quad (iii)$$

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255 where: S_x = the bed slope at point x; S_0 = the bed slope at source; ϕ = a constant. At the scale
256 of the entire river length and at steady state, it can be assumed that bed slope is a good
257 approximation of the water surface slope in Equation (ii) (Wilson, 1994). Equation (iii) can be
258 readily calibrated for any catchment; here this was done by reference to altitudes of gauging
259 stations. If it is assumed that the river has a rectangular cross-sectional area, then:

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261
$$\frac{a_{cross}}{p} = \frac{dw}{(2d+w)} \quad (iv)$$

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263 where: d = river channel depth and w = river channel width. For a rectangular cross-section,
264 the width of the river does not vary with discharge and so it is only necessary to find an
265 expression for river width change with river length. Worrall et al. (2014b) give the result for
266 other possible cross-section configurations (e.g. trapezoidal) but also showed that for many UK
267 rivers (including the Trent) the assumption of rectangular cross-section and constant width
268 across the range of river discharge was reasonable when considering in-stream residence times.

To calibrate equation (iv) with respect to width, we used the equation of Worrall et al. (2014a) which augmented the bankfull width data of Dangerfield (1997) to create an empirical equation for river width variation with catchment area.

$$w = 0.061C + 9.0 \quad r^2 = 0.73, n = 129 \quad (v)$$

where: C = catchment area (km^2); and w_0 = river channel width at source (m). Based upon data from the UK Flood Studies Report (NERC, 1975), it possible to predict that the main channel length (l) is:

$$l = 1.75C^{0.54} \quad r^2 = 0.77, n = 129 \quad (vi)$$

River channel depth, the other component of Equation (iv), will vary with flow and we propose the following form of equation:

$$^f d_x = ^f d_m - \beta e^{\left(\frac{x}{\gamma}\right)^\delta} \quad (vii)$$

where: $^f d_x$ = depth at exceedance flow f (eg. 10% exceedance) at river length x (m); $^f d_m$ = depth of the river at the monitoring point m for exceedance flow f ; and β, γ, δ = constants where β approximates to $^f d_m - ^f d_0$. Equation (vii) can be calibrated against observations of river depths at gauging stations for a given exceedance flow.

Applying equations (ii)-(vii) means that the velocity profile of the main channel at any flow could be calculated. Furthermore, the stream power (Ω - W/m length of stream channel) could be calculated from:

$$\Omega_x = \rho g v_x d_x w_x S_x \quad (\text{viii})$$

where all variables are as defined above.

Given that the velocity profile of the main channel can be derived from the above, then the in-stream residence time (t_r) can be defined as:

$$t_r = \int_{x_e}^{x_m} \frac{x}{v} dx \quad (\text{ix})$$

where: v = the mean cross-sectional velocity at point x as defined in Equation (ii); x = the downstream distance along the river channel; x_m = the downstream monitoring point; and x_e = the upstream point of interest. For example, x_m could be the river mouth and x_e would be the point at which a particle enters the channel.

2.4 Suspended sediment rating curve

The rating curves for all three sites were constructed from all the available suspended sediment concentration data. Three sampling sites along the River Trent were considered (Figure 2). These sampling sites are the three sites on the River Trent that are part of the Harmonised Monitoring Network (HMS - Bellamy and Wilkinson, 2001). The suspended sediment concentration was measured 769 times at Yoxall; 782 times at Colwick; and 759 times at North Muskham over a 36 year period – such a sampling frequency is an average of once every 2.5 weeks for 36 years. For Yoxall, the suspended sediment concentrations were taken on the 0 to 99.8th percentile flows when compared to the available daily flow records (1959 to 2015). For Colwick, 0.3 to 99.7th percentile flows when compared to the available daily flow records (1958 to 2015). For North Muskham, 0.0 to 99.9th percentile flows when compared to the available

daily flow records (1968 to 2015). For the POM concentration there 293 samples at Yoxall; 231 samples at Nottingham; and 477 samples at Colwick all over the same 36 year period as for the suspended sediment concentration. The suspended sediment and POM concentration can be plotted against discharge, stream velocity and stream power.

2.5 Suspended sediment travel distance

Wainwright et al. (2008) proposed the following equation for the travel distance (m) of a particle of known size:

$$L = 728e^{(7.33 \times 10^{-3} \Omega)} e^{(-6.127 D)} \quad (x)$$

where: D = particle diameter (m); and Ω = stream power (W/m length of stream channel).

The total travel distance was then considered with respect to the tidal limit and, for each day in 2011 (the year chosen because it was the most recent year without a single day of flow records missing), the stream power profiles for all flows were calculated together with the distance that a particle would have travelled. By viewing the catchment from the perspective of the tidal limit, it was possible to consider at which point along the river channels the particle started travelling on that day. The above calculation was performed for a 2 μm and an 80 μm particle for the year 2011. The particle sizes were chosen to represent the boundary of clay and silt size particles (2 μm) while an 80 μm particle size is approximately the particle size at the minimum in the Hjulström curve representing the boundary between erosion and transport.

2.6 Application of Hjulström curve

The Hjulström curve (Hjulström, 1939) as later extended by Sundborg (Sundborg, 1956) relates grain size to stream velocity to define flow regimes that lead to the erosion, transport or deposition of particles of that grain size. In the original publications that presented the Hjulström curve (Hjulström, 1939, Sundborg, 1956), the equations for their threshold curves were not given. The Hjulström curves were digitised and polynomial curves fitted to the transcribed data. For the transition between deposition and transport the boundary for the range 0.004 to 25 mm and a mean stream velocity of between 0.3 and 300 m/s (these ranges defined by the original Hjulström curve) is given by:

$$\log_{10}v = 0.0107\log_{10}D^6 + 0.0103\log_{10}D^5 - 0.1084\log_{10}D^4 - 0.1061\log_{10}D^3 + 0.4599\log_{10}D^2 + 0.4544\log_{10}D + 1.348 \quad (\text{xi})$$

and for the boundary between transport and erosion the best-fit polynomial was

$$\log_{10}v = -0.0258\log_{10}D^4 - 0.0363\log_{10}D^3 + 0.0245\log_{10}D^2 + 1.0225\log_{10}D + 0.8585 \quad (\text{xii})$$

Therefore, given the longitudinal velocity profiles for the main channel of the Trent for a range of exceedance flows means that for a given a particle size, at given distance along the main channel, and for a given exceedance flow, it becomes possible to classify whether a particle would be deposited, transported or whether a particle of that size would be added to the flow. As with the application of Equation (x) particle sizes of 2 and 80 μm were selected. The particle sizes were chosen to represent the boundary of clay and silt size particles (2 μm) while an 80 μm particle size is approximately the particle size at the minimum in the Hjulström curve

representing the boundary between erosion and transport. Wass and Leeks (1999) found the median particle size at North Muskham to be 8.96 μm (mean particle size = 8.69 μm , $n = 2$).

3. Results

3.1 Suspended sediment and POM flux

The average concentration and fluxes for the three main-channel monitoring sites are detailed in Table 1 and the last available decade of POM fluxes are given in Figure 3. The Anderson-Darling test (Anderson and Darling, 1952) had shown that a log normal distribution was a better description of the distribution of the suspended sediment and POM concentration data and thus the geometric mean is quoted. The stream power for the main channel of the River Trent reaches a maximum at 149 km from the source but only under bankfull conditions (Figure 4). The velocities and depths predicted mean that the critical value of the Froude number is never exceeded (i.e. flow remains sub-critical and so the use of the Manning Equation - Equation (ii) - across all conditions is reasonable) along the length of the channel even under bankfull conditions.

3.2 Overbank sedimentation

Using the estimates of days of bankfull discharge and the highest daily fluxes gives an estimate that, for one day each year, the loss to floodplains of suspended sediment flux is 2.5% of the total flux leaving the catchment, and therefore the maximum percentage lost to overbank sedimentation would be 27.5% (i.e. for 11 days per year of bankfull or greater discharge). The same analysis for POM flux shows that only 0.97% of the flux is lost per day of overbank flow, in which case, after 11 days of overbank flow only 10.9% of the POM flux would be removed (Figure 5). Note that the percentage losses are less for POM than for suspended sediment, i.e. POM is not fractionated into being concentrated into overbank storage relative to suspended

sediment and this may be due to the fact that some sources of POM, such as sewage outfalls, are not influenced by flow. In the UK case the proportion of suspended sediment that is organic matter decreases as flow increases.

Given the measurements of Nixon (1959) for the River Trent, then 10.5% of the sediment flux would be removed while 2% of the POM flux would be removed. Walling et al. (1999) estimated overbank sedimentation for the Yorkshire Ouse as 30% of the outlet flux (23% of influent suspended sediment flux) and as 40% of the outlet flux (29% of influent flux) for the River Tweed, i.e. at the high end of the estimates for all UK rivers. Erkens (2009) gave a long-term, Holocene-accumulation rate of total sediment in the Rhine floodplain as 27% of the upstream input, but this was not a measure of the organic carbon storage. Hoffman et al. (2009) suggested that the long-term storage of carbon on the Rhine floodplain was equivalent to the downstream flux of POC at the catchment outlet. In contrast, Gomez et al. (2003) found only 4% POC storage in a New Zealand floodplain. In estimating overbank sedimentation, Walling et al. (1999) measured accumulation at sites on floodplains where accumulation was known to be depositing and scaled this observation for the estimated area of the floodplain whereas in this study we estimate the amount that could have left the channel and so it is not surprising that our values are lower than those of Walling et al. (1999). But it should also be recognised that the method used in this study assumed that all the suspended sediment being transported on a day of overbank flow will be deposited and stored in the floodplain and that the whole river had the same overbank conditions and so even the estimate of this study should be considered a maximum value.

3.3 Comparison of sediment rating curves

The semi-log plot of suspended sediment concentration against stream power gives a good comparison between sites (Figure 6). The range of suspended sediment concentrations is

similar at all sites even though stream power increases downstream. We interpret this being that the river is dominantly transporting sediment in its course from Yoxall to the tidal limit (North Muskham). Obviously the amount of water (discharge) increases downstream and so the actual flux of suspended sediment is increasing but the concentration is not changing, suggesting that deposition is not occurring and if anything, additional sources are contributing either because new high-concentration sources are found in the lower course of the river (e.g. combined storm overflows; sewage treatments works; or tributaries of particularly high relative sediment load) or it could be that the additional capacity of the river is met by erosion in the lower course of the river.

3.4 Sediment transport distance

Equation (x) is insensitive to changes in grain size as the term in D rapidly approaches unity for $D < 1$ mm. With respect to the outlet (156 km from source by main channel length), then particles will come from within 50 km of the source (i.e. 1 storm had a travel distance of 106 km) on a 2.5% exceedance flow. This means that transport progressively dominates with distance from source but that within 50 km of the start of the river, transport is slow and sediment entering the upper reaches would be stored, while sediment entering at least 50 km downstream would have a good chance of being transported out of the catchment in that year. Figure 7 suggests that in-channel storage is possible simply because smaller events at the end of one year are not sufficient to remove particles until the biggest event in the following year. Alternatively, using Equation (x) shows that a sediment travel distance of 156 km (i.e. the entire main channel length) would occur for 0.01% exceedance flow, i.e. a flow that would have occurred for this catchment 1 in 28 years, and that would be true for particles up to 1 mm diameter.

3.5 *Hjulström curve*

The downstream velocity profiles for a range of exceedance flows for a 2µm particle shows that transport dominates the entire length of the main channel except for the very highest flows and in lowest 50 km (i.e. the river stretch nearest the sea) of the river (Figure 8). For an 80 µm particle deposition dominates for the first 10 km of main channel length and, depending upon the flow state, transport dominates from 10 km to 110 km of main channel length with erosion beginning for the highest flows from 30 km onwards (Figures 9).

4. Discussion

Other studies have considered the transport distance and residence times of suspended sediment in rivers. Whiting et al. (2015), in a study of the Yellowstone River, found that the distance that suspended sediment had travelled to point of sampling increased with distance along the main channel with a travel distance of 5 km at 3 km along the channel length and 1360 km at 100 km along the channel length, i.e. a result consistent with that found by this study that in headwaters travel distances were small but in the lower course suspended sediment would be readily flushed out of the river system by the highest flows. Bonniwell et al. (1999) found transport distances on the peak flows they sampled were 60 km with residence times on the highest flows being up to 32.5 days. Matisoff et al. (2005) used the $^7\text{Be}/^{210}\text{Pb}$ ratio method to give a sediment age of 50 to 80 days for a number of rivers including the Fish River, Alabama (47 km long, 510 km²). Le Cloarec et al. (2007) used the $^7\text{Be}/^{210}\text{Pb}$ ratio method to measure residence times for the River Seine, France and found residence times of between 115 and 307 days in catchments from 7 and 65700 km². Similarly, Smith et al. (2014) found residence times of between 185 and 256 days for English catchments of between 38 and 920 km². These results from radionuclide studies support the result of this study in that at small catchments areas, rivers have too low a stream power to move the sediment and that at all scales the critical time

period is between large storms. Thus residence times represent the time between the last large storm of winter and the first large storm of the next one, that next being typically in early winter of the same calendar year. Given the approach above and for the year 2011 (the last year for which all data were available for all sites), then the maximum residence time for the bottom 92 km of the river would be 300 days between the 27th February 2011 and the 23rd December 2011.

As an alternative approach to those taken above, we could consider settling of particles in a moving stream (Whiting et al., 2015). Hunken and Mutz (2007) measured the settling rate of lacustrine POM (0.45 and 53 μm) in a flowing stream and found a median settling velocity of 0.139 m/hr (with a range of 0.085 and 0.257 m/hr). Given such settling velocities and the stream velocities and flow depths predicted by the approach of this study, then the distance over which POM particles of between 0.45 and 53 μm would travel for the 2.5% exceedance flow (the flow exceedance at which a travel distance of 106 km was predicted above) is between 76 and 110 km.

The picture of behaviour that emerges from the tests applied in this study is that deposition dominates in the upper course of the river; further down the channel, transport dominates with erosion only becoming meaningful in the very lowest course of this river. The classical picture of the river system is one of erosion in the headwaters, transport in the middle course and deposition in its lower course (Schumm, 1977), but that is not consistent with the observations and analysis of this river channel. Schumm's model may better refer to the catchment as a whole whereby eroding slopes in the headwaters of a catchment supply sediments to small headwater streams or to the floodplain from where it can be eroded by migrating channels, but these headwater streams are not powerful enough to move this material very quickly. At some point downstream the stream has sufficient power to start transporting material in considerable amounts and far downstream the stream power is sufficient to erode.

Part of the difference between this study and models such as Schumm (1977) is that of time. The study here is using data over timescales of years to decades, predominantly the former over the latter; extreme flood events with return periods of the order of a century are not considered. However, the results presented here would suggest that even in the largest events all that would happen is that the channel length over which erosion is dominant would expand further back up the river channel and so too would that of the transport-dominated zone. The headwaters would not become erosion dominated; rather transport conditions might extend into this zone and thus act to clear them of a store of accumulated sediment rather than generating fresh erosion.

The results presented here for the River Trent also imply that the main source of sediment is in the middle and lower courses of the river. The study has shown that silt-grade sediment in the bottom 106 km of the river would be removed within one year and therefore, if the suspended sediment flux of the river averages 65.8 ktonnes/yr (Table 1), then at least this amount has to be entering the river from sources within the bottom 106 km. In the bottom 106 km of the River Trent there are some major tributaries (Figure 1) but unless these tributaries have a very different stream power profile from that the main channel of the River Trent, they would not behave substantially differently from the main channel of the River Trent. Also, in the lower course of the Trent there are the substantial urban centres with their associated sewage treatment works; their outfalls will be substantial sources of organic-rich suspended sediment though the organic carbon content of particulates discharged from sewage treatment works is not known. However, the results of this study imply that on a year to year basis the most important source of sediment is bank erosion and the migration of the main channel. Assuming that the bank height is 2m and is made up of soil of average bulk density of 1600 kg/m³, then 65.8 ktonnes/yr could be supplied by an average 9.5 cm retreat over the lowest 106 km of the river channel, but this would not supply the POM present in the flux from the

catchment. Assuming that the POM can be supplied from elsewhere, then average bank retreat will be 8.5 cm/yr. Collins and Anthony (2006) estimated that for England and Wales, 15% of sediment yield came from bank erosion and only 9% from all urban sources. Examining the discharge consents for the River Trent catchment showed that in 2011 the total consent for suspended sediment was 22.8 ktonnes. Applying the correction for actual discharge compared to observed discharge correction (Roberts and Williams, 1997 – cited in Collins and Anthony (2006)), i.e. that only 43% of the discharge consent is actually used, gives a discharge of 9.8 ktonnes/yr. The importance of urban centres and sewage treatment works as sources of POM may be the reason why there is an increase in 10-year average annual POM flux to Colwick, but a decline after Colwick to North Muskham (Table 1). Of course, the presence of large urban centres in the catchment means also that water abstraction will be occurring and water abstraction from the river will also be removing suspended sediment and POM (Finlay et al., 2016).

In the case of the Trent the discrepancy with the Schumm model (Schumm, 1977) in this catchment would arise from the relative change in slope compared to discharge. Stream power is a matter of both discharge and stream slope (Equation viii) and for most rivers the slope decreases along the main channel but also discharge increases; therefore the trade-off between slope decrease and discharge increase could mean that the focus of erosion may not be at the lowest point of the river and a site of deposition might exist in the main channel. Alternatively, the important sites of headwater erosion may not be the main channel but rather side channels; the main channel is the longest channel line in the catchment but it may not be the steepest and so may not represent areas of erosion. However, the point still holds that discharge in headwater streams is generally too low for dominance of channel erosion. A further point to bear in mind in relation to the Schumm model is that the River Trent is, by

global standards, a short river, whereas the Schumm model was intended to apply to all scales of drainage basin including those much larger than the Trent.

This study set out to establish the fate of POM transiting through a catchment. Worrall et al. (2014a) by considering the flux of particulate organic matter from 80 catchments across the UK and by allowing for differences in soils and land use, meant it was possible to show that there was 20% loss of POM in transit through UK catchments. The River Trent is the third largest catchment in the UK and therefore far larger than the average UK catchment at the tidal limit. Applying the approach of Worrall et al. (2014a) for the River Trent would suggest an average POM loss of 42.6% across the catchment to the tidal limit.

From the perspective of understanding carbon and nutrient turnover, the in-stream travel time (Equation (ix)) from 50 km from the river source (106 km to the tidal limit) is 19 hours at bankfull discharge and 49 hours for a 10% exceedance flow. Moody et al. (2013) measured removal rates of between 3 and 8% per day for POC in-stream, and Worrall and Moody (2014) found rates from 0 to 33% /day for POC in stream with a median value of 10% /day. Although this study aimed to assess the fate of POC in transit, it has shown that for most of the channel length for most of the year, particles will be in temporary storage on the river bed but, once in transit, the residence time will be the order of one day, i.e. 10% removal in suspension for the lowest 106 km of the River Trent. The loss to the overbank storage predicted by the method above gives only 2% loss, leaving 30% loss to be accounted for.

We recognise that it is not always possible to re-interpret studies of organic matter turnover in rivers in terms of POC or POM turnover as many studies are of whole-stream organic matter processes rather than just POM (e.g. Griffiths et al., 2012). Webster and Meyer (1997) reviewed a range of stream organic matter budgets for forested catchments and in most cases there was insufficient information to understand the percentage removal of POC. In two cases where there was sufficient information, for Oregon streams their annual removal rate for

a 1 km² catchment was between 3.6 and 14.1%/yr. Webster et al. (1999) reviewed studies of FPOM (fine particulate organic matter, < 1 mm) respiration in Coweeta streams and found rates of between 0.08 and 3.93 mg C/gC/yr with a median of 0.96 mg C/gC/yr giving annualised rates of between 2.7 and 145% with a median of 35%. Webster et al. (1999) reported the average turnover distance of FPOM as 42.4 km. Yoshimura et al. (2008) found annualised FPOM respiration rates of between 52 and 148%/yr. Pusch (1996) measured turnover rates of benthic organic matter as between 6 and 51%/yr. Crenshaw et al. (2002) measured turnover in hyporheic sediments and found rates of between 16 and 25%/yr. These literature values suggest that for the River Trent up to 2% is lost to overbank storage and 10% is lost whilst in the water column. From the literature values, that it is reasonable to suggest that the remaining 31% is turned over while in temporary storage, assuming negligible, permanent in-channel storage. However, this study would suggest that the turnover rates are only true for the lower two thirds of the river system. When re-scaled to the UK level (River Trent = 8231 km² compared to UK = 244000 km²), then 1.5% would be lost to overbank sedimentation, 5% turned over in the water column and 14% turned over while in temporary storage. Given the flux of POC at the tidal limit of the UK (863 ktonnes C/yr - Worrall et al., 2014a) and the amount estimated to be lost in transit through the river network (264 ktonnes C/yr) means that on the basis of this study then 13 ktonnes C/yr goes into longer term storage in overbank environments (Figure 10). This study would then assume that the remaining 251 ktonnes C/yr would be lost to the atmosphere. However, Finlay et al. (2016) using the same dataset as here has shown that the median POC removal by water abstraction from UK rivers was 19 ktonnes C/yr, i.e. more important on an annual scale than overbank storage. This value for water abstraction would mean that while 1.5% of the POC loss is to overbank sedimentation, then 1.7% was lost to water abstraction; 4.4% turned over in the water column; and 12.4% turned over while in temporary storage.

Therefore, 232 ktonnes C/yr (0.95 tonnes/km²/yr across the UK) of the POC would be lost to the atmosphere (Figure 10).

This study has not considered water management as sink or source term within this approach. Regnier et al. (2013) estimated that globally the amount stored in lakes and reservoirs was between 200 and 500 Mtonnes C/yr. In the UK most major rivers are not impounded on their main channel (the Trent is not) and most supply reservoirs are either in the steeper-sided valleys of the headwaters (as is the case for the River Derwent – a tributary of the Trent) or are off-channel (as for the Thames). Water management can also be a source of POM at sewage treatment works and a sink at water treatment works where POM will be settled out of abstracted waters. This study has considered net processes and, with respect to carbon losses, the net process is the important consideration, but when sinks and stores are considered, then the probability that POM is produced in-stream will matter. Helie and Hillaire-Marcel (2006) showed that for the St Lawrence River that aquatically-produced POC dominated over terrestrially-sourced POC throughout the year.

5. Conclusions

Relative to the hypotheses set by this study, this study can show that:

- 1) That since overbank storage can only occur if overbank flow has occurred then for the River Trent, the overbank storage represented a maximum of only 2% of the annual POM flux;
- 2) The change in suspended sediment rating curves shows that transport is the dominant process for the lower 85% of the study river.
- 3) Travel lengths show that the upper third of the river is dominated by in-channel storage and transport comes to dominate the further downstream being considered. After 50 km

channel length from the source a particle would be transported from the river within 1 year.

- 4) The application of the Hjulström curve confirms that deposition dominates in the upper third of the main channel and erosion only occurred in the lower third of the river and only on the highest flows.

Furthermore, this study of in-channel transport of suspended sediment and POM in a major UK catchment over periods of years to decades has also shown that:

- 1) In the lower two thirds of the river, the sediment transport is dominated by a few storms each year which means that in-stream residence time of sediment is dominated by time spent in temporary storage with a typical residence being of the order of 100s of days.
- 2) In-stream transit times would result in 10% turnover but there would be capacity to remove 30% of the POM whilst in temporary, benthic stores. This translates to 1%, 5% and 14% removal respectively at a national scale.
- 3) It therefore follows that the suspended sediment transport is not conservative as up to 30% of the in-stream load comprises non-conservative POM which is removed by in-stream processing either during transport or whilst in in-channel storage.

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791

792 Table 1. Characteristics of the River Trent relative the most downstream gauging station.

Catchment characteristic	North Muskham	Colwick	Yoxall
Area (km ²)	8231	7486	1229
Main channel length from source – km)	156	106	24
Max. altitude (m above sea level)	634	634	324
Average slope to site (m/km)	0.22	0.49	
Annual average rainfall (mm)	747	761	746
50% exceedance flow (m ³ /s)	63.5	58.9	9.6
Geometric mean suspended sediment (mg/l)	21.6	59.9	15.6
No. of suspended sediment samples	745	603	697
Geometric mean POM (mg/l)	4.9	4.7	3.7
No. of POM samples	478	252	301
10 year average sediment flux (ktonnes/yr)	65.8	50.3	7.1
10 year average POM flux (ktonnes/yr)	7.6	10.0	1.4

793

Figure 1. a) Conceptualisation of the flux of particulate organic matter as developed and measured by Worrall et al., (2014a).

b) The conceptualisation of the flux of particulate organic matter as considered in this study.

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Figure 2. Location and outline of the River Trent catchment showing primary sample locations.

Figure 3. The POM flux from the three monitored sites over the last decade for which POM concentration was available. The error bars are $\pm 2\%$ based on the precision predicted for Equation (i). The values were not bias-corrected.

Figure 4. The longitudinal stream power profile for the main channel of the River Trent for a range of flows with the position of monitoring sites marked.

Figure 5. Comparison of the percentage of the median annual sediment, and POM, flux lost to overbank storage for varying number of days of overbank flow each year.

Figure 6. Comparison of the suspended sediment rating curves in terms of stream power for the three stations on the main channel of the River Trent as shown in Figure 2.

Figure 7. The distance from the source from which a particle has travelled to the catchment outlet for each day of 2011 for 80 μm particles.

Figure 8. The classification from the Hjulstrom curve (.... = deposition dominated; _ = transport dominated; and ---- = erosion dominated) for a range of velocity profiles for a 2 μm particle.

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820 Figure 9. The classification from the Hjulstrom curve (... = deposition dominated; _ =
821 transport dominated; and ---- = erosion dominated) for a range of velocity profiles for a 80 μm
822 particle.

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824 Figure 10. Schematic Summary of flux, sinks and sources of POM.

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