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EDITED BY
Eliot Atekwana,
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REVIEWED BY
Emily Iskin,
Boise State University, United States
João Miguel Merces Bega,
University of São Paulo, Brazil

*CORRESPONDENCE
Ben Christopher Howard,
ben.howard@imperial.ac.uk

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Effects of instream wood reintroduction on transport and storage processes in a lowland sandy stream

Ben Christopher Howard[1]*, Ian Baker[2], Wouter Buytaert[1], Jen Drummond[3], Nicholas Kettridge[3,4], Sami Ullah[3,4] and Stefan Krause[3,4,5]

[1]Department of Civil and Environmental Engineering, Imperial College London, London, United Kingdom, [2]Catalys Ltd., Broseley, United Kingdom, [3]School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, United Kingdom, [4]Birmingham Institute of Forest Research, University of Birmingham, Birmingham, United Kingdom, [5]Water Research Centre, BISCA – Birmingham Institute for Sustainability and Climate Action, Birmingham, United Kingdom

The reintroduction of instream wood is a common technique to restore degraded streams, for example to reinstate transport and storage processes - primary controls of the movement of water, solutes, and particulates through the stream corridor - with the aim of initiating a shift towards a more natural or sustainable state. In the United Kingdom, this kind of restoration occurs predominantly in lowland sandy streams, yet to date no study has explicitly investigated its effects on transport and storage processes in such contexts. Here, we used a before-after-control-impact (BACI) experiment to test the effects of reintroducing instream wood on transport and storage processes in a lowland sandy stream under a range of stream discharges (*Q*), with an average of 0.0079 m^3/s. In the restored reach, as compared to the control reach, the average hydraulic retention time increased by 27.6%, the average transient storage increased by 28.4%, and the residence time therein increased by 13%. Although these differences were not statistically significant, we attribute this to the inevitable large variability of field tests compared to controlled laboratory environments. We interpret the observed changes as an indication of a potential increase to transient storage overall but limited subsurface transient storage, especially during higher *Q* conditions. Overall, our results suggest limited effects of instream wood reintroduction on transport and storage processes in a lowland sandy stream, but also highlight challenges in evidencing such effects. Given the sensitivity of transport and storage processes to environmental setting, it may be challenging to predict the effects of restoration based on a small set of conditions or generalizations.

KEYWORDS

transport and storage processes, transient storage, instream wood, before-after-control-impact, river restoration, nature-based solutions

1 Introduction

Stream transport and storage processes are important controls of aquatic ecosystem function and, therefore, the delivery of many important ecosystem services (Hester and Gooseff, 2010; Lewandowski et al., 2019; Ferreira et al., 2022). How water, solutes, and particulates move through the stream corridor regulates ecological interactions, biogeochemical interactions, and geomorphological processes (Poole, 2010; Boano et al., 2014; Dean et al., 2016). For example, the transient storage of water and solutes in in-channel eddies, stagnant zones, or in sediments can increase stream microbial metabolism and related biogeochemical activity, driving nutrient and carbon turnover (Shelley et al., 2017) and improving water quality (Peralta–Maraver et al., 2021). It can buffer temperature extremes, providing refuge for invertebrates (Klaar et al., 2020), and moderate hydrological extremes, reducing the impact of flood and drought events (Bruno et al., 2020). However, many streams globally are in a degraded condition with modified transport and storage processes, and therefore the delivery of these ecosystem services is compromised (Brookes, 1985; Sawyer et al., 2011; Stofleth et al., 2007).

One such mismanagement is the removal of instream wood, a widespread practice which has taken place in streams around the world (Montgomery et al., 2003; Wohl, 2014; Ockelford et al., 2024). Instream wood is an important control of transport and storage processes because it can create obstacles and blockages in the channel, which can result in altered stream velocities (generally slower at the reach scale, but characterised by localised areas of low and high velocity, e.g., upstream and downstream of features, respectively), flow heterogeneity (e.g., turbulent mixing), transient storage properties (volume, exchange rate, location, and residence time), and surface water–groundwater exchange (e.g., hyporheic exchange - the transport of surface water through sediments in flow paths that return to surface water) (Smith et al., 1993; Mutz et al., 2007; Klaar et al., 2011; Sawyer et al., 2011; Boano et al., 2014; Wohl et al., 2017; Verdonschot and Verdonschot, 2023). This is evidenced in a range of environmental settings, including lowland sandy streams (Klaar et al., 2016; Klaar et al., 2020). Also well evidenced is that the removal of instream wood leads to a simplification of the river corridor and a reversal or reduction of these properties (Smith et al., 1993; Kasahara and Wondzell, 2003; Wondzell, et al., 2009; Ockelford et al., 2024).

The restoration of instream wood is a promising technique to restore stream transport and storage processes, amongst many other ecosystem functions (Brooks et al., 2006; Hester and Gooseff, 2010; Lewandowski et al., 2019; Magliozzi et al., 2019; Ockelford et al., 2024). This is most ideally achieved through natural recovery by tree and branch fall, but this can take up to 250 years when a healthy riparian zone is already present, and 100 years longer if not (Beechie et al., 2000; Stout et al., 2018). Therefore, active reintroduction has become a common technique in river restoration (Roni et al., 2015; Grabowski et al., 2019; Ockelford et al., 2024). With the shift in strategies of river restoration from primarily form-based approaches towards process-based approaches, wood-based restoration now focusses on reinstating natural hydrogeomorphological processes, which aims to catalyse a shift towards a more natural and sustainable state, i.e., which maintains ecological integrity (Wohl et al., 2015; Grabowski et al., 2019). To inform process-based instream wood restoration, evidence is required of the effects of such practices in different environmental settings, including the effects on transport and storage processes, which as discussed are a primary control of other ecosystem processes and the delivery of ecosystem services.

The effects of river restoration differ between upland and lowland settings, in general being more pronounced in smaller headwater streams than large rivers, which is explained by differences in hydrogeomorphological characteristics (Krause et al., 2014; Levi and McIntyre, 2020; Feng et al., 2022). Upland streams are characterised by high gradients, high energy, and high sediment hydraulic conductivity (e.g., coarse boulder and gravel sediments), in contrast to lowland streams (Sternberg, 1875; Knighton, 1999; Verdonschot and Verdonschot, 2023). The effects of instream wood on flow vary between these different environmental settings. For example, in upland settings the high stream gradient affords the opportunity to generate large vertical hydraulic head gradients (e.g., from upstream to downstream of a weir or logjam) and the high flow energy can drive hydrodynamic forcing of flow into the streambed, both of which can lead to substantial volumes of subsurface transient storage, i.e., hyporheic exchange (Hester et al., 2009; Ader et al., 2021; Marshall et al., 2023; Verdonschot and Verdonschot, 2023). In contrast, in lowland streams the low gradient limits the opportunity for the generation of large vertical hydraulic head gradients and the low flow energy limits hydrodynamic forcing, but large volumes can be impounded (e.g., backwaters upstream of a weir or logjam), which can lead to substantial volumes of surface transient storage (Stofleth et al., 2007; Klaar et al., 2020). Furthermore, in lowland streams transport and storage processes and their response to instream wood are likely to be more influenced by spatially variable groundwater upwelling and downwelling (Krause et al., 2014). Given the wide range in potential stream responses to the reintroduction of instream wood, it is imperative to evidence its effects in the environmental settings in which it is likely to be applied.

Several studies have already investigated the effects of reintroducing instream wood on stream transport and storage processes with field-based experiments (Lo et al., 2024). Upland experiments tend to find an increase in hydraulic gradients surrounding wood (e.g., by up to an order of magnitude, Hester et al., 2009), an increase in reach-scale hyporheic exchange (e.g., +0.1% of discharge (Q); Sawyer and Cardenas, 2012), and an increase in transient storage (Rana et al., 2017). Fewer studies have directly investigated the effects in lowland systems, but of those results indicate insignificant effects (Matheson et al., 2017a) or effects that may represent negative consequences for the delivery of ecosystem services, such as declines in transient storage (Herzog et al., 2019) and residence time therein (Marshall et al., 2023). Whilst the effects of reintroducing instream wood on transport and storage processes in a lowland sandy stream have been investigated in laboratory flumes (e.g., Mutz et al., 2007; Sawyer et al., 2011; Wilhelmsen et al., 2021), we are not aware of any studies that have explicitly done so in a field experiment. Despite this paucity of context-relevant evidence, a large proportion of wood-based restoration in the United Kingdom occurs in lowland settings (79%) and on sedimentary geologies (63%), meaning that lowland sandy streams are likely to be the predominant environmental setting in which wood-based restoration is applied (Cashman et al., 2018).

In this study, we experimentally tested the effects of reintroducing instream wood on transport and storage processes in a lowland sandy stream in the United Kingdom. We aim to provide context-relevant evidence that can guide researchers and practitioners in predicting the effects of instream wood restoration on transport and storage processes in lowland sandy streams, highlighting associated risks and opportunities (e.g., for the delivery of ecosystem (dis)services). We intend this evidence to be useful in making informed decisions about whether, when, and where to deploy instream wood restoration.

2 Data and methods

2.1 Experimental design

Transport and storage processes are sensitive to multiple dynamic conditions, such as Q and groundwater upwelling and downwelling (Rana et al., 2017; Ward et al., 2013; Krause et al., 2014; Ward et al., 2018). Therefore, we adopted a before-after-control-impact (BACI) experimental design, which theoretically allows the isolation of the effect of an impact (in this case, the reintroduction of instream wood) from environmental variability in time (i.e., throughout the study period) and space (i.e., between sites), enabling useful insights to be drawn from relatively small sample sizes (Stewart-Oaten and Bence, 2001; Seger et al., 2021). Because such conditions are common in experiments of transport and storage processes and instream wood, BACIs are increasingly adopted, e.g., Díez et al. (2000), Matheson et al. (2017b), Ward et al. (2018), Lo et al. (2024), and Gates and Smiley (2024). The BACI experimental design also enabled an investigation into the influence of Q on the effects of instream wood on transport and storage processes, which is an important control (Rana et al., 2017; Ward et al., 2013; Ward et al., 2018.).

2.2 Study site

Wood Brook is a second-order stream (Strahler stream order) which flows through the Birmingham Institute of Forest Research (BIFoR) field site in Staffordshire, United Kingdom (lat 52.80268, long −2.29855) (Figure 1). It drains a catchment area of 3.1 km^2 which is dominated by Permo-Triassic red sandstone geology and the stream is mostly disconnected to the water table by an underlying layer of clay (Blaen et al., 2017). The catchment has an elevation ranging from 90 to 150 m asl, a mean annual temperature of 9°C, and a mean total annual precipitation of 690 mm (Norby et al., 2016; Blaen et al., 2017). The study reach is primarily covered by riparian woodland of deciduous trees, including hazel (*Corylus avellana*), alder (*Alnus glutinosa*) and oak (*Quercus petraea, Quercus robur*). The stream reach has been previously straightened and deepened and largely cleared of instream wood, although some wood has since accumulated (Figure 2).

2.3 Hydrological monitoring

Q was monitored 400 m downstream of the study reach throughout the 8-month experimental period using a stage-Q relation established by salt-dilution gauging and automated water level recording (Hudson and Fraser, 2005), described in detail in section 1 of the Supporting Information. Significant gains or losses along the 625 m flow length between the injection point (more details are provided in Section 2.6), and the Q monitoring point were unlikely due to an underlying clay layer and disconnected water table (Khamis et al., 2021). The average Q throughout the period was 0.0079 (m^3/s), with a maximum of 0.1040 (m^3/s) observed in July 2021 (Figure 1c). The baseflow index was 0.0616 (m^3/s), calculated using daily average Q in the *EflowStats* R package (Mills et al., 2017). The average Q for the tracer injections performed in this study was 0.0049 (m^3/s) before intervention and 0.0056 (m^3/s) after restoration. The Q at each injection date is reported in Supplementary Table S1.

2.4 Characterization of sub-reaches

Two sub-reaches representing control and impact treatments were identified (yellow and purple lines in Figure 1b) and comprehensively surveyed in 5 m sections for geomorphological and instream wood characteristics (Table 1). Channel width, depth, and gradient were measured during baseflow in March 2021, the latter using an automatic surveying level placed in the channel. Sinuosity was calculated by dividing the length of the stream channel by the Euclidian distance between the start and end of the sub-reach. Sediment samples of 500 mL were taken from the top 10 cm of the streambed every 10 m along the thalweg of the stream in April 2021. Samples from each sub-reach were mixed and grain size analysis was performed by mechanical sieving of sediment into five size fractions (>2 mm, 0.5–2 mm, 0.25–0.5 mm, 0.063–0.25 mm, <0.063 mm) and weighing each component before calculating relative weight contribution (%). A survey of instream wood was conducted for the purposes of comparing the sub reaches, which was aided by the creation of an index based on Harman et al. (2017). This survey served only to provide a baseline of the instream wood characteristics in each sub-reach, rather than to monitor changes to them that are likely to have occurred during the study period. Wood pieces (Table 1) were classified by mid-diameter: small (20–50 mm), medium (50–100 mm) and large (>100 mm) based on the prevalence of piece sizes in the channels (Wohl et al., 2010). Further details of the wood index method are provided in in Section 2 of the Supplementary Information. Most of the stream characteristics are similar between reaches, but minor differences (e.g., mean gradient) are not problematic because they are accounted for in the BACI experimental design (Seger et al., 2021).

2.5 Instream wood additions

In June 2021, eight channel-spanning features (Figure 1d) were installed in the impact reach with a spacing of ≥10 m, which is far enough to limit the influence of one feature on others (Hester et al., 2018; Li et al., 2022). Hazel coppice wood bundles with a length

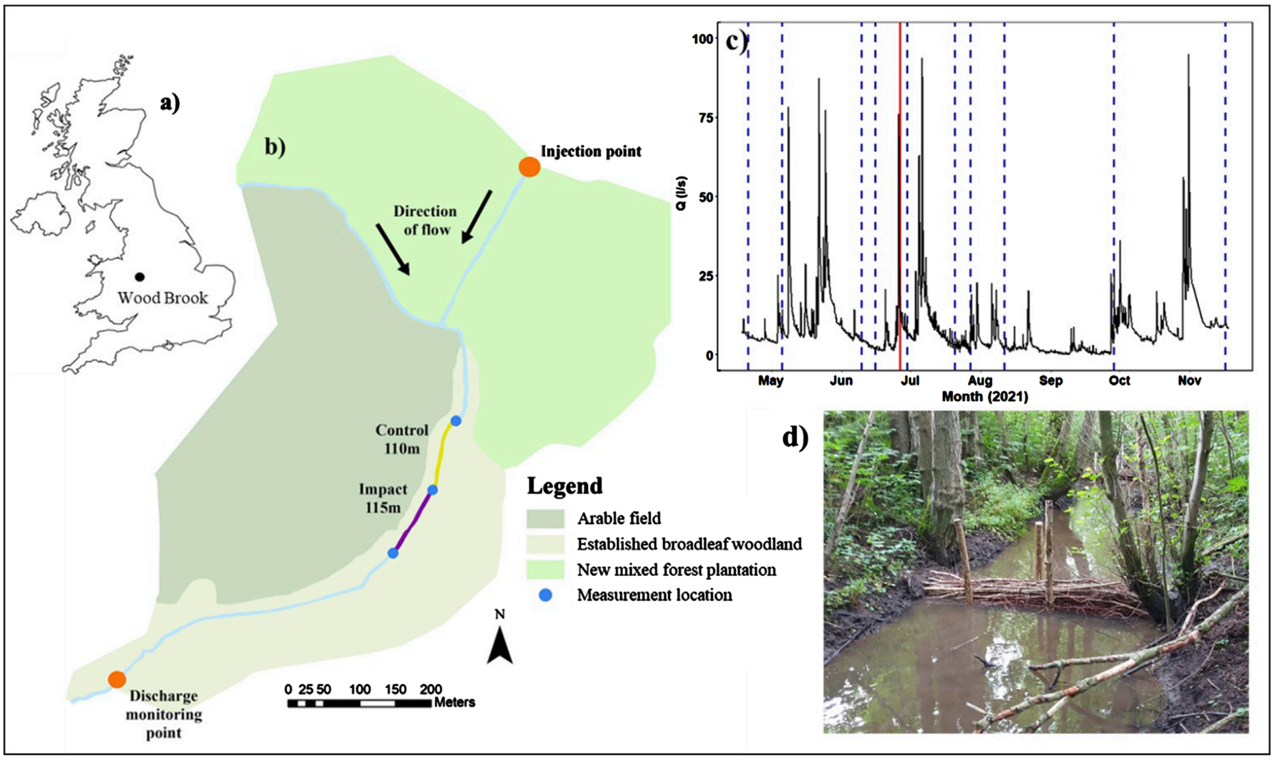

FIGURE 1
(a) The location of Wood Brook within the United Kingdom. **(b)** The dominant land use, study reach with control and impact sub-reaches, injection point, tracer measurement locations and Q monitoring point. **(c)** The Q (L/s) throughout the experimental period (April-November 2021) derived from the stage-Q relation presented in Supplementary Figure S1. Tracer injection periods are indicated by dashed blue lines. The solid red line indicates the date of restoration. **(d)** An example of a channel-spanning wood feature immediately after installation in June 2021.

similar to the stream width and a diameter of approximately 60 cm were pinned with 5 chestnut (*Aesculus hippocastanum*) stakes (2 upstream and 3 downstream), hammered into the streambed with a fence post driver, and finally secured with sisal rope. Details of the materials and costs are reported in Section 3 of the Supplementary Information. During baseflow conditions, the features protruded from the surface water (Figure 1d) but were submerged during even small events of Q higher than baseflow. Wood features were added to complement an existing wood loading which was similar in both reaches (Table 1; Figure 2). The installation of the wood features almost doubled the abundance of wood in the impact reach, increasing the wood index from 23.3 to 40.7 immediately after installation (Figure 2).

2.6 Solute tracer injections

A series (n = 10) of conservative tracer injections were conducted before (n = 4) and after (n = 6) restoration, between April and November 2021. Dissolved NaCl was injected almost instantaneously (in a slug injection) 250 m upstream of the study reach (injection point in Figure 1b) at a location that allowed full mixing of the tracer during all flow conditions, determined by Comer-Warner et al. (2021). The injection mass for NaCl ranged between 3–26 kg (tracer masses for each injection are reported in Supplementary Table S1). The injection mass was adjusted to account for changes in Q, and in some cases to allow for the detection of breakthrough curves (BTCs) in river sediments, although this data is not presented here. Electric conductivity (EC) was measured at 10 s intervals using automatic sensors (Levelogger 5 LTC, Solinst Canada Ltd.) at the start and end of each sub-reach (measurement locations in Figure 1b), which yielded a total of 30 BTCs (Jones and Mulholland, 2000).

2.7 Determination of breakthrough curves, data processing, and analysis

EC was corrected for background at injection time (t = 0) and BTCs were normalized for the maximum observed EC. To extend experimentally truncated BTCs and to calculate transport and storage metrics a continuous time random walk mobile-immobile model solute transport model was fitted to each EC BTC, using an adapted version of source code published by Drummond et al. (2019) which was run in MATLAB (version 2021a). In this model the mobile zone (i.e., flowing water in the channel) is described by instream velocity, v (m s^{-1}), and dispersion, D (m^2 s^{-1}). The rate of water exchange between the mobile zone and immobile zone (i.e., dead zones in the channel and subsurface storage) is described by λ (m^2), and the residence time therein is defined by the power law residence time distribution of solute within the immobile zone, set by the power law slope, β (Drummond et al.,

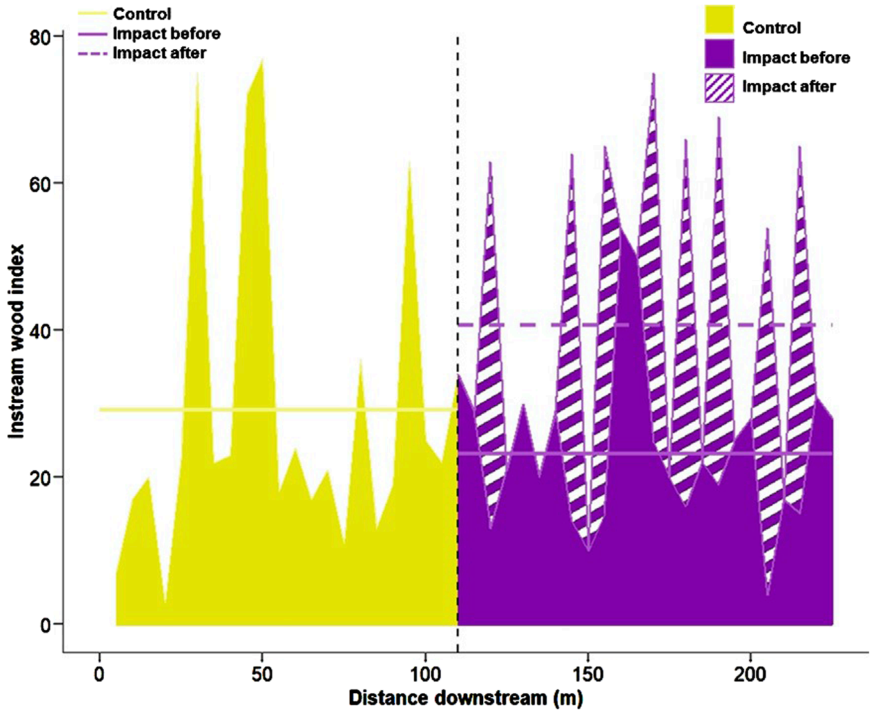

FIGURE 2
The distribution of instream wood along the study reach. The horizontal lines represent average wood index scores in the control (yellow) sub-reach, and in the impact (purple) before (solid) and after (dashed) restoration. The vertical black line represents the transition between sub-reaches.

2019). The parameter space was sampled using the Latin Hypercube approach (n = 27,000) using the balanced mean square error equation as the objective function. Parameter identifiability was tested by plotting model error vs. parameter values (i.e., dotty plots) (Supplementary Figure S2) (Bottacin-Busolin et al., 2011). Modelled BTCs were truncated using the method from Drummond et al. (2012). BTCs from the first measurement location (at the start of the control sub-reach) were modelled using the slug injection (t = 60 s) as the input boundary condition. Subsequent BTCs (i.e., those at the end of the control and impact sub-reaches) were modelled using the BTC of the location immediately upstream as the boundary input condition, after Blaen et al. (2018). The model output well fitted the tracer BTCs at every measurement location (Figure 3). The best fit parameters for each reach and injection are presented in Supplementary Table S2. Along with an analysis of the model parameters, time series analysis of BTCs following Ward et al. (2013) provided insight into transport and storage characteristics – the total suite of parameters is summarised in Table 2.

2.8 Statistical analysis

The aim of the statistical analysis was to characterise the effect of restoration on the transport and storage metrics described above by comparing period (before-after [BA]), reach (control-impact [CI]) and the interaction between both (period*reach), i.e., the BACI effects. Normality was tested with Shapiro-Wilk normality tests and QQ-plots. Normality in *CV* was achieved by $\log_{10}$ transformation. Only λ could not by transformed to a normal distribution. Two statistical approaches were employed to balance the potential risk of type one error (i.e., spurious rejection of a true null hypothesis) and type two error (i.e., failure to reject a false null hypothesis).

Residual maximum likelihood (REML) was used to ensure that statistical bias was not introduced by the unbalanced (non-orthogonal) monitoring periods before and after restoration (Robinson, 1987). The *lme4* R package was used to fit the REML model (Bates et al., 2015). The date of tracer injection was included as a random effect which accounts for repeated measures of the same reaches and for the unbalanced experimental design (Barr et al., 2013). Period, reach, and their interaction (period*reach) were included as fixed effects. Additionally, a two-way analysis of variance (ANOVA) was performed (with factors: period, reach, and period*reach), which is one of the most commonly applied approaches to analyse BACI experiments (Smokorowski and Randall, 2017). Tukey post-hoc tests (TPH) were applied to ANOVAs to allow pairwise comparison. To investigate the effect of *Q*, a two-way analysis of covariance (ANCOVA) (with factors: period, reach, and period*reach, and co-variate: *Q*) was performed. A level of significance (alpha) of 0.05 was used for all tests, but the effects of using different alphas (0.1 and 0.01) was investigated also (Supplementary Table S5). Before significance was assessed, *P* values of the REML, ANOVA and ANCOVA were corrected using the estimated marginal means method (*emmeans* R package) which can further account for the

TABLE 1 Physical, geomorphic and instream wood characteristics of the sub-reaches, measured in March and April 2021 before tracer injections.

Variable	Control	Impact
Channel geometry		
Mean width at BF (m)	2.13	2.18
Mean depth at BF (m)	0.23	0.23
Mean gradient (%)	0.44	0.15
Length (m)	110	115
Sinuosity	1.0185	1.0087
Grain size distribution (%)		
>2 mm	27.86	34.24
0.5–2 mm	11.99	9.05
0.25–0.5 mm	28.29	23.07
0.063–0.25 mm	21.72	22.73
<0.063 mm	10.14	10.91
Wood distribution		
Mean no. large accumulations/m	0.08	0.05
Mean no. medium accumulations/m	0.06	0.07
Mean no. small accumulations/m	0.07	0.08
Mean no. of individual pieces/m	2.17	2.29
Mean wood index score before restoration	29.2	23.3
Mean % visible organic matter cover	15.57	11.85
Mean no. trees <1 m from channel/m	1.08	0.77

BF, baseflow.

unbalanced experimental design (Lenth, 2022). We also performed Student's t-tests on sub-sets of the dataset (i.e. including only BA or CI data) to test the effect of using a full BACI approach compared to a simpler BA or CI (Supplementary Table S5). Kruskal Wallis (KW) was used instead of REML/ANOVA and Mann Whitney U instead of a Student's t-test for λ.

Trends in transport and storage metrics were also interpreted qualitatively using timeseries graphs (Figure 4), point graphs of mean metrics before and after restoration (Figure 5), and by performing linear regression analysis (with Q) to interpret the direction (i.e., positive, negative, or neutral) of, and changes to, these trends throughout the experimental period and under different Q conditions (Figure 6) (as in Ward et al., 2018). Regression equations and coefficients of determination are reported in Table 3. Only the results of the REML are reported in text except where extra information was provided by the ANOVA and TPH, for example in the pairwise comparison of the reach*period interaction. A comprehensive overview of model outputs is presented in Supplementary Table S3. All statistical analysis was performed in R version 4.1.0 (R Core Team, 2021).

3 Results

3.1 Effects of restoration on transport and storage processes

We found no statistically significant effect of the instream wood reintroduction for any of the transport and storage metrics when using the BACI approach (Supplementary Table S3). However, in seven out of nine metrics (M_1, M_1/t_{peak}, skewness, *CV*, holdback, *D*, and *v*), a statistically significant effect of restoration was observed when considering BA or CI effects in isolation, i.e., in the Student's t-tests. To avoid distraction from the main aim of this paper, we primarily report the statistical results of the BACI experiments and the qualitative analyses in the main manuscript, reporting the results BA and CI tests in the SI (text S5 and S6, Tables S5 and S6).

Qualitative analyses in the timeseries (Figure 4) and point (Figure 5) indicates a slight divergence in M_1 and M_1/t_{peak} between the control and impact reaches after the restoration. M_1 increased in the impact reach more than the control (Figure 4a), representing an increase in the average arrival time of the solute of 33% (from 5.18 h to 7.73 h) in the impact reach, whereas a change of only 5.4% was observed in the control reach (from 1.25 h to 1.32 h). The change in M_1 from before to after restoration was significant in the impact reach (TPH, $P < 0.05$) but not in the control reach (TPH, $P > 0.05$) (Supplementary Table S3.1). This trend was also evident in the estimates of *v*, which slowed by about half in the restored reach compared to before restoration. Similar patterns were observed for M_1/t_{peak} which overall increased by 17.4% in the impact reach and decreased by 11% in the control (Figure 5b), a divergence that seems to have occurred only after the addition of wood features (Figure 4b). However, substantial variability in M_1 and M_1/t_{peak} in the impact reach gives low confidence in the reliability of these trends. Nonmonotonic patterns (i.e., increasing and decreasing) were exhibited by the other metrics with no discernible trends, or similar patterns were observed in both the control and impact reaches, indicating no measurable effects of restoration on transport and storage processes.

3.2 Relations between restoration, discharge, and transport and storage processes

None of the metrics had a statistically significantly relation to Q (ANCOVA, $P > 0.05$) but the qualitative analysis (Table 3; Figure 5) may tentatively suggest effects of restoration on the interactions between Q and some transport and storage processes. Overall, linear regressions did not very well describe the relation between Q and most of the metrics we derived, especially in the period after restoration which represented a larger range of Q values, suggesting high uncertainty in these trends (see r^2 in Table 3).

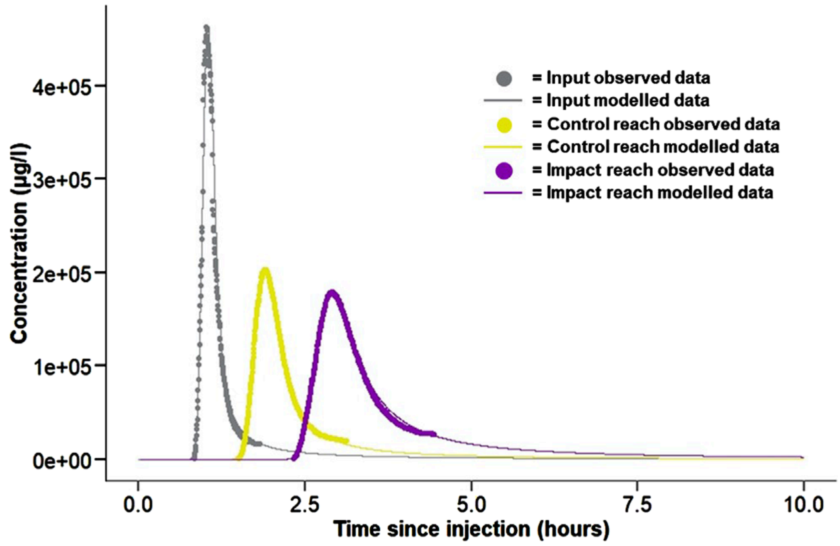

FIGURE 3
An example (from the tracer injection on 09-06-21 using an injection mass of 3 kg NaCl) of observed BTC data and the continuous time random walk mobile-immobile model fits at each of the measurement locations, that is at the start of the control reach (after complete mixing of the tracer), at the end of the control reach and start of the impact reach, and at the end of the impact reach. The modelled BTC time is further truncated in the plot.

TABLE 2 A summary of the metrics used to test transport and storage characteristics.

Metric	Abbrev.	Description	References
First normalized moment	M_1	Median advective time of the solute in the study reach	Drummond et al. (2012)
Transient storage proxy	M_1/t_{peak}	Ratio of advective time to that of preferential flow path. Higher M_1/t_{peak} = higher transient storage	Nikolakopoulou et al. (2018)
Skewness	Skewness	Describes the asymmetry of the BTC and indicates tailing behaviour relative to rising limb of the BTC. High skewness indicates high influence of transient storage	Nikolakopoulou et al. (2018)
Coefficient of variation	*CV*	Normalized measure of temporal variance to allow comparison across different advective times	Nikolakopoulou et al. (2018)
Holdback	Holdback	describes the delay in the transport of solutes moving through the system (i.e. deviation from plug flow), where values closer to 1 indicate more holdback	Danckwerts (1953)
Velocity*	v	Rate of solute transport from upstream to downstream	Drummond et al. (2019)
Dispersion*	D	Spreading of solutes from areas of high to low concentration	Drummond et al. (2019)
Rate of exchange*	λ	Rate of water exchange between the mobile zone and immobile zone	Drummond et al. (2019)
Immobile zone residence time*	β	Power law residence time distribution of solute within the immobile zone	Drummond et al. (2019)

Model parameters are indicated with *.

For M_1, λ, and β the relation with Q seemed to change in the impact reach following restoration, but not in the control reach (Figures 6a,h,i). A negative relation between M_1 and Q was observed in both reaches (Table 3), which was reversed only in the impact reach following restoration (Figure 6a). This reversal was primarily driven by two observations at 0.00659 m^3/s and 0.00985 m^3/s (see Supplementary Table S1), but the other high Q observation (0.00714 m^3/s) that occurred in the week immediately following restoration did not elicit the same response. A positive relation between Q and β was observed in both reaches before restoration (weak linear regression: control $r^2 = 0.135$, n = 4; impact $r^2 = 0.221$, n = 6) which reversed only in the impact reach after restoration (Figure 6i; Table 3). Similar patterns were also observed Q and λ (Figure 6h). After restoration, the relation between Q and D showed a marked change in the intercept of the regression only in the impact reach (Figure 6g; table 3), whereas the direction of the relation (gradient) switched in the control reach (weak linear regression: control $r^2 = 0.0032$, n = 4; impact $r^2 = 0.0049$, n = 6).

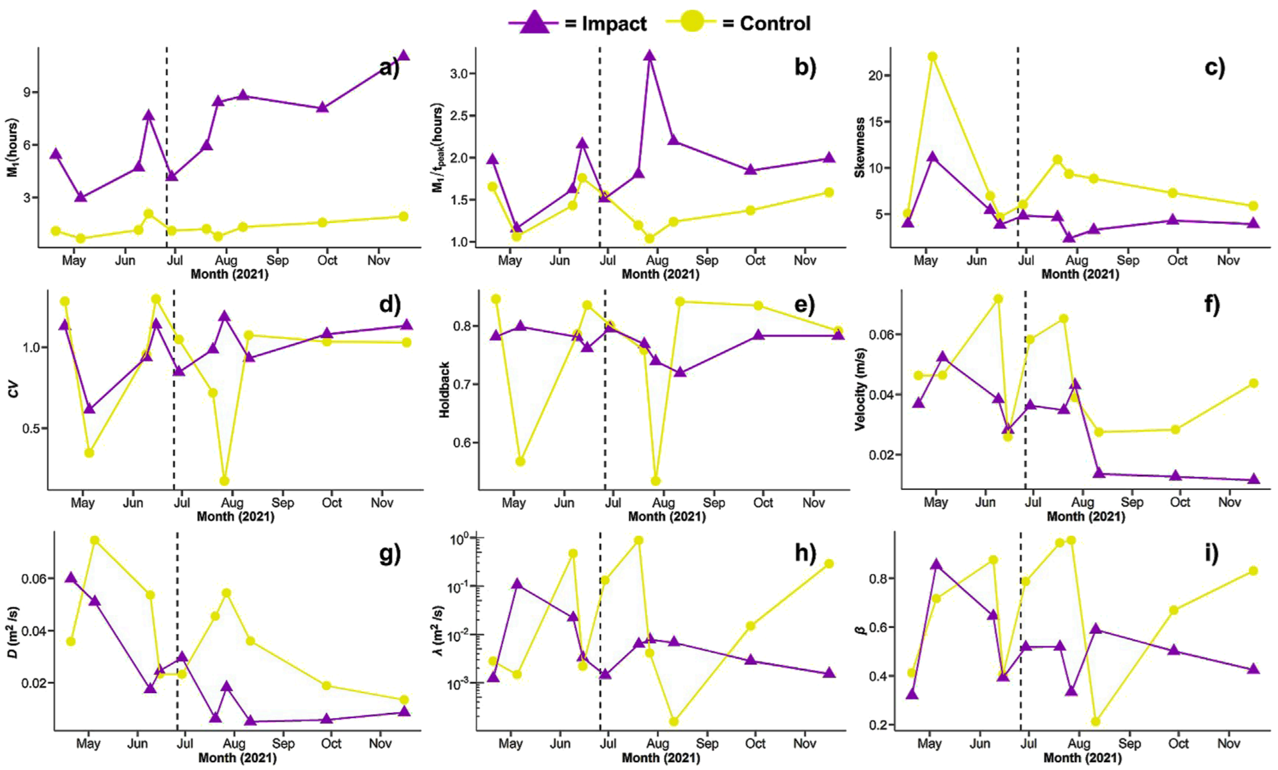

FIGURE 4
Timeseries of model parameters and derived metrics at each tracer injection. The vertical dashed line represents the date of restoration in the impact reach. **(a)** Median advective time (M_1), **(b)** ratio of advective time to that of preferential flow path (M_1/t_{peak}), **(c)** asymmetry of the BTC (skewness), **(d)** coefficient of variation (*CV*), **(e)** holdback, **(f)** velocity (*v*), **(g)** dispersion *(D)*, **(h)** the rate of exchange of solutes with the mobile zone and immobile zone (λ), and **(i)** residence time in immobile zones (β).

M_1/t_{peak} was negatively related to *Q* before restoration but switched to a positive relation after restoration (Figure 6b). This change was primarily driven by the value observed during the highest *Q* event of the experimental period (0.00985 m^3/s on 16/11/2021) (Supplementary Table S1).

Some transport and storage metrics were different between the control and impact reaches throughout the whole experimental period but did not change in response to restoration. For example, holdback and *Q* exhibited a negative relation in the control reach but a positive relation in the impact reach, with no discernible effect of restoration (Figure 6e). This difference was driven by two low values in the control reach recorded at a similar *Q* (0.00657 and 0.00659 m^3/s) but at different periods in the experiment (05/05/2021 and 27/07/2021) (Supplementary Table S1). These especially low values were also observed in *CV* but there they did not change the overall nature of the relation (Figure 6d). For some of the transport and storage metrics the relation with *Q* was consistent for most of the experimental period but exhibited anomalies at an extremity of the *Q* conditions observed. For example, *v* increased with *Q* in both reaches throughout the experimental period, although the relation was poorly described by a linear regression (Table 3). However, in the impact reach during the highest *Q* (0.00985 m^3/s) this response was not elicited; instead the lowest *v* (0.012 m/s) of the whole experimental period was observed. This outlier to the relation was not as strongly exhibited in the control reach.

4 Discussion

We found qualitative evidence for the effects of instream wood reintroduction on transport and storage processes in a lowland sandy stream in the United Kingdom. However, in line with other field-based studies of instream wood reintroduction in lowland systems (e.g., Matheson et al., 2017a), we found no statistically significant effects of the BACI experiment. Following similar studies (e.g., Ward et al., 2018), we interpret our results to suggest that such effects are likely to exist, but the magnitude and sensitivity of these effects to environmental conditions (e.g., *Q*) remain uncertain. Additionally, our results highlight the complexity of confounding factors in field experiments and the risks of adopting simplified experiments (i.e., BA or CI) and modelling simulations.

4.1 The effects of restoration on transport and storage processes

Our results indicate the effects of restoration include a decrease in reach scale *v*, an increase in hydraulic retention time, and an increase in transient storage and the residence time therein. Velocity (*v*) reduced by approximately one-quarter and accordingly the hydraulic retention time (M_1) increased

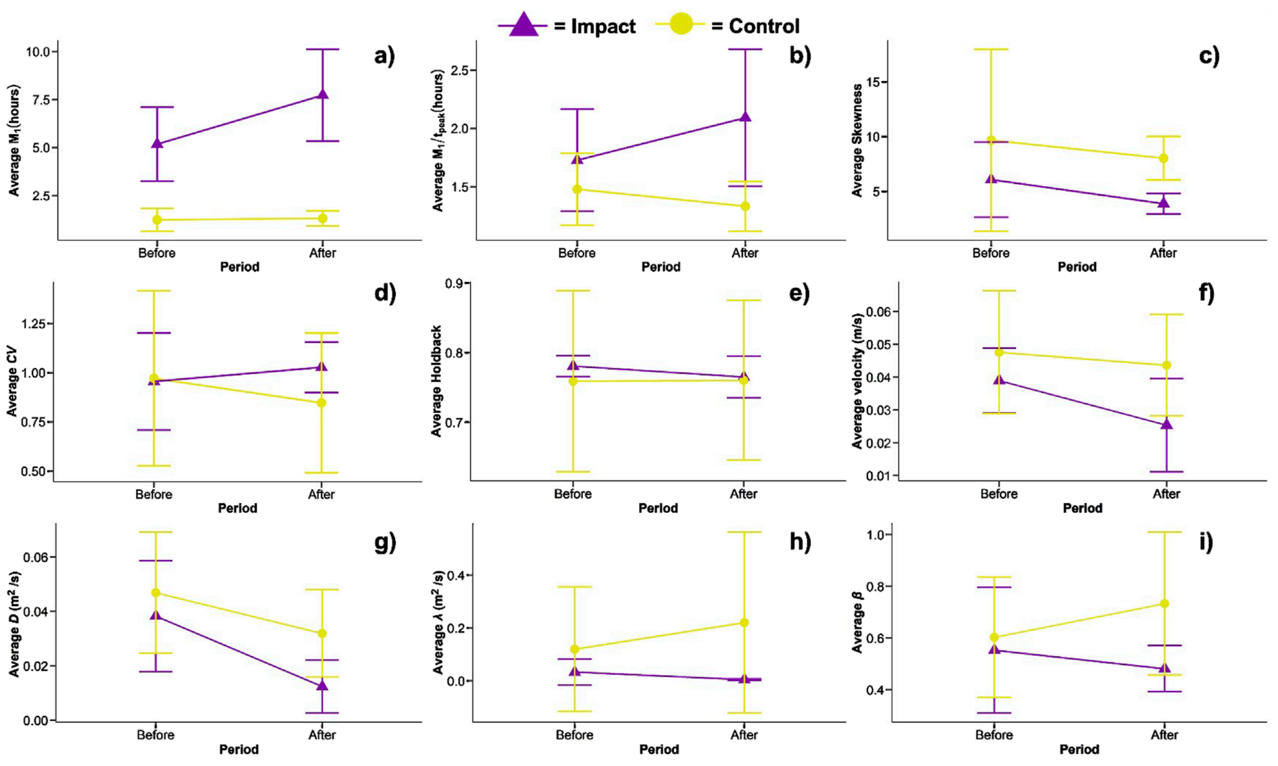

FIGURE 5
Average model parameters and derived metrics plotted separately for the impact (purple) and control (yellow) reaches for the before and after periods. **(a)** Median advective time (M_1), **(b)** ratio of advective time to that of preferential flow path (M_1/t_{peak}), **(c)** asymmetry of the BTC (skewness), **(d)** coefficient of variation (CV), **(e)** holdback, **(f)** velocity (v), **(g)** dispersion **(d)**, **(h)** the rate of exchange of solutes with the mobile zone and immobile zone (λ), and **(i)** residence time in immobile zones (β).

by approximately one-quarter. We found an average increase in the transient storage proxy (M_1/t_{peak}) of 28.4% in the impact reach as compared to the same period in the control reach. A slight lengthening of the residence time in immobile zones (i.e., a decrease in *β)*, a minor decrease in the rate of exchange between the mobile and immobile zones (λ), and a minor relative increase in temporal variance (*CV*) might also suggest a trend towards slower water velocities and/or longer flow paths, which could also point to increased transient storage (Dentz and Bolster, 2010; Nikolakopoulou et al., 2018; Ward et al., 2018; Drummond et al., 2019).

Similar results were observed by Rana et al. (2017), who explained them by an increase in the cross-sectional area of transient storage, for example by the impounding of water upstream of instream wood. In upland systems, the impounding of water can generate a hydraulic head gradient and hydrodynamic forcing, both of which can induce hyporheic exchange (Li et al., 2022; Briggs et al., 2012; Klaar et al., 2016; Schalko and Weitbrecht, 2022). Hyporheic exchange is particularly important for ecosystem function because it generates a matrix of physiochemical conditions that facilitate a range of biogeochemical reactions and ecological interactions (Boano et al., 2014; Lewandowski et al., 2019; Krause et al., 2022). Such hyporheic inducing effects could be especially beneficial in lowland sandy streams, where hyporheic exchange represents only 0.1%–0.49% of transient storage; however, these mechanisms are likely to be less prevalent here, e.g., due to low gradients and low energy (Stofleth et al., 2007; Krause et al., 2014). Although our analysis did not explicitly enable the separation of surface and subsurface transient storage (i.e., hyporheic exchange), the latter is often associated with lower dispersion (*D*) (Ward et al., 2013; Nikolakopoulou et al., 2018). We found no change in dispersion (*D*) after wood reintroductions, potentially indicating that of the additional transient storage generated, very little was in the subsurface. This could be associated with a clay layer underlying the streambed, although it is probably at sufficient depth (approximately 0.3–0.8 m) to still allow shallow subsurface storage (Khamis et al., 2021). Furthermore, other authors have associated complexities in transport and storage processes like those observed here primarily with surface backwaters rather than subsurface exchange (Marshall et al., 2023). Overall, our results suggest an increase in the volumetric area of transient storage and an increase in the retention time of water and solutes in transient storage zones, most of which probably exists in surface storage zones like backwaters and eddies.

In general, these trends are in line with other studies on the effects of existing instream wood in lowland systems (Stofleth et al., 2007; Klaar et al., 2016; Klaar et al., 2020), but in contrast to studies that have explicitly tested the effects of instream wood reintroduction in such contexts (Herzog et al., 2019; Marshall et al., 2023). The overall trends found here (e.g., lack of statistical significance and limited subsurface storage) are in contradiction to a flume-based study that attempted to simulate similar experimental conditions to our field study and found that wood increased the water flux across the streambed (i.e., between surface and subsurface

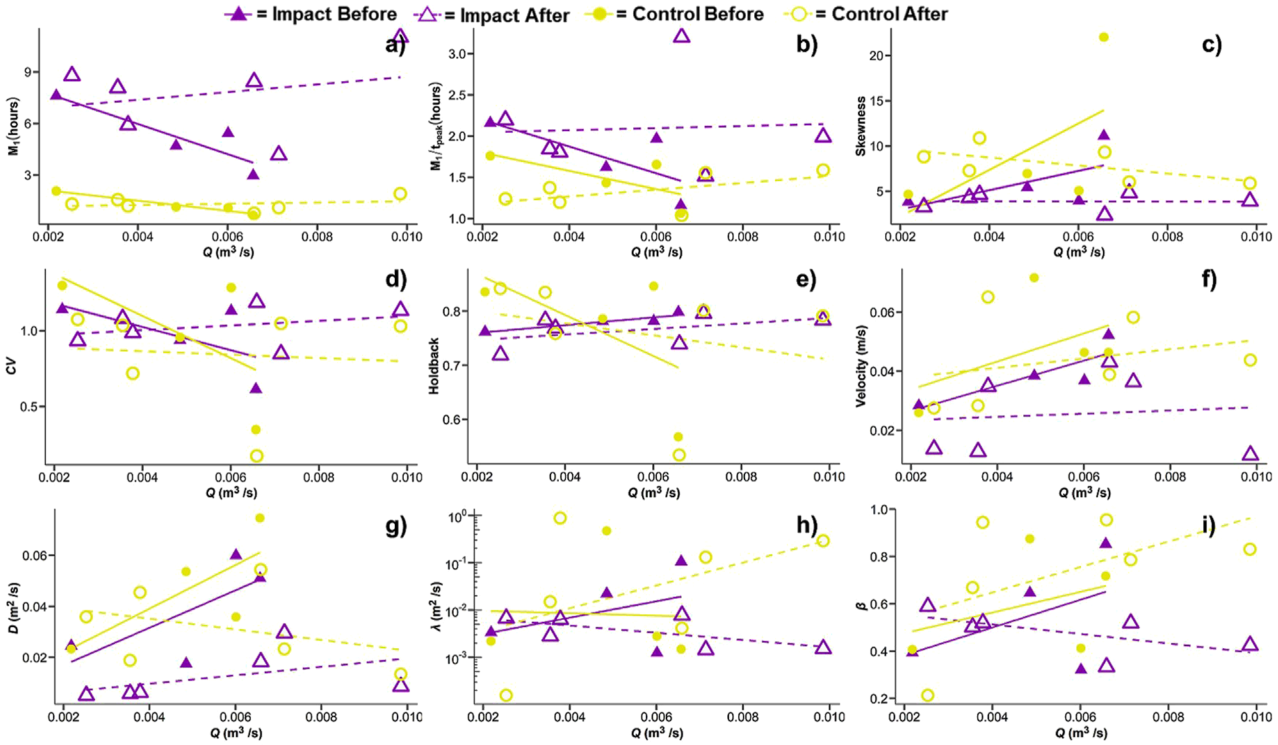

FIGURE 6
Model parameters and derived metrics regressed against discharge (Q) separately for before and after restoration and impact and control reaches. **(a)** Median advective time (M_1), **(b)** ratio of advective time to that of preferential flow path (M_1/t_{peak}), **(c)** asymmetry of the BTC (skewness), **(d)** coefficient of variation (CV), **(e)** holdback, **(f)** velocity (v), **(g)** dispersion **(d)**, **(h)** the rate of exchange of solutes with the mobile zone and immobile zone (λ), and **(i)** residence time in immobile zones (β).

storage) by a factor of 1.8–2.5, as well as the vertical mixing depth (Mutz et al., 2007). This might be explained by the neglect of variable groundwater conditions in the flume study (Krause et al., 2014), highlighting the challenges in simulating complex fluvial systems. Ideally, we would also compare the trends we observed to those found in upland studies (e.g., Hester et al., 2009; Sawyer and Cardenas, 2012; Rana et al., 2017) but this is made challenging by the lack of common reporting (e.g., most do not report a percentage change in transient storage before and after restoration).

4.2 The effects of discharge on the interaction between instream wood and transport and storage processes

We found only qualitative evidence for effects of Q on the relations between instream wood restoration and transport and storage processes in a lowland sandy stream. Nonetheless, this evidence may suggest that the reintroduction of instream wood changed the relation between Q with metrics relating to the properties of transient storage. In the control reach throughout and in the impact reach before restoration, the rate of exchange (λ) increased with Q and the residence time in transient storage decreased (i.e., increase in β) with Q (Figures 6h,i). In the restored reach, these relations were reversed so that the exchange rate (λ) mildly decreased with Q and the residence time in transient storage mildly increased (i.e., decrease in β) with Q, supported by a good fit of the linear regression, although in the control reach the relation with Q appears to be more complex. Together, these relations show that in both reaches the rate of exchange between storage and mobile zones changes proportionally to the residence time in storage zones (e.g., a lower exchange rate is associated with a longer residence time). This is likely indicative of a limited effect of dynamic Q on the area of transient storage, also demonstrated by the neutral relation between Q and the transient storage proxy (M_1/t_{peak}) in both reaches (Nikolakopoulou et al., 2018). It could also be associated with an increase in the proportion of transient storage which occurs in the surface (compared to the subsurface) during higher Q conditions in the restored reach (Gooseff et al., 2005). This is tentatively indicated by the positive relation between Q and dispersion (D) in the restored reach compared to the control (Ward et al., 2013; Nikolakopoulou et al., 2018). Drummond et al. (2020) observed a similar phenomenon and Wang and Cirpka (2021) demonstrated that these dynamics are controlled by Q. This would also explain the contradiction of our results to those of Rana et al. (2017), who found a positive relation between Q and transient storage zone area (somewhat comparable to M_1/t_{peak}) in an upland setting and attributed this to subsurface storage.

For most other transport and storage metrics, the effects of Q seemed to be consistent, or not to change in discernible patterns, between reaches and despite restoration. Indeed, the

TABLE 3 Details of linear regression equations and coefficient of determination (r^2) between model parameters and derived metrics and discharge.

Metric	Period*Reach	Gradient	Intercept	r^2
M_1	Control Before	−297	2.7	0.951
	Impact Before	−877	9.5	0.791
	Control After	36	1.1	0.0651
	Impact After	224	6.5	0.0673
M_1/t_{peak}	Control Before	−110	2	0.489
	Impact Before	−162	2.5	0.519
	Control After	41	1.1	0.286
	Impact After	13	2	0.00353
Skewness	Control Before	2,566	−2.9	0.364
	Impact Before	1,067	0.86	0.369
	Control After	−443	11	0.383
	Impact After	−8.7	3.9	0.000663
CV	Control Before	−139	1.7	0.369
	Impact Before	−77	1.3	0.37
	Control After	−11	0.91	0.00767
	Impact After	15	0.94	0.108
Holdback	Control Before	−38	0.94	0.322
	Impact Before	7.1	0.75	0.876
	Control After	−11	0.82	0.0726
	Impact After	5.1	0.74	0.228
v	Control Before	4.8	0.024	0.245
	Impact Before	4.3	0.018	0.708
	Control After	1.6	0.035	0.0794
	Impact After	0.54	0.022	0.011
D	Control Before	8.5	0.0049	0.561
	Impact Before	7.3	0.0024	0.491
	Control After	−2.1	0.043	0.128
	Impact After	1.6	0.0032	0.219
λ	Control Before	−2.2	0.13	0.000336
	Impact Before	15	−0.039	0.336
	Control After	−4.2	0.24	0.00115
	Impact After	−0.55	0.0075	0.284

(Continued on the following page)

TABLE 3 (*Continued*) Details of linear regression equations and coefficient of determination (r^2) between model parameters and derived metrics and discharge.

Metric	Period*Reach	Gradient	Intercept	r^2
β	Control Before	44	0.39	0.135
	Impact Before	59	0.27	0.221
	Control After	54	0.43	0.291
	Impact After	−20	0.59	0.392

M_1, Median advective time; M_1/t_{peak}, ratio of advective time to that of preferential flow path; *CV*, coefficient of variation; *v*, velocity; *D*, dispersion; λ, the rate of exchange of solutes with the mobile zone and immobile zone; Β, residence time in immobile zones.

weakness of the fit to a linear regression for most metrics suggests that the relation between *Q* and transport and storage processes is complex (i.e., not linear), which is expected in lowland (low gradient) streams (Ward et al., 2018). This suggests that the reintroduction of instream wood did not induce substantial changes to the effects of *Q* on transport and storage processes. However, we find some qualitative evidence for potential threshold effects of *Q*. For some derived metrics (M_1, M_1/t_{peak}, and *v*), strong relations with *Q* were observed only at the highest *Q* condition. For example, M_1 increased dramatically at the highest *Q* condition compared to at lower *Q* conditions, accompanied by a corresponding decrease in *v*. Such threshold effects of *Q* on restoration impacts have also been observed by other authors (e.g., Rana et al., 2017). For example, Ward et al. (2018) found that the effects of restoration on transport and storage were not measurable during the lowest *Q* conditions.

We also found some evidence that may suggest a potential lag time or evolution in the effects of wood reintroduction on transport and storage processes. For example, in the three injections immediately after restoration, *v* and the relation to *Q* remained largely unchanged (Figures 5f, 6f). However, approximately 6 weeks after restoration (i.e., injections from 11/08/2021), a marked decrease in *v* was observed, and the relation between *v* and *Q* was different. Similar patterns were observed for M_1. Two high *Q* conditions ($0.00659\ m^3/s$ and $0.00985\ m^3/s$) resulted in higher M_1 than expected given the relation between M_1 and *Q* before restoration. However, the high *Q* observation that occurred in the week following restoration ($0.00714\ m^3/s$) did not elicit the same response. We interpret this as an initial failure of the high porosity features to impound water upstream, which increased as sediment and organic matter was captured at the wood structures (Marshall et al., 2023; Lo et al., 2024). Rana et al. (2017) found a similar evolving response to restoration, although they also changed the number of restoration features during the experimental period. The effect of wood on transport and storage processes may change over time because of changing background conditions (e.g., groundwater table) and development of features (e.g., a reduction in effective porosity by colmation) and local geomorphological setting (Kasahara and Hill, 2008; Wondzell et al., 2009). Some studies have suggested that the evolution of the geomorphological setting can have a more significant effect on transient storage than restoration itself and can take >10 years to equilibrate (Fanelli and Lautz, 2008), although others disagree (Ader et al., 2021).

Our analysis points to the potential sensitivity of the effects of wood reintroduction on transport and storage processes to dynamic *Q*. However, experimental challenges in evidencing such effects reduce confidence in the magnitude of these trends, and their reliability during a large range of environmental conditions. For example, the highest *Q* captured (0.00985 m^3/s) was <10% of the maximum *Q* observed during the whole experimental period, meaning the relations between *Q* and transport and storage metrics that we report are only representative for the lowest 10% of flow conditions. The lowest *Q* conditions may exhibit the most pronounced relations with transport and storage (Rana et al., 2017) and the periods of highest hyporheic exchange (Azinheira et al., 2014), but overall capturing a small range of conditions limits our ability to quantify the relations between *Q* and the effects of instream wood on transport and storage processes. Furthermore, the duration and timing of the experimental period and the unbalanced design resulted in the capture of different *Q* before and after restoration, making it difficult to directly compare the response to *Q* events. This is a fundamental challenge in undertaking research on *Q* and transport and storage processes (Rana et al., 2017). Despite these limitations, interpretation of trends observed during the lowest 10% of *Q* conditions may point to interesting behaviours that could inform hypotheses for future testing.

4.3 Comment on the before-after-control-impact experimental design

Using BA and CI experimental designs led to statistically significant effects for most metrics (7 out of 9), in contrast to the full BACI design which led to none. We interpret this to demonstrate the superior statistical rigor of the BACI experiment, as has been noted by others, but also its sensitivity to experimental design (Smokorowski and Randall, 2017; Damgaard, 2019). For example, small effective sample size (and degrees of freedom) (n = 10), unbalanced groups (n = 4 before, n = 6 after), and the short duration of the experimental period (<1 year), whilst common limitations, reduced statistical power and the likelihood of detecting a real effect in this experiment (Christie, et al., 2020). A qualitative assessment of trends was able to reveal useful information which contextualised in the range of existing knowledge provides arguably more scientifically and practically meaningful results than statistically significant results of obviously flawed BA or CI experiments (Pogrow, 2019; Wasserstein et al., 2019; Ziliak, 2019). However, confidence in these trends remains low, and therefore implications must be applied with caution. Rather than offering predictive capability, our results may guide others in formulating hypotheses to quantitatively evidence the effects of instream wood reintroduction on transport and storage processes in lowland streams, and to make predictions about the impacts of instream wood reintroduction in lowland streams.

5 Conclusion

This study investigated the effects of instream wood reintroduction on transport and storage processes in a lowland sandy stream, representing the first evaluation of this common restoration technique in the predominant setting in which it is applied. Overall, substantial effects were not observed with high confidence. This corroborates previous studies that have struggled to evidence substantive restorative effects of instream wood reintroduction on hydrogeomorphological processes in lowland sandy streams (Matheson et al., 2017a; Herzog et al., 2019; Marshall et al., 2023). Whilst this evidence may prompt caution in the widespread application of this practice in these contexts, it should be considered alongside the abundance of evidence that supports the restorative effects of instream wood reintroduction for other management objectives (e.g., biodiversity, amenity, and flood management), for which it can provide an effective nature-based solution. Furthermore, our results indicate likely effects that should be further investigated, such as increases to the hydraulic residence time, transient storage, and the residence time therein, which overall could prove restorative. Future research should seek to test the effects of instream wood reintroduction over a longer period and during a higher range of *Q* conditions, ideally using multiple BACI experiments.

As other authors have noted, it is likely that the effects of restoration on transport and storage are governed primarily by the environmental setting. Given the sensitivity of transport and storage processes and the complexity of fluvial systems, it may be challenging to predict the effects of restoration based on a small set of conditions or generalizations such as lowland or upland. Therefore, scientifically rigorous predictions and evaluations of the effects of river restoration are necessary on a case-by-case basis.

Data availability statement

Datasets (measured and modelled) for this research are available in the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) data repository, Hydroshare (Howard and Krause, 2023). Software used in this research is published in Drummond et al. (2019) and is available to those with a MATLAB (2022) license.

Author contributions

BCH: Conceptualization, Data curation, Formal analysis, Investigation, Software, Methodology, Visualization, Writing – original draft, Writing – review and editing. IB: Supervision, Resources, Conceptualization, Writing – review and editing. WB: Writing – review and editing. JD: Software, Formal analysis, Writing – review and editing. NK: Supervision, Resources, Conceptualization, Methodology, Writing – review and editing. SU: Supervision, Resources, Conceptualization, Methodology, Writing – review and editing. SK: Supervision, Resources, Conceptualization, Methodology, Writing – review and editing.

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Conflict of interest

Author IB was employed by Catalys Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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This article has been corrected with minor changes. These changes do not impact the scientific content of the article.

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The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2025.1593726/full#supplementary-material

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