Seasonal and inter-annual changes in sediment transport identified through sediment rating curves.

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Abstract

Sediment dynamics of lowland rivers are of importance in building resilient strategies to manage environmental change. Yet the effects of natural and anthropogenic disturbances on sediment dynamics are poorly understood. Here a low-frequency suspended sediment sampling dataset is used to assess the spatial and temporal variations of suspended sediment fluxes in the River Thames (UK). Sediment rating curves (SRCs) were used to analyse both the spatial and the temporal variation of catchment suspended sediment transport. SRC exponents for the River Thames were found to be between 0.21 and 1.13. The 95% confidence interval was also determined through a bootstrapping technique. The seasonal and inter-annual variability of SRC parameters were analysed to reveal seasonal and secular changes. The results are used to quantify the seasonal flushing effect, in which suspended sediment concentrations are typically substantially higher during the first floods after the summer dry period. The suspended sediment concentrations of the River Thames during the first floods after summer are estimated to be around 1.5-2 times those of other floods,

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22 for a given water discharge. A decrease in the flushing effect which began in the 1990s
23 is observed (around 50% of its original magnitude), which may be attributable to
24 changes in catchment and river channel management.

25 *Keywords:* sediment transport, sediment rating curve, flushing effect, River Thames,
26 sediment modelling

27

Introduction

One of the main aims of erosion and sedimentation research is to understand the mechanisms governing sediment export by rivers. Nevertheless, some aspects of fluvial sediment dynamics remain poorly understood. The lack of data has been widely acknowledged as probably the most compelling limitation to soil erosion and sediment transport research (Cerdà et al., 2013). To overcome this problem, some authors have tried to take advantage of alternative sources of sediment transport data, such as reservoir sedimentation volumes (Bussi et al., 2014a, 2013).

In many locations, measured suspended sediment concentration data are available only at low-frequency sampling intervals, usually ranging between one week and one month. An example is the Harmonised Monitoring Scheme (HMS) dataset (Bellamy and Wilkinson, 2001), collected by the Environment Agency for England and Wales, which has an average sampling interval of two weeks. These datasets have important limitations for use in sediment transport research, as they are unlikely to include all the most significant sediment transport events (cf. Kirchner et al., 2004). Nonetheless, low-frequency data can provide significant insights into spatial and temporal patterns of sediment and nutrient transport (Burt et al., 2011; Worrall et al., 2013b).

One of the best known techniques to analyse low-frequency suspended sediment data is the sediment rating curve (SRC), which has been used in the past to fill data gaps and obtain continuous series of suspended sediment concentration estimates, to compute suspended sediment yield (the total amount of sediment exported from a catchment per unit area per year) or to characterise the sediment response of a catchment. The SRC approach is described in Miller (1951). The fitted relation is typically a power-law (Eq. 1) relating sediment concentration to water discharge:

52 $C_s = cQ_w^a$ 1

53 Where C_s is the suspended sediment concentration (mg L^{-1}), Q_w is water discharge
54 ($\text{m}^3 \text{s}^{-1}$), c is a coefficient describing unit suspended sediment concentration and a is
55 an exponent. The parameters of the rating curve do not have a direct correspondence
56 with parameters developed in the physical theory of sediment transport, because the
57 SRC is a “black box” model (Cohn, 1995), but some authors have tried to associate
58 them with environmental properties (see Asselman, 2000 and Parsons et al., 2001).

59 The SRC parameter values depend on several factors, but often have a seasonal
60 behaviour. Walling (1977b) found that a large part of the SRC variability for two rivers
61 in the south of England could be explained by splitting the suspended sediment
62 concentration samples into seasonal groups and fitting different SRCs for each group.
63 Asselman (2000) also grouped suspended sediment concentration samples
64 depending on the season to understand the seasonal sediment patterns of the River
65 Rhine. Similarly, in this paper, the variation in SRC parameters to disentangle the
66 spatial and temporal sediment patterns is analysed, rather than treating the SRC
67 variability as random noise.

68 In spite of the considerable uncertainties on total mass flux estimated using suspended
69 sediment rating curves, described, for example by Walling (1977a, 1977b), information
70 on the temporal variability in the sediment rating curve relation can still provide
71 important diagnostic information about the sediment response of a catchment to a
72 series of rainfall events. By tracking changes in the parameters of fitted SRCs, it is
73 often possible to diagnose and quantify disturbances within the catchment that deliver
74 sediment to the river network. In this way, changes in the properties of rating curves
75 can be used to quantify alterations in catchment properties due to a specific catchment

disturbance or triggering factor. For example, Dadson et al. (2004) used SRCs to study the impact of a large earthquake on sediment delivery to river channels in Taiwan.

Bussi et al. (2014b) used event-based SRCs to analyse the influence of sediment deposited into the river network prior to a flood event. Event-based SRC plots clearly show the influence of stream network deposits on sediment transport. When plotting the SRC of a single flood event, a hysteresis loop is often observed. The shape and direction of the loop depend on runoff and sediment transport processes and on the sediment source location(s) (Seeger et al., 2004; Williams, 1989). In particular, clockwise hysteresis is usually observed when material is rapidly transported from the drainage network to the monitoring location during the rising limb of a flood. This effect is usually referred to as the flushing effect, or clean-out effect (Piest et al., 1975; Bussi et al., 2014b), and is due to the removal of easily-mobilised material deposited in the drainage network prior to the flood event, leading to higher suspended sediment concentrations during the rising limb than the falling limb, given the same water discharge. This is directly linked to the degree of connectivity between the channel network and the sources of sediment (Buendia et al., 2015; Keesstra, 2007; Keesstra et al., 2009; Marchamalo et al., 2015; Masselink et al., 2016). Despite the great amount of work regarding the use of SRCs found in the literature, many insights can still be gained by their use.

In the present study, a SRC-based approach has been used to characterise sediment dynamics within the River Thames catchment (UK). This catchment was used as a case-study owing to its relevance for human water supply, its high ecological value and the availability of a long low-frequency suspended sediment concentration dataset. The HMS dataset collected by the Environment Agency for England and Wales was used, providing low-frequency measurements of suspended sediment

concentration at ten different gauging stations. SRCs were used to assess the seasonal flushing effect. The inter-annual variation of SRC parameters was also studied and quantified. The objective of this paper is to show a methodology to characterise the flushing effect and its spatio-temporal variations due to natural and anthropogenic disturbances within a catchment using low-frequency suspended sediment data, and to analyse its results for the case of the River Thames.

Study region and datasets description

In this study, the sediment transport within the Thames catchment (UK) was analysed. The Thames catchment is located in the south of England (**Fig. 1**). The River Thames drains towards the city of London. It provides freshwater to around 14 million people, the non-tidal course receives wastewater from a population equivalent of almost 3 million (Kinniburgh and Barnett, 2009), it is also used for navigation and has a very high ecological value.

The Thames catchment covers around 10,000 km² up to its tidal reach in Kingston-Upon-Thames (South-West of London). 14% of the total catchment is occupied by urban land, although in the lower part the urban fraction rises to almost 30%. The headwaters are characterised by large proportions of arable land, with some forest and pasture (46%, 11% and 37% respectively for the part of the catchment drained by station 6001, **Fig. 1**). The geology varies across the catchment: the headwaters are mainly underlain by limestone (for example, the Thames at Farmoor sub-catchment – 6001 station in **Fig. 1**) and clay or mudstone (for example the Cherwell sub-catchment – 6002 station in **Fig. 1**). A chalk strip crosses the catchment from SW to NE, especially affecting the Kennet and Colne sub-catchments (Bussi et al., 2016).

Data from nine HMS gauging stations were made available (**Table 1**, **Fig. 1**); two on the River Thames (Farmoor and Teddington) and the other seven on some of the main tributaries within the Thames catchment (Rivers Cherwell, Thame, Colne, Kennet, Loddon, Wey, Mole). Water discharge and suspended sediment concentrations were measured at these locations with a variable frequency, from once a week to once a month (**Table 1**). The resulting average number of days between collected samples varies between 14 (Thames River at Teddington) and 27 (Rivers Cherwell, Colne and Wey). The suspended concentration was measured by collecting a single water sample for each measurement.

The suspended sediment concentration measurements range from 1974 to present; although data up to the end of 2012 is used here (39 years of suspended sediment concentration data). The Environment Agency also provides instantaneous water discharge measurements, taken at the same time as the suspended sediment samples. For most stations, these water discharge measurements start at the beginning of 1985 and continue until the present with the exception of the Thames at Farmoor and Teddington (stations 6001 and 6010), where the water discharge measurements start in 1974.

Use of the HMS dataset has already been reported in the literature (Worrall et al., 2007, 2014). It has already been used for estimating suspended sediment loads (Worrall et al., 2013a). For the Thames at Teddington, 24.9% of the suspended sediment samples were collected with discharges below Q25 ($21 \text{ m}^3 \text{ s}^{-1}$), 50.0% of the samples when the discharge was below Q50 ($42 \text{ m}^3 \text{ s}^{-1}$), 74.2% of the samples with discharges below Q75 ($87 \text{ m}^3 \text{ s}^{-1}$), 89.7% of the samples with discharges below Q90 ($157 \text{ m}^3 \text{ s}^{-1}$), 95.0% of the samples with discharges below Q95 ($216 \text{ m}^3 \text{ s}^{-1}$) and 99.1% of the samples with discharges below Q99 ($316 \text{ m}^3 \text{ s}^{-1}$). The HMS dataset also covers

the majority of major flood events (72% of flood events at station 6010 have at least one sample).

Some of the stations used here are located close to National River Flow Archive hydrometric stations (NRFA, www.ceh.ac.uk/data/nrfa/; see **Table 1**). In this case, NRFA continuous water discharge series were also used when a continuous water discharge series was needed (see sections 0 and 0). NRFA data date back to 1883 for the Thames at Teddington, while it started in 1992 for the Thames at Farmoor, in 1991 for the Thames at Staines, in 1995 for the Loddon at Twyford, in 1979 for the Wey at the confluence and in 1984 for the Mole at the confluence.

Methodology

Variability of the SRC coefficients and exponents

In this study, the SRC technique was used to analyse the suspended sediment transport of the Thames catchment.

Fitting a SRC on a low-frequency dataset such as the one provided by the HMS could return an unrealistic curve, owing to the low number of samples available, especially high flow samples. To address this concern, the following methodology was employed. First, the range of water discharge values was divided into n regular intervals. Second, three pairs of water discharge and suspended sediment concentration values were randomly selected from within each of these n intervals. Then, a SRC is fitted to the $3 \cdot n$ selected values. This resampling procedure was repeated m times selecting each time $3 \cdot n$ pairs of values, in a manner which is similar to that used in the bootstrap technique (Efron, 1979) employed by Rustomji and Wilkinson (2008). The result is a set of m different SRCs.

This procedure allows assignment of the same weight to different flow intervals (for example, high flows, intermediate flows and low flows), ensuring that sampling bias towards low flows does not exert a stronger influence on the SRC parameters. On the other hand, the dependence of the SRC on the set of samples used to fit it is also taken into account by producing a range of m SRC coefficients rather than only one, in order to quantify the uncertainty affecting the SRC. After a sensitivity analysis on the values of m and n , it was decided to employ $m = 100$ (number of SRCs fitted to a single dataset) and $n = 4$ (number of intervals). In particular, regarding the n value, it was noticed that, given the reduced number of available suspended sediment concentration samples, larger values often led to intervals with a very small number of samples, and therefore it was decided not to use an n value larger than 4.

Seasonal variability of the SRC coefficient

In this study, the change in sediment rating curve due to an event-based flushing effect is analysed. In the case of the River Thames, this phenomenon typically occurs after summer, when the first floods take place, usually from October to January (Bowes et al., 2015; Johnes and Burt, 1991). To quantify this process, a flood event classification was implemented by ranking the floods that take place after summer and fitting different SRCs depending on the event rank. The flood classification was carried out as follows: the first flood event (peak flow > Q95) after the 31st of August was ranked No. 1. Then, larger events that take place after that were subsequently ranked with increased numbers. A flood event with a smaller peak flow than the previous one was not ranked (if no subsequent flood exceeds the magnitude of the first flood, only a flood ranked No. 1 will exist during that hydrological year). This way of ranking flood events allows the classification of flood events based on the timing of their occurrence after the drought period. This methodology requires continuous water discharge

records and it was applied only at stations which also had continuous discharge records available.

Based on the flood event ranking, the available samples were split into different groups, depending on the rank of the event during which they were collected. Samples collected during non-ranked flood events, or during drought periods were not ranked. Then, m SRCs were fitted to each of the four resulting samples groups (samples ranked 1, samples ranked 2, samples ranked 3 and samples ranked 4 or more). No distinction was made depending on whether suspended sediment samples were collected during the rising or falling stage of a flood event. Although this distinction is widely acknowledged to be relevant (Piest et al., 1975; Bussi et al., 2014b), it would require the sample datasets to be separated into further sub-groups, which would produce subsets that were too small to be used to fit SRCs robustly.

This procedure was used to estimate a range of values of SRC exponents and coefficients for each station. However, a slight change in one of the two SRC parameters (coefficient or exponent) can strongly affect the other. This could present an important limitation when comparing exponents and coefficients from different subsets or different time periods. For this reason, the exponent of the SRC was fixed for each station and only the SRC coefficient was varied, using the bootstrapping methodology described above. In this way, a comparison of the temporal variations of SRC coefficients can be carried out without being conditioned on the value of the exponent. Furthermore, the SRC exponent describes how the coefficient scales with the discharge: if exponent > 1 then bigger floods recruit disproportionately more sediment, indicating the mobilization of sediment stores at high discharge conditions (i.e., the river is essentially transport limited). If exponent < 1 then sediment is exhausted at high discharge (i.e., the system is essentially supply limited), and for this

reason it should be considered as a catchment property which remains unchanged from a flood event to another. A similar approach was also used by Dadson et al. (2004) and Lauer and Parker (2008b). This technique allows the production of four groups (one for each of the ranks) of m SRC coefficients which can be subsequently compared to detect changes in sediment dynamics. Then, the subsets of m SRC coefficients for each of the four groups were compared using an analysis of variance (ANOVA) followed by a Tukey test to detect changes in behaviour of the different groups.

The SRC exponents were computed in the first stage of this study by fitting m SRCs for each station using all available data and allowing both the coefficient and the exponent to vary. The median of the m resulting exponents (for each station) was chosen as the fixed SRC exponent value. The choice to constrain the SRC exponents should not be seen as a limitation to this approach. In fact, the coefficient in the SRC has a physical interpretation as the unit suspended sediment concentration, i.e., the sediment concentration scaled to a unit discharge. The SRC exponents were fixed rather than the coefficients because their range of variations (typically between 0 and 2) is much smaller than the range of variation of the coefficients (between 10^{-4} and 10^3), as can be found in the literature (Walling, 1977a; Sarma, 1986; Webb et al., 1997; Asselman, 2000; Syvitski et al., 2000; Horowitz, 2003; Lauer and Parker, 2008b; Hu et al., 2011).

Inter-annual variability of the SRC coefficient

The inter-annual variability of the River Thames sediment transport was also analysed to look for possible temporal trends. The suspended sediment concentration data series were split into various groups depending on their date of collection. Three

groups were created: the first containing the suspended sediment samples collected from 1974 to 1995, the second from 1985 to 2005 and the third from 1995 to 2012. Different SRCs were fitted to each suspended sediment sample group, varying the SRC coefficient but constraining the SRC exponent to a fixed value, different for each station, and the resulting coefficients were compared between each other. The same procedure for establishing the constant exponent was used here as in the previous section. Only stations 6008 (Wey at the confluence) and 6010 (Thames at Teddington) had a number of samples collected in 1975–1995 large enough to use the SRC fitting methodology. For the rest of stations, only 1985–2005 and 1995–2012 were considered (the stations and their locations are described in the Study Area section). For each sub-group extracted from a different time window the same analysis was repeated, fitting different SRC coefficients (and maintaining the same exponent) depending on the rank. The resulting SRC coefficients were compared to detect possible temporal changes.

HMS data analysis and discussion

Variability of the SRC coefficients and exponents

The resulting SRCs are shown in **Fig. 3**, where the confidence intervals described by the grey-shaded areas indicate the range of variations (95% probability) of the m SRC coefficients obtained with the bootstrapping methodology. The median SRC exponent values shown in **Table 2** were used as station-specific exponents. In **Fig. 3**, the dots represent the suspended sediment concentration against water discharge samples. The black broken lines represent the median SRC (obtained using the median of the m coefficients and the median of the m exponents). The red dotted lines represent the SRC fitted with the non-linear least-square methods on all the available samples. The

grey areas represent the 95% confidence intervals obtained by using the bootstrapping technique. As can be seen in **Fig. 3**, the SRC obtained with the median exponent and coefficient from the bootstrap methodology is in general very similar to the SRC obtained using the best fit parameters (i.e., the ones obtained through non-linear least-square fitting on all the available samples), although in some cases (stations 6004, 6009 and 6010) there can be a large difference. The median exponent was chosen as station-specific exponent, rather than the best fit exponent because the latter is strongly affected by the larger number of samples collected during low flows compared to the relatively small number collected during high flows.

The goodness of fit of the SRCs was also assessed. The correlation coefficients of the median SRCs were 0.45, 0.74, 0.55, 0.60, 0.53, 0.58, 0.23, 0.59, 0.37 and 0.67 for station 6001 to 2010, respectively. The average errors (i.e. the average of the biases calculated for each pair flow-suspended sediment concentration) were -16%, -18%, -14%, -11%, +21%, -26%, -25%, -11%, -32% and -31%, respectively.

Seasonal variability of the SRC coefficient

Following the flow ranking procedure, the results for the Thames at Teddington are shown in **Fig. 4**. In this figure, the SRCs fitted to suspended sediment concentration records of a given rank (red dots) are shown (black broken lines) along with their 95% confidence intervals (grey shaded areas). All the available samples, regardless of their rank, are displayed in the background (black dots). Ranks go from 1 to 4 from left to right. The black broken lines represent the median SRCs obtained with fixed exponent, regardless of ranks. The blue broken lines represent the median SRCs varying both the SRC coefficient and exponent.

293 SRCs vary depending on the event rank. The SRCs coefficients (i.e., unit sediment
294 concentrations) are 2.19, 1.16, 0.90 and 0.96 for samples collected during floods
295 ranked No. 1, 2, 3 and 4 respectively. There is a decrease in the SRC coefficient from
296 samples ranked No 1 to samples ranked No 2, 3 and ≥ 4 . This result indicates that the
297 first flood events after the summer carry a larger suspended sediment concentration
298 than the other flood events, and that the proportionality between water discharge and
299 suspended sediment concentration is smaller for the following events. For the Thames
300 at Teddington, the suspended sediment concentration for the first floods after summer
301 is expected to be around double the suspended sediment concentration of other flood
302 events, for a given water discharge. The variation of the SRC depending on the flood
303 event rank (and thus the variation of its coefficient) indicates that a large amount of
304 material is mobilised after the summer. The source of this material is unknown but may
305 include the products of hillslope erosion, bank and channel erosion, sediment from
306 agricultural drains, farm tracks, urban surfaces, and waste water treatment works. This
307 sediment is mobilised by the first flood after the summer. The median SRC obtained
308 varying both coefficient and exponent is also represented in **Fig. 4** (blue broken lines).
309 The same analysis was carried out for all the HMS stations with continuous discharge
310 monitoring available from an NRFA station. The results are shown in **Fig. 5**. The box
311 and whisker plots indicate the range of variability of all coefficients corresponding to a
312 given rank at a given HMS station (**Fig. 5**, crosses are the mean values, boxes indicates
313 the variance, the horizontal lines within the boxes is the median value and the whiskers
314 are minimum/maximum values). In the case of stations 6001 (Thames at Farmoor),
315 6005 (Loddon at Twyford), and 6006 (Thames at Staines), due the reduced amount of
316 samples that had a rank assigned, samples ranked two or more were grouped in a

317 single rank. In the case of stations 6008 (Wey at the confluence) and 6009 (Mole at
318 the confluence), samples ranked three or more were grouped in a single rank.

319 **Fig. 5** indicates that the decrease in the SRC coefficient noted in **Fig. 4** for the station
320 6010 (Thames at Teddington) can be observed for other stations, such as 6001, 6005,
321 6006 and 6008. An ANOVA test confirmed the statistical significance of the difference
322 between groups, and a Tukey multiple comparisons gave P values <0.05 for all pair-
323 wise comparisons, apart from subsets of samples with ranks No. 3 and 4 at station
324 6010 (Thames at Teddington). This result indicates that, at station 6010, the flushing
325 effect is exhausted after two events of increasing magnitude.

326 The average SRC coefficient of samples ranked one was greater than the median
327 coefficient for the samples ranked two by a factor of 1.5, 1.8, 1.8, 2.0 and 1.9 for
328 stations 6001, 6005, 6006, 6008 and 6010, respectively. This suggests that flushing
329 increases the suspended sediment concentration of the first floods after summer by a
330 factor of between 1.5 and 2 compared with the floods that follow.

331 Although the available data is not detailed enough to be correlated to the physical
332 causes of the seasonal variations, it might be argued that these are strictly related to
333 land use and land management. The Thames catchment is characterised by extensive
334 portions of arable land, which is the primary source of sediment. Many studies have
335 shown the correlation between arable land management and variations in soil erosion
336 or sediment yield (Bisantino et al., 2015; Grimaldi et al., 2015; Porto et al., 2015; Zema
337 et al., 2015). Nevertheless, a different approach, for example including the use of a
338 physically-based model, would be needed in this case to disentangle the impact of
339 land use variations on suspended sediment yield.

The downward trend in SRC coefficients as rank increases cannot be seen at station 6009 (River Mole). A possible explanation is that the River Mole catchment is highly urbanised (22% of its area is urban land, following Fuller et al., 2002), and that the flushing effect is mostly related to natural processes (soil weathering, riparian zone erosion and natural bank erosion, etc.). This could reflect the fact that there is less sediment storage in urban channel systems. Nevertheless, it should be noted that the number of samples is smaller than for the rest of stations (see **Table 1**). This limitation could strongly affect the final results, given that the available samples were further split in sub-groups.

Inter-annual variability of the SRC coefficient

In **Table 3**, the SRC coefficients fitted to different time windows are shown. Both SRC coefficients fitted to all samples and SRC coefficients fitted to samples ranked No. 1 are shown. Station 6005 is not shown because the resulting subsets of samples were too small to apply the SRC fitting technique used in this study.

As can be seen in **Table 3**, no strong variation can be observed in the SRC coefficients fitted using all the available samples. However, some of the stations show a decrease in SRC coefficients fitted using only samples ranked No. 1 for the 1995-2012 window, namely 6006 (Thames at Staines), 6008 (Wey at confluence) and 6010 (Thames at Teddington). This decrease is statistically significant, following an ANOVA analysis with Tukey test on the population of SRC coefficients generated by fitting SRCs with the bootstrapping methodology. Again, station 6009 (Mole at the confluence) shows a different behaviour compared to the rest of stations: the SRC coefficients corresponding to all samples show a decrease from 1985-2005 to 1995-2012 but the SRC coefficients corresponding to samples ranked No. 1 do not.

364 The decrease in the flushing effect is also evident in **Fig. 6**, where the boxplots for the
365 SRC coefficients corresponding to ranks 1, 2 and 3 are shown for four stations (6001
366 – Thames at Farmoor, 6006 – Thames at Staines, 6008 – Wey at the confluence and
367 6010 – Thames at Teddington). For stations 6008 and 6010, only small changes were
368 observed between the first period (1975-1995) and the second (1985-2005), while an
369 important decrease in SRC coefficients of samples ranked No. 1 is evident from the
370 second period to the third (1995-2012). Surprisingly, station 6001, located on the River
371 Thames at Farmoor, does not show this decreasing trend, although it must be noted
372 that only two samples ranked No. 1 were collected before 1995, thus making this
373 analysis much less reliable. Not enough samples were available for the time window
374 1975-1995 for the stations 6001 and 6006.

375 This reduction could be related to a decrease in total soil erosion, due for example to
376 land-use change. From 1990 to 2000, the total arable land in the Thames catchment
377 decreased from 63% to 46%, while the urban area increased from 18% to 28%,
378 following the UK Land Cover Map 1990 (Fuller et al., 1994) and 2000 (Fuller et al.,
379 2002). This change could have reduced the amount of sediment deposited into the
380 drainage network before the summer, when arable lands are tilled for crop production.
381 Another plausible cause is a change in land management, especially regarding
382 riparian zone management, which could have led to an important decrease of available
383 sediment. As an example, McKergow et al. (2003) showed a decrease in suspended
384 sediment load in a small Australian catchment after riparian zone management, as a
385 result of increased bank stability. A third possible explanation is the implementation of
386 the UK Water Resources Act of 1991, which regulated all the discharges from sewage
387 treatment plants into rivers, including grit removal. Nevertheless, in this study it was
388 not possible to relate this phenomenon to its causes with reasonable certainty, given

the available data. Nevertheless, these explanations are quite speculative at this stage, and further research is required to detect the causes of this historical decrease. For example, this could be done by reconstructing in detail past land-use change and changes in land management policy within the River Thames catchment, and correlating the decrease in total soil erosion and in suspended sediment load of the first floods after the summer for a long-term gauging station such as Teddington with these changes.

Conclusions

This study observed and quantified the widely-hypothesised seasonal flushing effect in the Thames. There is a systematic increase in suspended sediment concentration due to the flushing of material deposited into the drainage network during the summer. Our findings demonstrate that the first floods after summer typically carry large suspended sediment loads compared with subsequent flood events (1.5 – 2 times). In this study we have measured the first-flush effect, which was previously known but has never been quantified, using low-frequency suspended sediment samples. The inter-annual variability of sediment transport was also analysed and it was found that, although no clear temporal trend can be discerned within the Thames catchment, a decrease in sediment transport of the first floods after summer is likely to have taken place during the 1990s.

The results of this study can be of help for water resources management and prevention of reservoir siltation but also for the navigation on the River Thames and dredging planning. The findings of this study can be useful for catchment managers and practitioners looking to quantify and understand the seasonal/inter-annual behaviour of the sediment transport in the River Thames. For example, they could be

used for defining river water abstraction operational rules based on the seasonal variability of the SRC in order to minimise the concentration of suspended sediment entering offline reservoirs such as the ones that can be found on the River Thames. Furthermore, the methodology used in this study can be extrapolated to other catchments with similar low-frequency water availability, with the aim of assessing the flushing effect and the spatio-temporal patterns of sediment yield.

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Supplemental Data

A document showing the application of the methodology described in this paper but using the shorter and more detailed Thames Initiative dataset (Bowes et al., 2012) is available online in the ASCE Library (ascelibrary.org), with the aim of validating the outcomes of the HMS dataset analysis.

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555 **Tables**

556 **Table 1.** HMS stations and corresponding NRFA stations.

HM code	River	Location	Drainage area (km ²)	No of suspended sediment concentration records	Avg No of days between samples	NRFA code
6001	Thames	Farmoor	1596	786	18	39129
6002	Cherwell	Oxford	900	533	26	-
6003	Thame	Confluence	687	572	25	-
6004	Kennett	Confluence	1156	583	24	-
6005	Loddon	Twyford	742	541	26	39138
6006	Thames	Staines	8153	871	16	39111
6007	Colne	Confluence	994	518	27	-
6008	Wey	Confluence	997	515	27	39079
6009	Mole	Confluence	477	653	22	39104
6010	Thames	Teddington	9927	985	14	39001

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558 **Table 2.** Median SRC coefficients and exponents of all the HMS stations and confidence intervals.

HMS code	Median SRC coefficient	95% confidence interval	Median SRC exponent	95% confidence interval
6001	5.20	0.47 – 21.46	0.52	0.10 – 1.17
6002	3.48	1.53 – 9.13	0.83	0.52 – 1.13
6003	8.04	3.66 – 18.92	0.44	0.11 – 0.72
6004	3.11	0.85 – 11.27	0.64	0.22 – 1.11
6005	3.99	1.93 – 13.88	0.68	0.34 – 0.95
6006	1.53	0.33 – 10.74	0.56	0.14 – 0.91
6007	8.33	4.69 – 21.45	0.23	-0.25 – 0.56
6008	5.29	1.89 – 18.18	0.61	0.27 – 0.92
6009	2.06	0.90 – 5.11	1.13	0.86 – 1.37
6010	1.05	0.18 – 9.34	0.71	0.25 – 1.07

559

560 **Table 3.** Median SRC coefficients fitted to different time windows using all HMS sediment

561 concentrations and NRFA flows (upper part); and the same fitted only on samples ranked No. 1.

	Time window	6001 Thames at Farmoor	6006 Thames at Staines	6008 Wey at confluence	6009 Mole at confluence	6010 Thames at Teddington
All samples	1975-1995	-	-	6.34	-	1.39
	1985-2005	1.68	0.72	4.51	13.18	1.02
	1995-2012	1.38	0.69	6.30	6.30	1.00
Samples ranked No. 1	1975-1995	-	-	15.45	-	2.70
	1985-2005	1.63	2.39	13.67	5.68	2.88
	1995-2012	1.67	0.81	10.46	6.07	1.81

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563 **Figures**

564 **Fig. 1.** Location of the Harmonised Monitoring Scheme stations (blue triangles) and Thames Initiative
565 stations (orange circles).

566 **Fig. 2.** Example of event ranking (Thames at Teddington, 1987-1988).

567 **Fig. 3.** Sediment rating curves for all Thames HMS stations used in the present analysis.

568 **Fig. 4.** SRC variation depending on the rank of the event (Thames at Teddington).

569 **Fig. 5.** Variation of the SRC coefficient depending on the rank of the event for different HMS stations.

570 **Fig. 6.** Variation of SRC coefficient depending on the calculation time window for stations 6001, 6006,
571 6008 and 6010.

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