Reintroduced large wood modifies fine sediment transport and storage in a lowland river channel

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Abstract

This paper explores changes in suspended sediment transport and fine sediment storage at the reach and patch scale associated with the reintroduction of partial LW jams in an artificially over-widened lowland river. The field site incorporates two adjacent reaches: a downstream section where LW jams were reintroduced in 2010 and a reach immediately upstream where no LW was introduced. LW pieces were organised into 'partial' jams incorporating several 'key pieces' which were later colonised by substantial stands of aquatic and wetland plants. Reach-scale suspended sediment transport was investigated using arrays of time-integrated suspended sediment samplers. Patch-scale suspended sediment transport was explored experimentally using turbidity sensors to track the magnitude and velocity of artificially generated sediment plumes. Fine sediment storage was quantified at both reach and patch scales by repeat surveys of fine sediment depth. The results show that partial LW jams influence fine sediment dynamics at both the patch and reach scale. At the patch-scale, introduction of LW led to a reduction in the

concentration and increase in the time lag of released sediment plumes within the LW, indicating increased diffusion of plumes. This contrasted with higher concentrations and lower time lags in areas adjacent to the LW; indicating more effective advection processes. This led to increased fine sediment storage within the LW compared with areas adjacent to the LW. At the reach-scale there was a greater increase in fine sediment storage through time within the restored reach relative to the unrestored reach, although the changes in sediment transport responsible for this were not evident from time-integrated suspended sediment data. The results of the study have been used to develop a conceptual model which may inform restoration design.

Keywords

Large wood; organic debris; suspended sediment; fine sediment; river restoration; sediment transport, sediment storage

Introduction

In-stream large wood (LW) can be defined as living or dead wood greater than 1 m in length and 0.1 m in diameter (Thevenet et al., 1998) and occurs naturally in wooded river systems. LW influences channel morphology (Montgomery et al., 2003; Wohl, 2016) and performs an array of important ecological functions (Abbe and Montgomery, 1996; Benke et al., 1985; Gurnell et al., 2005; Sweka and Hartman, 2006). LW can affect fluvial sediment dynamics at a range of scales including the reach-scale and the patch-scale (Montgomery et al., 2003). At the reach-scale, LW may reduce total sediment transport and increase sediment storage by physically blocking sediment transport (Hart, 2002; Montgomery et al., 2003), generating local flow divergence (Montgomery et al., 2003), and reducing the shear stress available for sediment transport by increasing roughness

(Assani and Petit, 1995; Manga and Kirchner, 2000). The resulting sediment storage can be highly significant (Bilby and Ward, 1989; Brown et al., 1999; Hart, 2002; Montgomery et al., 2003; Mosley, 1981; Nakamura and Swanson, 1993; Ryan et al., 2014; Skalak and Pizzuto, 2010). As an example, Elosegi et al. (2016) projected that basin-wide restoration of LW loading would store 60% of the current annual sediment yield in four streams draining into the Añarbe Reservoir in Spain. As a result of this increased storage, river systems with large quantities of LW can have reduced variability in sediment transport rates (Lancaster et al., 2001; Massong and Montgomery, 2000) and the removal of LW can result in large increases in sediment transport as stored sediment is released (Beschta, 1979; Bilby, 1981; Heede, 1985; Smith et al., 1993a).

At the patch-scale, LW influences the spatial variability of sediment dynamics by inducing strong spatial variations in shear stress and, therefore, sediment transport and bed material size (Cherry and Beschta, 1989; Smith et al., 1993b). Flow may be concentrated in areas adjacent to the LW, increasing local flow velocities (Hygelund and Manga, 2003) and creating local spatial variation in sediment transport rates and storage (Hilderbrand et al., 1998; Nakamura and Swanson, 1993; Skalak and Pizzuto, 2010; Trimble, 1997). For example, He et al. (2009) used two-dimensional hydrodynamic modelling to show that partial LW jams retarded flow and caused local deposition, whilst the flow in the rest of the channel was accelerated leading to erosion. While the effects of LW depend on the structural properties of the jams and the style of channel (Gurnell et al., 2002; Manners et al., 2007), river channels with abundant LW tend to be more hydrogeomorphologically complex and store more sediment than wood-depleted rivers and streams (Montgomery et al., 2003).

Despite the important contributions of LW to hydrogeomorphological processes and river health (Erskine and Webb, 2003; Nakamura and Swanson, 1993; Watts, 2006), floodplain development and river maintenance for navigation and flood risk management have resulted in a long history of LW removal (Wohl, 2014), particularly in lowland rivers (Gippel et al., 1996). More recently, increasing emphasis on improving the ecological status of water bodies (European Parliament, 2000) has led to an increase in the re-introduction of LW in river restoration projects (Cashman, 2014). Of the wood-based restorations in the UK's National River Restoration Inventory, some 84% were in lowland rivers and channel over-enlargement (38%) and fine sediment (30%) were the most commonly cited issues affecting the channels to be restored using LW (Cashman, 2014). Over-enlargement, also known as re-sectioning or over-widening, is where channel width is artificially increased in order to increase channel conveyance capacity, but the increase in width reduces sediment transport capacity so that sedimentation occurs (Brookes, 1985). The resulting fine sediment deposition can alter channel morphology (Doeg and Koehn, 1994; Nuttal, 1972; Wright and Berrie, 1987), reduce conveyance capacity (Singer et al., 2008), smother aquatic flora (Brookes, 1986; Edwards, 1969), and reduce the availability of important habitat for benthic invertebrates (Petts, 1984; Richards and Bacon, 1994; Schalchli, 1992) and fish (Armstrong et al., 2003; Sear, 1993; Soulsby et al., 2001).

Despite the importance of fine sediment dynamics, and the growing popularity of LW as a restoration tool within lowland rivers, the majority of research into the influence of LW on fluvial sediment dynamics has concentrated on naturally occurring LW in high-energy channels with coarse sediment beds (Montgomery et al., 2003; Wohl and Scott, 2016) with only a few exceptions (Keller and Swanson, 1979; Skalak and Pizzuto, 2010). The impact of LW differs between river types (Keller and Swanson, 1979; Wohl and Scott, 2016) and the lack of research on the impacts of LW on sediment dynamics in lowland rivers therefore represents an important knowledge gap. Furthermore, restored LW can have different structural properties to naturally occurring LW, with implications for hydromorphological processes (Cashman, 2014). This paper aims to quantify the influence of reintroduced partial LW jams on fine sediment dynamics in an artificially over-widened lowland river reach. In particular, two key research questions are addressed:

1. How has the introduction of partial LW jams influenced the transport of suspended sediment, at both the reach- and patch-scale?
2. How has the introduction of partial LW jams influenced the storage of fine sediment (sand and silt), at both the reach- and patch-scale?

Based upon findings of previous studies of naturally occurring LW in high energy channels, we hypothesised that, until a new equilibrium form is achieved, the reintroduced LW would reduce reach-scale suspended sediment transport, increase reach-scale fine sediment storage, and increase patch-scale variability in both suspended sediment transport and fine sediment storage.

Methods

Field site

The field site for this project was a 160 m reach of a lowland chalk stream, located at an altitude of approximately 12 m AOD on the River Bure in North Norfolk, UK (Figure 1). The majority of the upstream catchment land use is arable agriculture and the floodplain at the study reach is wet alder (*Alnus glutinosa*) woodland. Prior to 2010, LW falling into the channel had been removed as part of regular river maintenance and the channel was heavily silted as a result of historic over-widening and dredging related to mill developments dating back to the 18th Century. The bankfull channel width and mean depth were approximately 10 m and 1 m respectively, the bed slope along the reach was 0.0017, and the bed material consists of fine gravel overlain by up to 0.8 m of sand and silt.

In November 2010, river restoration works were performed on the downstream 60 m of the field site (by the UK National Trust) in response to concerns over the channel's ecological status. The overall aim of the project was to improve the physical habitat by reinstating in-stream LW features and hence natural processes. Riparian trees (Alder) were felled into the river from the wooded riparian zone. A total of 22 'key pieces' (whole felled trees, excluding rootwads, between 8 and 19 m in length) were organised into seven jams (Table 1 and Figure 1) and secured by anchoring to either the adjacent bank or the channel bed. All seven jams were classed as 'partial jams' (Gregory et al., 1985) since they did not span the full channel width. Following their introduction, the LW jams were colonised by aquatic plants, which included floating plants (e.g. *Lemna minor*), emergent shallow water species (e.g. *Nasturtium officinale*, *Apium nodiflorum*) and marginal emergent species (e.g. *Phalaris arundinacea*, *Epilobium hirsutum*). The field site consisted of the 60 m restoration reach where these partial LW jams were introduced ("R") and a further 100 m reach directly upstream with no LW jams ("NR"; Figure 1). Figure 2 presents the sampling schedule for the study within the context of the hydrological time series from a gauging station 2.5 km downstream of the research site.

Time-integrated sampling of suspended sediment transport

To investigate the impact of introducing partial LW jams on reach-scale suspended sediment transport rates, four arrays of time-integrated suspended sediment samplers were installed in May 2010, five months prior to the introduction of the LW. Each array consisted of three passive samplers based upon the ‘rocket’ design of Phillips et al. (2000). Within each array the three samplers were spaced evenly across the width of the channel and secured to the bed at 0.6 of the flow depth at the mean daily flow (Q_{31}) following Philips *et al.* (2000) using steel uprights. As illustrated in Figure 1, two arrays were located upstream of where LW was introduced: one at the upstream extent of the NR reach (‘U1’) and the other at the transition between the NR reach and the R reach (‘U2’). A further array was positioned within the restored section, approximately halfway along the R reach (‘D1’) and the other downstream of the R reach (‘D2’). The contents of each of the arrays were emptied, dried and weighed at the end of seven contiguous sampling periods (Figure 2). The first two sampling periods were prior to the LW introduction (May-July 2010 and July-November 2010) and the remaining five sampling periods followed the LW introduction (between November 2010 and July 2012). Mean dry mass was calculated for each array (n = 3 samplers) for each sampling period, and divided by the number of days in the sampling period to give the mean rate of sampled suspended sediment transport (g day^{-1}).

In-situ experimental assessment of patch-scale suspended sediment transport

To investigate the impact of individual LW jams on the transport of suspended sediment plumes at the patch-scale, in-situ experiments were designed to record the downstream transport of individual suspended sediment plumes created by controlled releases of silt following Harvey and Clifford (2010). Similar tracer experiments have been used to explore hydraulic habitat and retention in different channel types (Milner and Gilvear, 2012). Figure 3 illustrates the experimental set up for the release and measurement of the suspended sediment plumes. Artificial plumes were generated using 100 ml containers of fine sediment (D_{50}≈0.25 mm) collected from channel margins, spaced 0.1 m apart across the entire width of the flow. The number of containers used varied (48-103) to account for variations in flow width (4.8m-10.3m), ensuring consistent release concentrations at each cross section. The containers were emptied into the water simultaneously 5 m upstream of a cross-sectional array of turbidity sensors. Five infrared turbidity sensors (Left – “L”, Left Centre – “LC”, Centre – “C”, Right Centre – “RC”, and Right – “R”) were evenly spaced across the width of the channel cross-section. They were secured to the channel bed at a height of 0.6 of the water depth using steel uprights. Turbidity sensors were connected to a data logger, recording data at a frequency of 5 Hz for a period of 3 minutes following the release of a sediment plume. A similar experimental design has been applied in a lowland channel with relatively low flow velocities and shallow water depths (Harvey and Clifford, 2010). Turbidity was converted to sediment concentration (mg L^{-1}) by calibration ex-situ with known concentrations of sediment collected from the field site (D_{50}≈0.25 mm). Relationships between voltage output and suspended sediment concentration were quantified for each sensor by fitting polynomial regression curves (R^2 > 0.99 for all five sensors). Plume experiments were performed in triplicate at three cross-sections (Figure 1) at three times throughout the study period: once before the LW was introduced (August 2010), and twice following the LW introduction (April 2011 and July 2012; Figure 2). During all three experimental periods river discharges were between the Q_{75} and the Q_{50} (Figure 2). The three cross-sections were located as follows: one within the NR reach (‘NR’) and two within the R reach where LW was introduced in November 2010 (‘R_A’ and ‘R_B’).

Suspended sediment time series from the plume experiments were smoothed using a moving average window of two seconds in order to focus analysis on the characteristics of released sediment plumes rather than turbulence-driven sediment suspension events.

Characteristics of sediment plumes were assessed by plotting measured sediment concentration against time and by calculating the peak sediment concentration and time to peak following release, following Harvey and Clifford (2010). These data were used to explore differences before and after LW introduction both for cross-sections and for individual points within cross-sections.

Measurement of fine sediment bed storage

To quantify the impact of introduced LW jams on the deposition and storage of previously suspended sediment at both the reach- and patch-scale, surveys of fine (silt and sand) sediment depth were repeated six times throughout the sampling period (Figure 2). Two surveys were conducted before the introduction of LW and four surveys following LW introduction. For each survey fine sediment depth measurements were taken at 34 equally-spaced (5 m) cross-sections – 13 within the R reach and a further 21 in the NR reach. At each cross-section, four sample points were spaced equally across the width of the channel. At each sample point, a 3 mm diameter pin, 1 m in length, was pushed into the riverbed until it came into contact with underlying coarse substrate (Lisle and Hilton, 1992). This provided measurements of fine sediment depth at a total of 136 points during each of the survey periods: 52 in the R reach and 84 in the NR reach, with 36 of the points in the R reach in patches within LW jams and the remaining 16 points in the R reach in patches adjacent to LW jams. These data were used to explore differences in fine sediment storage before and after LW introduction, at both the reach- and patch-scale, and the trajectory of any changes over the sampling period.

Data analysis

Many of the collected data sets did not meet the assumptions of parametric tests and therefore non-parametric statistical tests were applied. Correlations between variables were assessed using Spearman's Rank, differences between group averages were explored using Mann Whitney U and Kruskal-Wallis H tests, and differences in the variability within groups were explored using Levene's test. Confidence levels >= 90% ($p \leq 0.1$) were applied in all cases. Analyses were undertaken in Minitab 17 and Microsoft Excel 2010.

Results

Influence of LW on reach-scale suspended sediment transport

The rate of suspended sediment transport at each of the sampling arrays throughout the period of record is given in Figure 4. The sampled rate of sediment transport ranged from 0.0061 g day^{-1} to 0.0944 g day^{-1} over the study. There was a statistically significant difference between the seven sampling periods (Kruskal-Wallis P = 0.002), but no significant difference between the four sampling locations (Kruskal-Wallis P = 0.712). Whilst the rate of suspended sediment transport measured at arrays downstream of LW was significantly higher following LW introduction (median = 0.0546 g day^{-1}) compared to before (median = 0.0188 g day^{-1}; Mann-Whitney P = 0.077), a similar trend was also identified at arrays upstream of LW (before median = 0.0248g day^{-1}; after median = 0.0587 g day^{-1}; Mann-Whitney P = 0.040). Thus, while an increase in sediment transport following LW reintroduction is apparent, it occurs both upstream and downstream of the LW.

Influence of LW on patch-scale suspended sediment transport

Comparisons between suspended sediment plume transport characteristics at cross-sections R_A and R_B before (2010) and after (2011) the LW introduction are given in Figure

5. There was no significant difference in peak sediment concentrations after the LW introductions at either R_A (median before = 0.138 g L^{-1}; after = 0.109 g L^{-1}; Mann-Whitney P = 0.927) or R_B (median before = 0.074 g L^{-1}; after = 0.095 g L^{-1}; Mann-Whitney P = 0.232). There was also no significant change in times to peak following the LW introduction at R_A (median before = 20.4 s, after = 27.4 s, Mann-Whitney P = 0.140), but there was a reduction in times to peak at R_B (median before = 92.6 s, after = 78.0 s, Mann-Whitney P = 0.054). Despite limited changes in average plume characteristics following LW introductions, there were significant increases in the variability of plume characteristics at both cross-sections: both for peak concentrations (R_A std. dev. before = 0.054 g L^{-1}, R_A std. dev. after = 0.096 g L^{-1}, Levene's test P = 0.054; R_B std. dev. before = 0.025gL^{-1}, R_B std. dev. after = 0.080 g L^{-1}, Levene's test P = 0.018); and times to peak (R_A std. dev. before = 3.98 s, R_A std. dev. after = 21.83 s, Levene's test P = 0.002; R_B std. dev. before = 16.62s, R_B std. dev. after = 37.06s, Levene's test P = 0.007).

The spatial organisation of plume characteristics is explored for individual cross-sections in Figure 6. At cross-section NR, where no wood was present, highest sediment concentrations were in the centre of the channel with slightly longer times to peak towards the left bank for two out of three experiments. In the 2012 experiment this pattern was disrupted when the growth of emergent vegetation adjacent to the left hand bank reduced the magnitude and velocity of the sediment plume on the left side of the channel. At the two cross-sections where LW was introduced, the spatial pattern of sediment concentration and time to peak was reorganised following LW introduction. At cross-section R_A prior to LW introduction, peak concentrations were relatively similar across most of the channel but with lower concentrations and longer time to peak at the margins. Following LW introduction peak concentrations decreased within the LW and increased in areas adjacent to the LW. There was also an increase in the time to peak within the LW. At cross-section R_B prior to LW introductions, peak concentrations and times to peak were similar across the channel width. Following LW introductions, the sediment plumes increased in magnitude and velocity in areas adjacent to the LW but remained lower in areas within the LW.

The changes to the sediment plumes are illustrated in greater detail for an example cross section (R_A) in Figure 7. A progressive differentiation between sediment traces within and adjacent to LW is evident following the LW introduction. Prior to LW introduction, the shape of sediment traces was similar across the channel width. Following LW introduction, the within-wood sensors displayed lower concentrations and longer time lags indicating less effective transmission of sediment plumes. In contrast, traces from sensors positioned adjacent to the LW exhibited similar or higher peak concentrations and shorter lag times following LW introduction.

Influence of LW on reach-scale and patch-scale fine sediment storage

Figure 8a illustrates that both the R and NR reaches experienced increases in fine sediment depth following LW introduction. However, the 95 mm increase in the median depth of the R reach (before = 0.175 m, after = 0.270 m, Mann-Whitney $P = 0.02$) was greater than the 35 mm increase in the median depth of the NR reach (before = 0.075 m, after = 0.110 m, Mann-Whitney test $P < 0.001$). Fine sediment depths also became more variable in the R reach (SD before = 0.166 m, std. dev. after = 0.186 m, Levene's test $P = 0.074$) but there was no increase in the variability within the NR reach (std. dev. before = 0.110 m, std. dev. after = 0.138 m, Levene's test $P = 0.480$).

Patch-scale sediment storage at points within and adjacent to the LW jams in reach R are presented in Figure 8b. Prior to LW introductions (2010) there was no significant difference between fine sediment storage in areas where LW was later introduced and the adjacent channel areas (wood median = 0.180 m, adjacent median = 0.155 m, Mann Whitney P = 1), but following LW introductions (2011) these LW patches became associated with significantly higher sediment storage than adjacent areas (wood median = 0.320 m, adjacent median = 0.170 m, Mann Whitney P = 0.008). This change reflects an increase in fine sediment storage in patches where LW was introduced following the LW introductions (before median = 0.180 m, after median = 0.320 m, Mann Whitney P < 0.001), while no significant change was identified for patches adjacent to the LW (before median = 0.155 m, after median = 0.170 m, Mann Whitney P = 1).

The trajectories of these reach-scale and patch-scale changes in fine sediment storage are explored in Figure 9. Positive trends between sediment depth and time were observed for both the R reach and the NR reach, and for points within the R reach both within and adjacent to the wood. However, while there was a general trend for sediment accumulation across the whole study site, the gradient of the trend is steeper in the R reach than the NR reach, and steeper at the points within the wood than at the points adjacent to the wood. Mean sediment accumulation in the R reach is at an average rate of 67 mm $year^{-1}$ whilst the mean accumulation in the NR reach is 26 mm $year^{-1}$. Similarly, mean sediment accumulation at the points within the wood is at a rate of 77 mm $year^{-1}$, while mean accumulation at points adjacent to the wood is just 42 mm $year^{-1}$.

Discussion

The reintroduced partial LW jams altered suspended sediment dynamics at both the patch- and reach-scale in the study river. At the patch-scale, results of the controlled sediment release experiments illustrate differences in suspended sediment transport within LW and adjacent patches, indicating spatial variability in mixing mechanisms at moderate flow levels (Q_{50} – Q_{75}). Within LW patches, sediment plumes show longer times to peak and lower peak sediment concentrations, indicating a dominance of diffusion processes whereby the sediment cloud spreads out vertically through the water column and/or transversely towards the banks from areas of high to low concentration (Rutherford, 1994). By contrast, in areas of flow concentration adjacent to the LW, shorter times to peak and higher peak turbidity values suggest more effective advection processes whereby the plume is moved downstream as a coherent body with less significant changes in concentration. This patch-scale variability in suspended sediment transport at moderate flow levels is reflected in differences in fine sediment storage between patches within LW and patches adjacent to LW. In turn, increased sediment storage within the LW signals that the dispersion processes lead to retention of sediment within the LW jam, while the maintenance of channel depth in patches adjacent to the LW reflects more efficient transport of sediment. Increases in spatial variability of sediment transport and storage caused by the reintroduced LW in this artificially over-widened lowland river channel reflect previous findings from studies of naturally occurring LW in higher energy environments (Montgomery et al., 2003; Nakamura and Swanson, 1993; Wohl and Scott, 2016) and, by creating a more diverse array of physical habitats for aquatic organisms, could help to address legislative requirements like the EU Water Framework Directive (European Parliament, 2000).

At the reach-scale, a measureable reduction in sediment transport was not evident in time-integrated suspended sediment data despite fine sediment storage increasing in both the R and NR reaches throughout the sampling period. It is possible that short-term modification of flow patterns in the R reach resulted in local sediment mobilisation during or immediately following restoration in the R reach. However, given the same trends are observed in both the R and NR reaches, it likely reflects the influence of catchment supply processes and the supply-limited nature of suspended sediment dynamics (Amos et al., 2004; Asselman, 1999; Einstein and Chien, 1953; Nicholas et al., 1995). Fine sediment storage did, however, increase at a faster rate within the restored reach relative to the unrestored reach. This demonstrates that the LW did reduce reach-scale sediment transport enough to encourage net sediment deposition, reflecting previous findings within higher energy channels (Bilby and Ward, 1989; Elosegi et al., 2016; Mosley, 1981; Nakamura and Swanson, 1993). However, the reduction in reach-scale sediment transport responsible for increased storage was not significant in relation to supply-driven variability in transport rates, findings which differ to those from higher energy systems (Lancaster et al., 2001; Massong and Montgomery, 2000).

It is important to note that extensive stands of wetland plants were associated with the reintroduced LW jams at this study site. This characteristic may be expected for other lowland rivers subject to restoration as management of the riparian zone can promote the growth of aquatic plants by reducing shading and elevating nutrient levels (Bunn et al., 1998; Duarte, 2012; Wersal and Madsen, 2011).

The results from this study can be used to develop a model of the influence of restored, vegetated, partial LW jams on suspended sediment dynamics in artificially over-widened lowland rivers, which includes two form-process feedback loops (Figure 10). The first occurs where the increase in local hydraulic roughness (Assani and Petit, 1995) and the physical barrier caused by a partial LW jam (Montgomery et al., 2003) reduces sediment transport through the LW, causing more fine sediment accumulation within the LW. This sediment accumulation acts to further increase local hydraulic roughness and the physical barrier created by the jam. Growth of aquatic plants around the LW, as characteristic of our study site and lowland rivers more generally, may amplify this process by contributing additional 'ecosystem engineering' capacity (Gurnell, 2014). The second form-process feedback loop occurs where the increased local hydraulic roughness and physical barrier created by the LW jam increases the proportion of flow diverted around the jam and therefore increases local shear stress and sediment transport around the jam (Hilderbrand et al., 1998; Nakamura and Swanson, 1993; Trimble, 1997). Elevated sediment transport around the jam acts to maintain the channel thalweg around the LW so that further increases in the obstruction caused by the LW may be counter-balanced by increased sediment transport around the LW. Based on these results, it can be hypothesised that, over time, these processes will result in the previously over-widened channel becoming narrower as the LW jams fill with sediment and become permanent morphological features. If this occurs, the channel should eventually achieve a new equilibrium form with narrower channel dimensions to support sufficient sediment transport capacity and reduce the likelihood of further aggradation. Further long-term monitoring would be required to assess these changes.

Conclusion

This paper shows patch and reach scale alterations to the sediment dynamics of an artificially over-widened lowland river as induced by reintroduced partial LW jams. The findings make an important contribution to the evidence base for using LW in lowland river restoration, where limited research on LW impacts on fine sediment dynamics has been performed. We show that reintroduced LW induces patch-scale changes in mixing mechanisms, altering local sediment dynamics leading to a combination of increased storage around LW and increased transport in intervening areas. At the reach-scale the LW caused aggradation, suggesting that sediment retention within LW jams exceeded the rate of sediment removal from adjacent areas of flow concentration. However, the influence that this had on reach-scale suspended sediment transport was not measurable amongst the supply-driven variability observed over the sampling period. The results of this study are directly relevant to LW-based restoration design within over-widened lowland river channels but may also provide a useful framework for assessing LW-based restoration design within other channel types, and for understanding how naturally occurring LW jams influence lowland river channels. Further research is now required to assess the influence of different types of LW jams, including naturally occurring LW, on fine sediment dynamics in lowland channels; to assess the influence of LW on suspended sediment transport across varying discharges; and to provide longer-term evaluation of the trajectory of change in restored channels following wood reintroductions.

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Figure 1: Site map for the study reach of the Bure including locations of LW pieces, suspended sediment samplers, and plume experiment cross-sections.

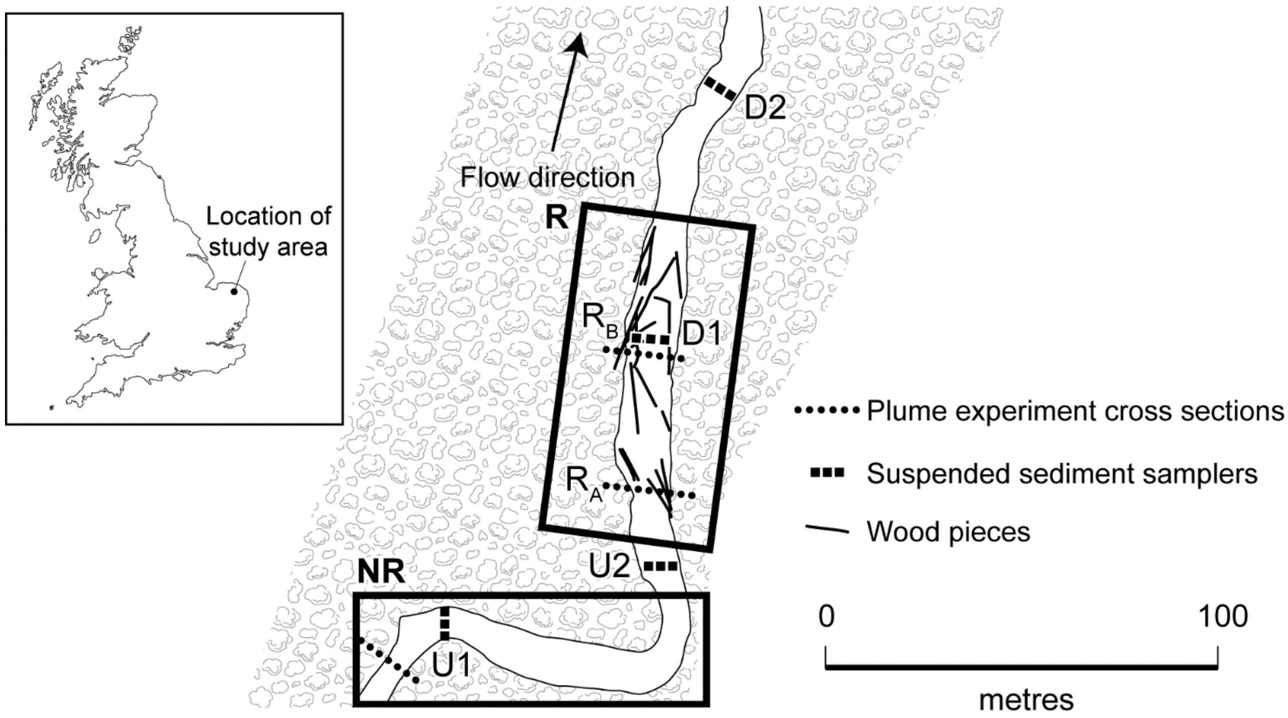

Figure 2: Timing of LW introductions, time-integrated sediment sampling periods, sediment plume experiments, and fine sediment depth measurements in relation to discharge as measured by the flow gauge at Ingworth, 2.5 km downstream of the study site (CEH NRFA gauge 34003). Numbered boxes represent time-integrated suspended sediment sampling periods. Upper, middle and lower horizontal lines indicate the Q_{10}, Q_{50} and Q_{90} respectively.

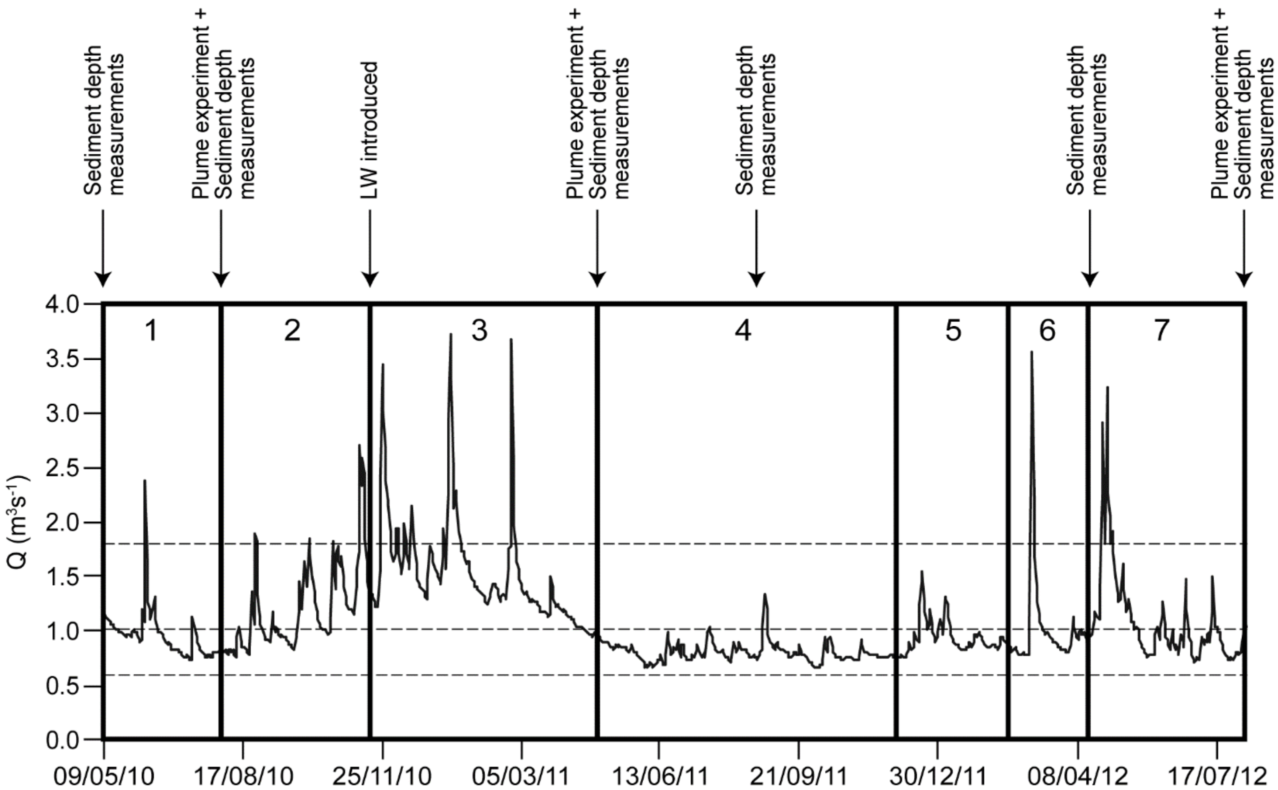

Figure 3: Experimental set up for the release and measurement of suspended sediment plumes – in plan (a) and profile (b)

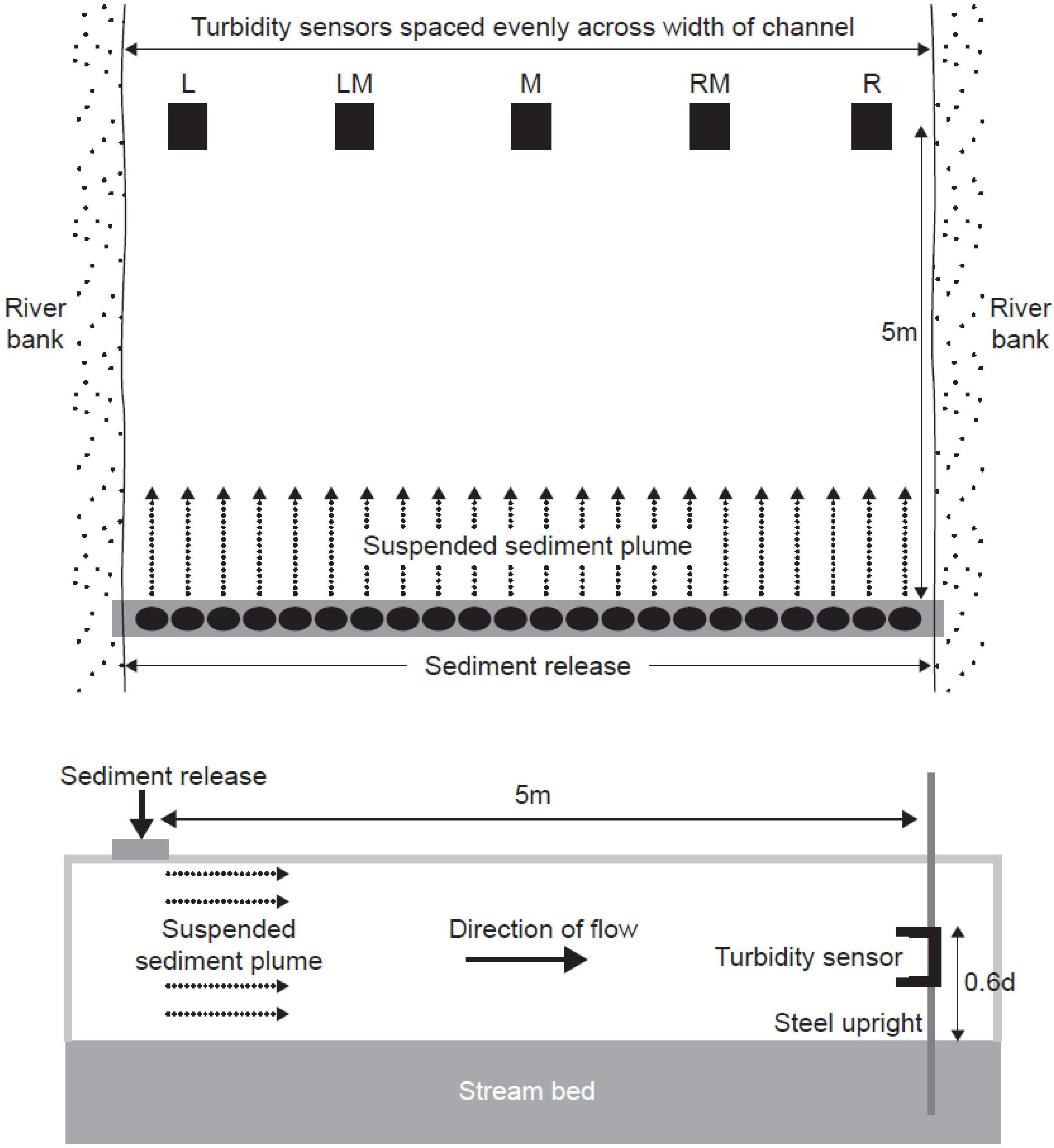

Figure 4: Mean rate of dry mass of suspended sediment collected across arrays of time-integrated samplers during each sampling period.

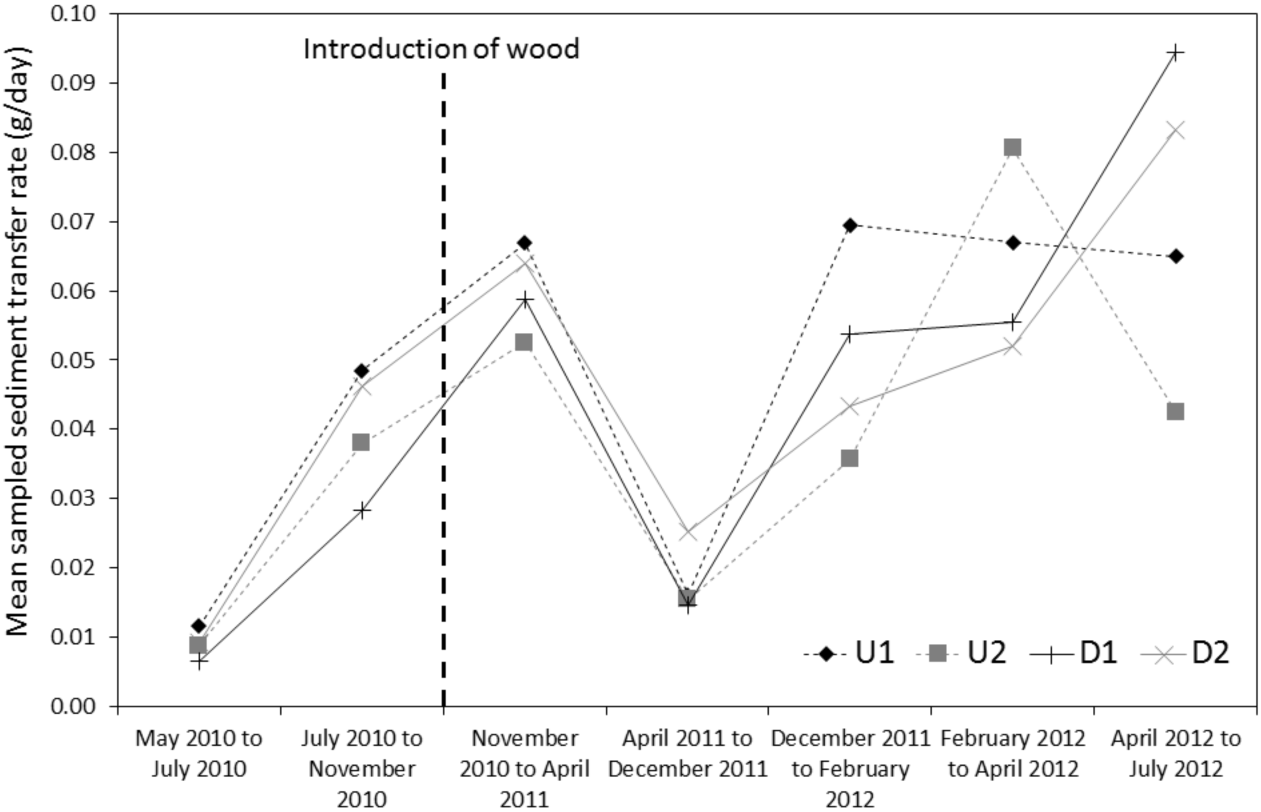

Figure 5: Comparison between cross-section characteristics of suspended sediment plume transport at cross-sections R_A and R_B before (2010) and after (2011) the introduction of LW: (a) Peak sediment concentrations; (b) Times to peak.

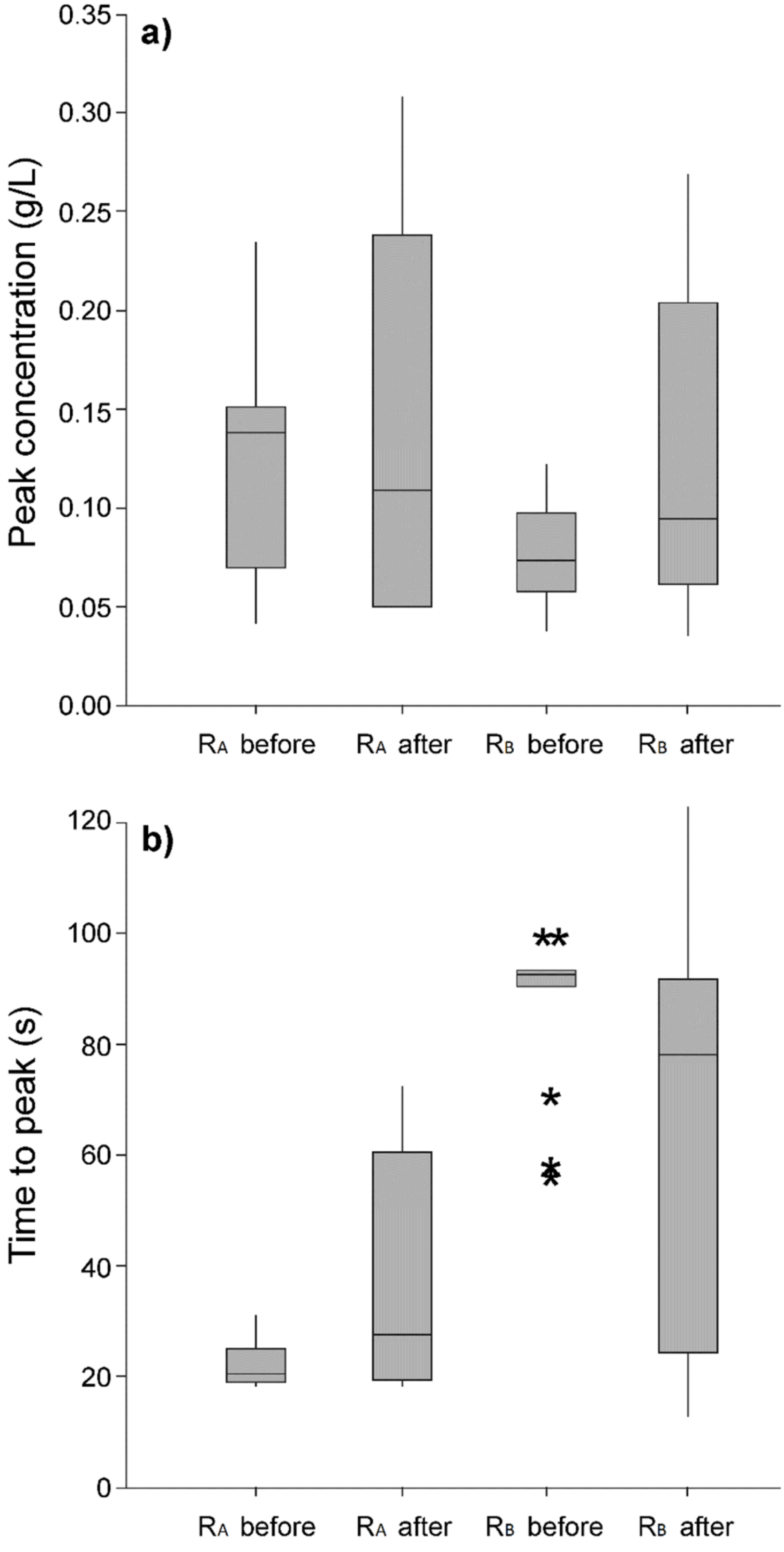

Figure 6: Peak sediment concentrations and times to peak for each sensor (L, LC, C, RC and R) during each set of sediment plume experiments (August 2010, April 2011 and July 2012) for a cross-section where no LW has been introduced (NR) and two cross-sections where LW was introduced in November 2010 (R_A and R_B).

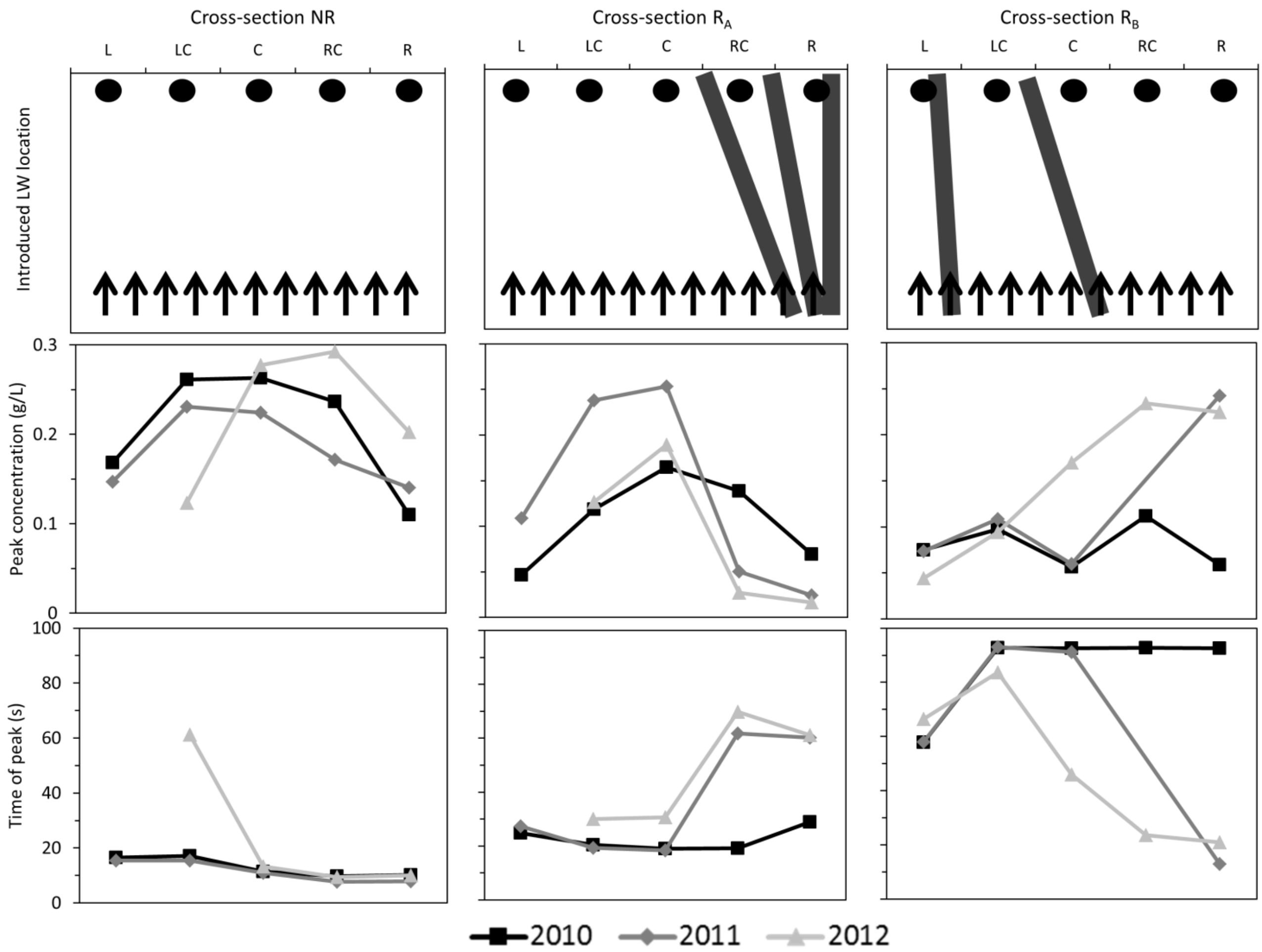

Figure 7: Sediment concentration readings at the R_A cross-section during the sediment plume experiments conducted in 2010, 2011 and 2012. No signal from the left sensor in 2012.

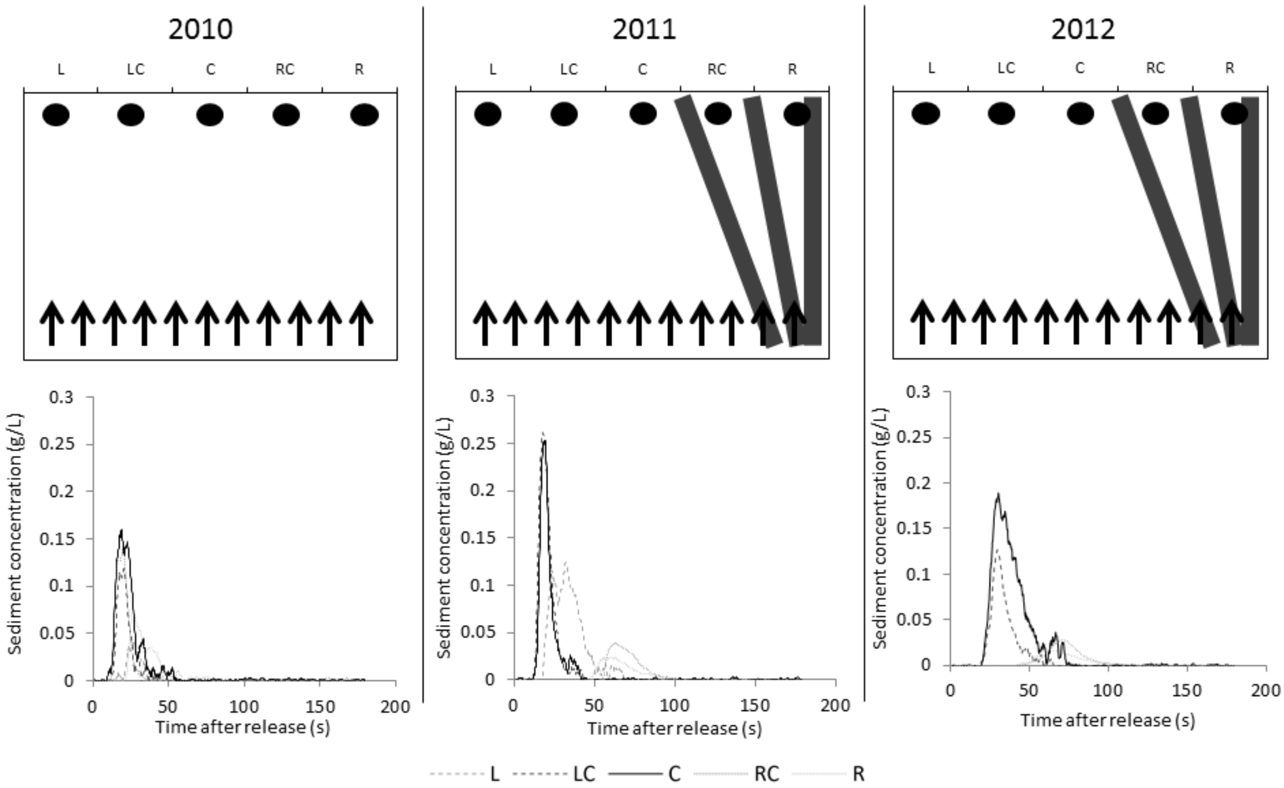

Figure 8: Comparison between fine sediment depths before (2010) and after (2011) LW was introduced for points in the R and NR reaches (a), and points in patches within and adjacent to wood (b).

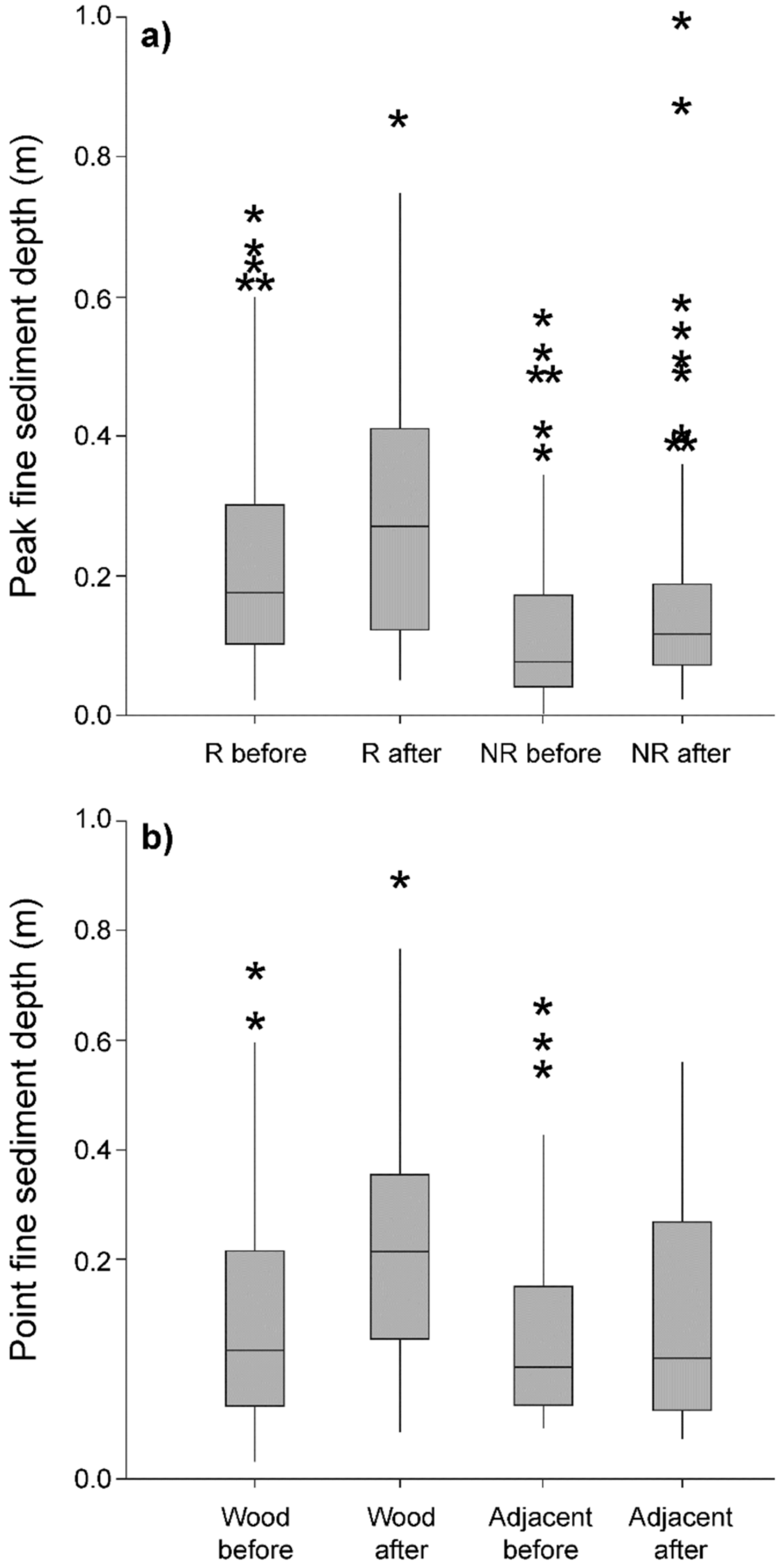

Figure 9: Trajectory of fine sediment depths over the sampling period.

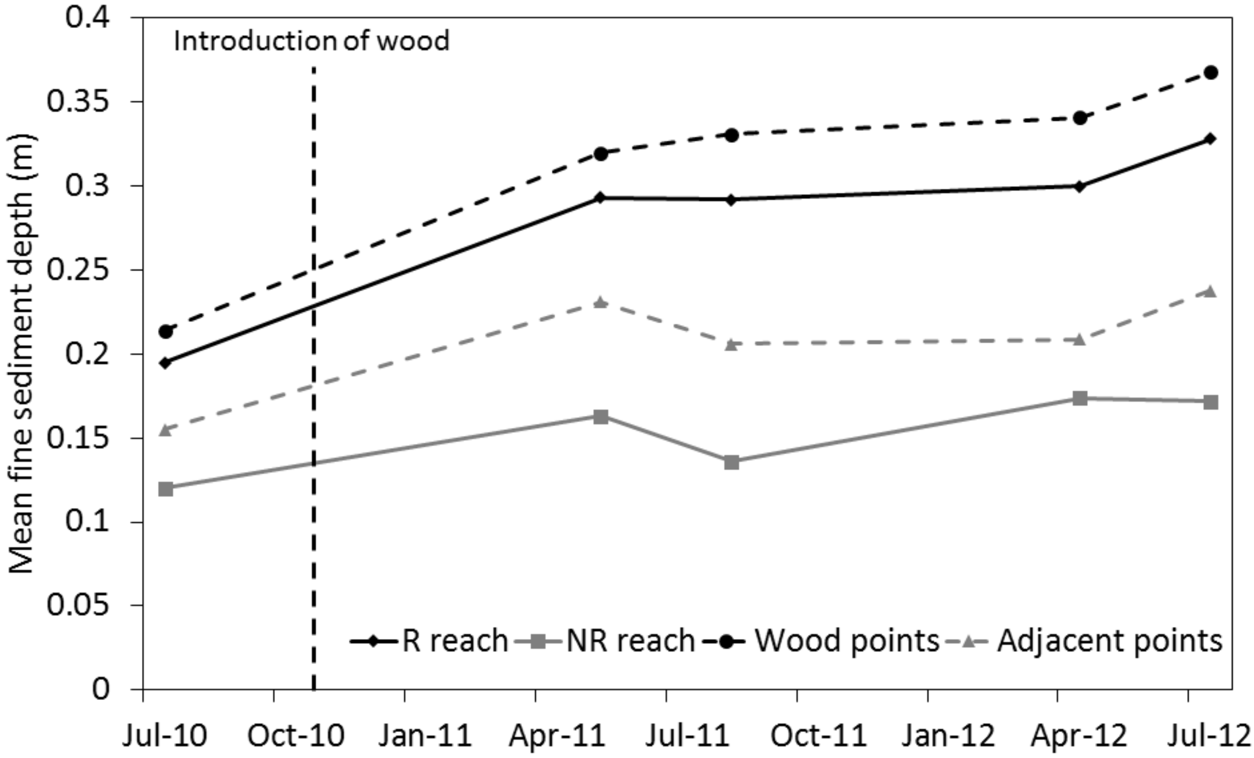

Figure 10: Model of the influence of partial jams of large wood on the suspended sediment dynamics in artificially over-widened lowland rivers. Boxes in grey represent assumed changes in variables not directly measured within this study.

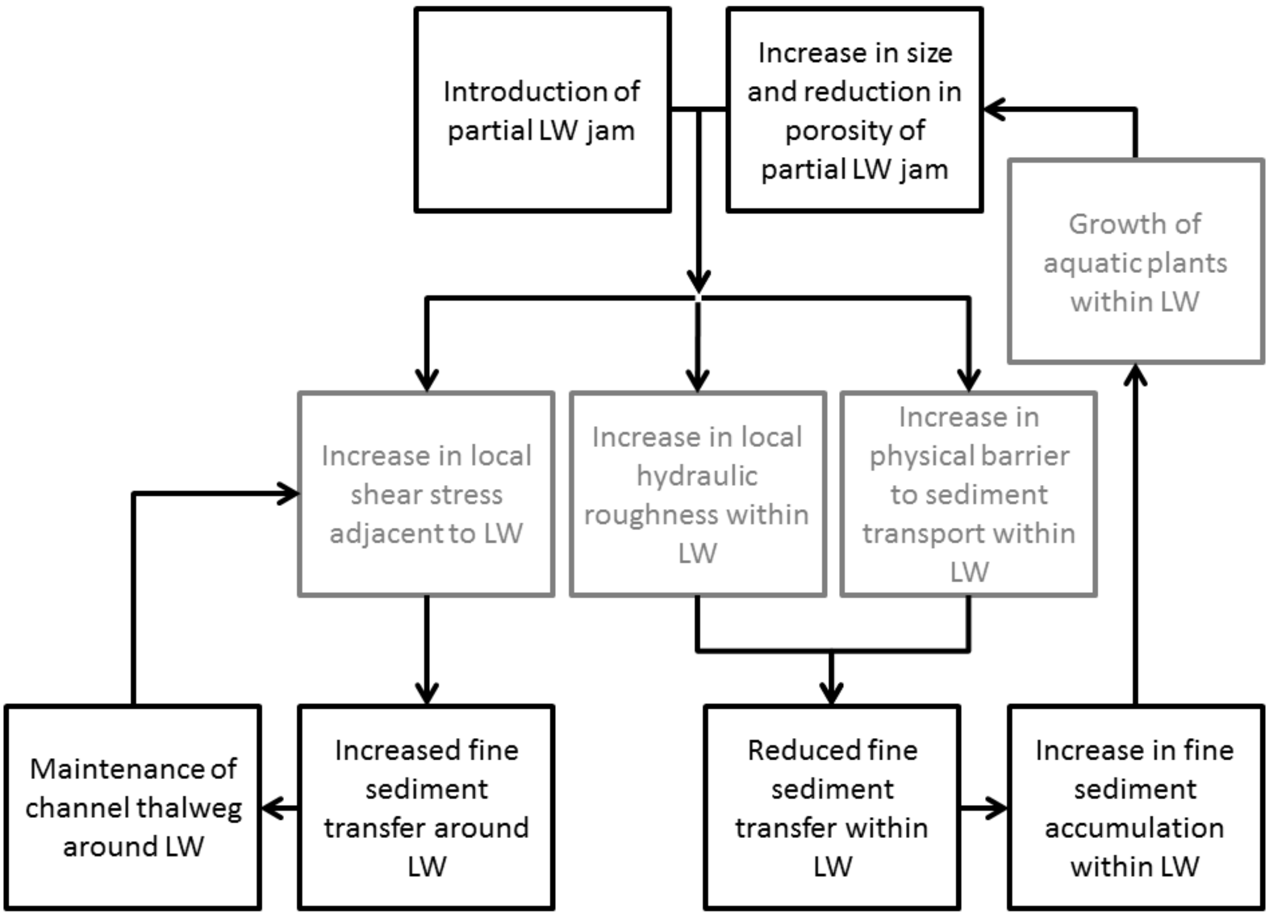

Table 1: Key properties for the seven wood jams introduced into the study reach of the River Bure. Jam orientation refers to deviation from the channel centreline.

Jam	No. wood pieces	Max piece length (m)	Max piece diameter (m)	Jam orientation (^{o})
A	2	10	0.5	20
B	3	14.2	0.41	15
C	3	16.2	0.5	10
D	5	19	0.65	20
E	3	15.2	29	170
F	3	8.2	0.35	150
G	3	10.2	0.59	20