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SPECIAL ISSUE PAPER

The complexities of measuring fine sediment accumulation within gravel-bed rivers

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Abstract
Fine sediment storage within gravel beds is a key component of catchment sediment budgets and affects the health of benthic and hyporheic habitats. Here, we assess the performance of two substrate infiltration traps for the characterization of fine sediment (<2 mm) accumulation. One design, the vertically extending sediment trap, permits both lateral and vertical exchange in the sediment column, whereas the second type, a more traditional fixed-area sediment trap with impermeable side walls, permits only vertical exchange. Traps were deployed at three sites on the River Tame, Birmingham (UK), over varying installation periods (14–401 days). Results indicate that the facilitation of multiple pathways of exchange within the vertically extending sediment traps (vertical and lateral) resulted in a significantly greater amount of fine sediment being accumulated than in adjacent fixed-area sediment traps. This suggests that lateral transport is an important component contributing to fine sediment accumulation. However, there are notable and inherent problems associated with the use of different types of sediment trap and in the way the data should be presented and interpreted. This paper discusses the practical implications of the study findings and reflects on the complexities of undertaking accurate sediment deposition measurements in the field.

KEYWORDS
fine sediment, gravel bed rivers, hydrological exchange, sediment trap design, sedimentation, vertical and lateral transport

1 | INTRODUCTION

The transport and storage of fine sediment in riverine substrates is a major component of catchment fine sediment budgets (Foster, 2001; Naden et al., 2016; Phillips & Walling, 1999) and is a natural facet of riverine functioning. However, anthropogenic modifications such as the intensification of agriculture, urbanization, and channel management practices (Wood, Armitage, Hill, Mathers, & Millett, 2016) have altered the quantity and composition of instream fine material (Foster et al., 2011; Walling & Collins, 2016). Gravel-bed substrates have the potential to act as both a sink and source of fine sediments and their associated contaminants, including sediment-associated heavy metals, pesticides, nutrients, and other potential pollutants that can cause deleterious effects for ecosystem functioning (Petts, Thoms, Brittan, & Atkin, 1989; Roig et al., 2014; Von Bertrab, Krein, Stendera, Thielen, & Hering, 2013).

Excessive quantities of fine sediment stored within river networks is an important driver of aquatic habitat degradation (Descloux, Datry, & Marmonier, 2013; Packman & MacKay, 2003; Phillips & Walling, 1999), which poses a serious long-term threat to in-stream ecosystems (Négrel et al., 2014; Prosser et al., 2001). Fine-grained sediment affects the entire aquatic ecosystem from reducing primary production (Jones, Duerdoth, Collins, Naden, & Sear, 2014; Wagenhoff, Lange, Townsend, & Matthaei, 2013) and altering macroinvertebrate diversity via enhanced drift and direct burial (Larsen & Ormerod, 2010; Wood, Toone, Greenwood, & Armitage, 2005), through to reducing habitat heterogeneity and limiting oxygen exchange within interstitial pore spaces (Huston & Fox, 2015; Owens et al., 2005). Understanding fine sediment deposition storage and the rates of accumulation are, therefore, important factors when considering land use management approaches.

Gravel riverbeds act as a temporary compartment for the deposition of suspended fine sediment (Owens et al., 2005; Owens, Walling, & Leeks, 1999; Walling, Owens, & Leeks, 1998), either for short-term storage on the surface substrates (Rosenberry & Healy, 2012; Warburton, 1992) or longer-term storage within the bed matrix (Heppell, Wharton, Cotton, Bass, & Roberts, 2009; Thoms, 1994). Sediment deposition is influenced by sediment supply and character (Petts, 1988), bed permeability (Hoyal, Bursik, Atkinson, & Depinto, 1997), local hydraulics (Buffington & Montgomery, 1999), vertical and lateral interstitial hydrological exchange (Boano, Revelli, & Ridolfi, 2007), and filtration of particles within the gravel matrix (Frings, Kleinhans, & Vollmer, 2008; Packman & Brooks, 1995). High-flow conditions, when critical shear stresses are exceeded, or localized areas of strong upwelling water can lead to the subsequent remobilization of fine sediments (Datry, Lamouroux, Thivin, Descloux, & Baudoin, 2015; Shields, 1936).

Despite significant advancements in our understanding of sediment dynamic processes at fine resolutions (temporally and spatially) via flume experiments (e.g., Huston & Fox, 2015; Vericat, Batalla, & Gibbins, 2008), field studies of in situ channel bed sediment dynamics remain limited and those which incorporate varying timeframes are even rarer. Disturbance/resuspension methodologies (Duerdoth et al., 2015; Lambert & Walling, 1988) can be used to assess channel storage of fine sediment at a specific time and place. This technique is useful and has been widely adopted in studies of sediment dynamics but provides little information about the depositional route or timing of the fine sediment. Freeze coring (Evans & Wilcox, 2014; Walkotten, 1973, 1976) has also been used to determine between-site differences in sedimentation processes with reference to both flow regulation (Petts, 1988) and urbanization (Thoms, 1987a). However, although intensive freeze-core surveys can effectively detect spatial changes in fine sediment storage within riverbeds (Petts et al., 1989), bed fabrics can be disrupted during probe driving (Kondolf, Lisle, & Wolman, 2003) and the destructive nature of the technique tends to limit the approach to annual surveys.

The most common method for monitoring fine sediment deposition rates over a known time interval is bed traps (Carling, 1984; Curran, Waters, & Cannatelli, 2015; Reiser, Ramey, & Lambert, 1985). A large variety of trap designs have been employed, but the accuracy of the calculated fluxes for the different bed trap designs remains poorly understood (Petticrew, Krein, & Walling, 2007). Deposition rates are likely to be strongly influenced by the trap efficiency (Carling, 1984; Sear, 1993), the grain size of particles in transport (Gibson, Abraham, Heath, & Schoellhamer, 2009), the relative dominance of intragravel (lateral) versus gravity (vertical hyporheic exchange) transport processes (Kondolf et al., 2003; Mathers & Wood, 2016), and the flow velocity during the sampling period (Eadie, 1997; Naden et al., 2016).

There are two main types of bed trap, the first of which are empty pit traps consisting of lidless, solid-walled containers set in, or upon, the channel bed (Kondolf et al., 2003; Tipping, Woof, & Clarke, 1993). Pit traps are effective for collecting fine sediment derived from the gravitational sedimentation of suspended sediment onto the surface of the channel bed as well as coarser material transported as bedload and provide useful information at event timescales. However, the artificial conditions they represent (i.e., no trapping of within-bed or intragravel transport) present a challenge for investigations into fine sediment storage and dynamics.

The second type of bed sediment trap is the substrate trap, which comprises a container that is filled with prescreened gravel (removing all material <2 mm; Tipping et al., 1993) and which seeks to represent the natural substratum framework as much as possible. Many studies have typically employed solid-walled containers, which permit vertical transport of fine sediment but limit the lateral intragravel transport of fine sediment, thereby potentially leading to the underestimation of ingress rates (Carling, 1984; Mathers & Wood, 2016; Petticrew et al., 2007). In addition, the exclusion of lateral flushing flows may lead to the pore spaces in the upper layers of the framework becoming clogged, which can create a seal and prevent subsequent infiltration of sediment into the trap gravel (Frostick, Lucas, & Reid, 1984). A number of recent studies have incorporated semipermeable walls (e.g., Mathers & Wood, 2016), which are typically utilized in ecological studies and facilitate simultaneous collection of sedimentological and ecological samples; however, these designs are not fully permeable, and thus, the full extent of intragravel and vertical exchange processes in field settings remains limited. Traditional solid-walled or semipermeable designs are also subject to scour events, which may expose the container above the surface of the riverbed, potentially affecting trapping rates associated with turbulent flow alterations (Lisle & Eads, 1991).

Infiltration baskets consisting of a wire mesh basket dug into the riverbed and filled with prescreened gravels allow for the lateral infiltration of fine sediment (Milan & Large, 2014; Sear, 1993; Thoms, 1987b). As with the solid-walled containers, infiltration baskets are vulnerable to removal by scour during flood events (Sear, 1993) and the presence of the wire mesh may affect the particle size distribution of sediment ingress. Infiltration baskets are also likely to be susceptible to infiltrated sediment and water being lost upon retrieval. A modified version of this trap consists of an impermeable bag that is buried within the gravel substrate and pulled up via cables, thereby including all deposited sediment in the trap area (Lisle & Eads, 1991).

To explore the complex nature of fine bed sediment storage and infiltration, we employed two sediment trap designs: one, which permits vertical deposition only, and one with permeable sides, which allows both vertical deposition and lateral movement. This paper (a) describes the two trap designs; (b) compares the results of the two sampling methods over a range of installation periods (14–401 days); and (c) reflects on the relative importance of lateral and vertical movement of fine sediment in gravel substratum and the complexities of undertaking accurate measurements in the field.

2 | MATERIALS AND METHODS

2.1 | Study sites

The study took place on the River Tame in Birmingham, UK (Figure 1). The Tame drains an area of approximately 408 km^2 and is dominated by urban land use (59.2%; National River Flow Archive, 2016).

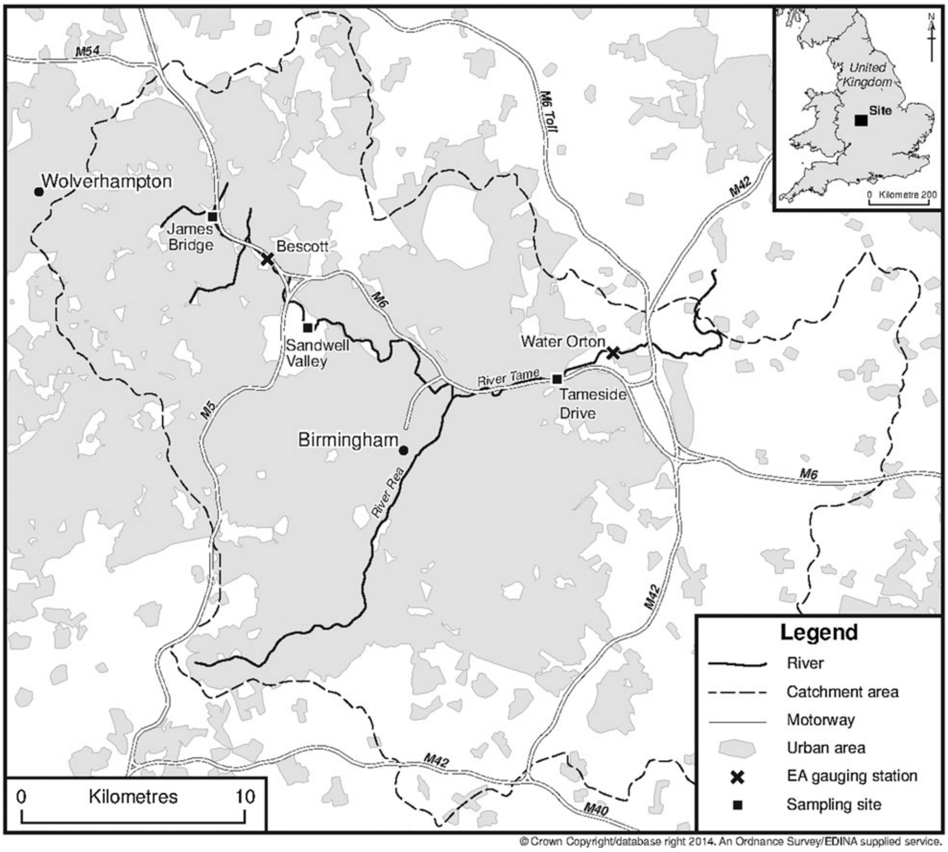

FIGURE 1 Location of study sites in the River Tame basin, Birmingham, UK

Sediment traps were installed at three morphologically different sites: James Bridge (52°34′N, 02°01′W), the most upstream point; Sandwell Valley (52°31′N, 01°57′W), in the middle reaches of the river system ~13 km downstream from James Bridge; and Tameside Drive (52°30′N, 01°47′W), 13 km downstream of Sandwell Valley and 2.5 km upstream of the Water Orton gauging station (41°74′N, 29°13′31″W). Channel width ranged from 6 to 17 m, with heavy engineering of the channel increasing upstream. Close to the catchment outlet, mean flow is ~5.4 m^3/s and Q_{10} (90th percentile) flow is ~9.6 m^3/s (NRFA, 2016). Discharge over the sampling period indicated a range of flow conditions such that the samples were representative of natural flow variability (Figure 2).

2.2 | Sampler design

The study utilized two versions of bed trap design: a basket-type bed trap (vertically extending sediment trap [VEST]) and a more traditional bed trap design (fixed-area sediment trap [FAST]) of identical size and shape (Figure S1). The VEST is similar to the infiltration bag described by Lisle and Eads (1991), however, one modification was made to address bag slippage problems during recovery of the samples (Petticrew *pers. comm*), which can lead to problems with calculating the volume of sampled gravels. The modified design here was made from collapsible and impermeable ventilation tubing in place of a bag, which was sprung with stainless steel wire (collapsed length 12 cm; maximum extendable length 30 cm; internal diameter 20 cm; cross section area 314 cm^2; maximum volume 9,425 cm^3). The trap was reinforced around the top with a stainless-steel rim and attached to a stainless-steel base with two flexible woven webbing handles fastened to the reinforcing ring. The highly flexible material allowed the walls of the trap to collapse down within the gravel bed during the sampling period, thus minimizing the physical effect of the trap on the natural particle exchange processes in the riverbed, while

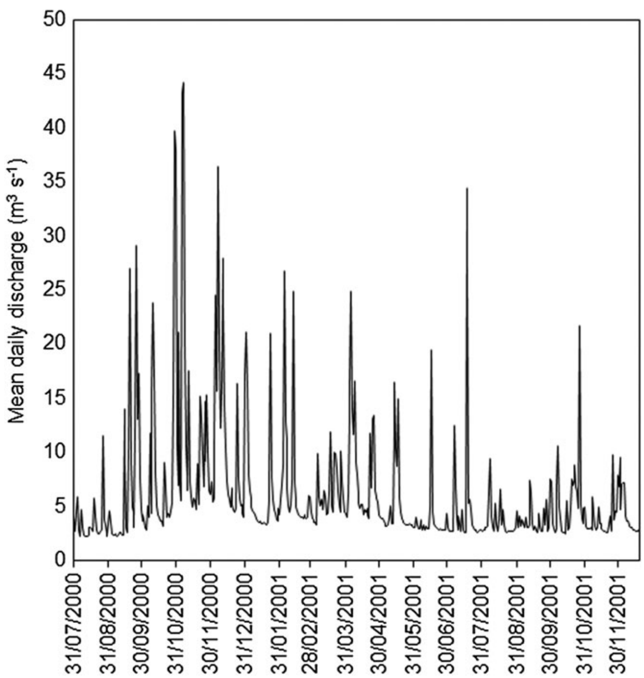

FIGURE 2 River discharge (m^3/s) for the River Tame basin, Birmingham, UK, during the sampling period

maximizing sampling efficiency upon recovery. The FAST sampler consisted of an impermeable plastic tube (length 30 cm; internal diameter 20 cm; cross section area 314 cm^2; maximum volume 9,425 cm^3), sealed at the bottom with an endcap, with two flexible woven webbing handles fastened to the rim.

The VEST and FAST traps were deployed in pairs at depths of 30 cm within the gravel substrate over a period of 401 days. Deployment methods are shown schematically in Figure 3. The number of traps deployed and deployment time at each site is shown in Table 1. The water column depth at each installation location was approximately 10–30 cm under low-flow conditions, to ensure traps were permanently inundated and to facilitate safe installation and recovery. Traps were filled with gravels excavated from the installation pits to provide a site-specific and natural gravel framework with which to assess infiltration rates. Prior to installation, gravels were wet sieved in situ to remove fines (<2 mm), and any extremely large or artificial clasts (e.g., large house bricks that would not fit within the diameter of the trap) were removed. This approach standardized the framework across the three sites as much as possible and avoided significant variation in the available pore space between individual traps.

Traps were removed by inserting a plastic tube (collar) around the top of the trap to a level above the height of the water column. This prevented the flow from removing accumulated fines from the surface and stabilized the hole thereby facilitating the reinstallation process. All gravels and fine material were emptied into large field-portable sieves, incorporating 4 × 25-L storage tanks, and sieved using river water with fines retained in the tanks. To calibrate for the inclusion of suspended sediment in the water column, a sample of river water was taken just before recovery to enable the total volume of trapped sediment to be adjusted relative to suspended sediment concentrations within the river. A lack of data for a 6-month sample at James Bridge was caused by a loss of the FAST sediment trap due to deep scour during a major flood. The downstream pair of traps at any given site was most frequently sampled in order to minimize disturbance (trampling) of upstream traps.

Only a limited number of samplers were available, and so, traps were reused (removed, cleaned, and reinstalled). Because of the significant effort required for installation and removal of the traps, replication of all sites was not feasible and, therefore, sediment accumulation comparisons are made using paired traps from all three sites, and is accounted for in the statistical model design; see below. Safety issues associated with access to an extremely flashy urban river system (Lawler, Petts, Foster, & Harper, 2006) led to some irregularity in deployment times. Each trap generated ~80–100 L of water for rinsing and cleaning, and this large volume further limited how many traps could be changed in one sampling event because the total volume was transported back to the laboratory for further analysis.

2.3 | Laboratory methods and data analysis

In the laboratory, sediment samples were allowed to settle for a minimum of 24 hrs. The supernatant was then decanted and fines <2 mm oven dried for a further 24 hr before dry-sieving to obtain the following particle size classes: 600–2,000, 125–600, 63–125, and <63 μm. Total sediment accumulated (kg) was determined for pairs of VEST and FAST traps installed for different residence times (range of 14–401 days; Table 1) over a 13-month period (n = 27). As traps from differing sites were used in the comparison of the mass of fine sediment accumulating

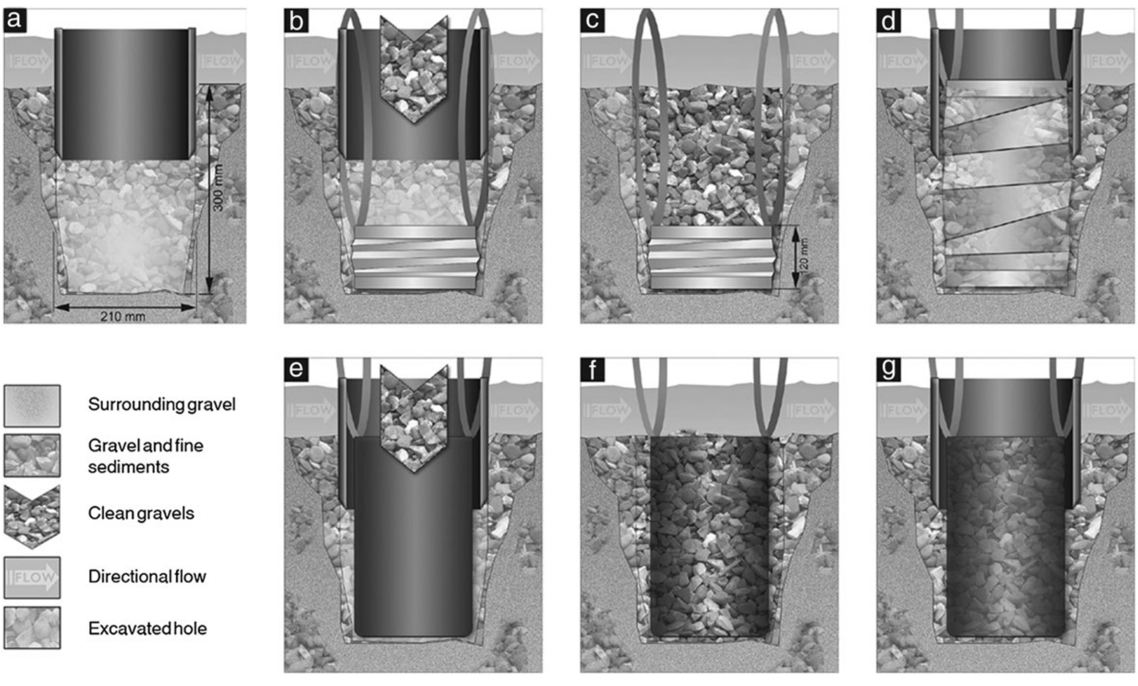

FIGURE 3 Schematic diagram illustrating the design, installation, and sampling techniques for the vertically extending sediment trap (VEST) and fixed-area sediment trap (FAST) sediment traps. VEST traps are lowered into an excavated hole protected by a plastic tube extending above river water level (a) with straps extending above the gravel bed (b). The hole is backfilled with cleaned gravel before removing the plastic tube to leave the gravel open to lateral and surface sediment ingress (c). The plastic tube is carefully placed over the trap before the straps are used to lift the VEST vertically through the gravels (d) in order to recover the sample. FAST installation (e–g) also uses the plastic tube to protect the trap during installation and removal (e–g), but the solid walls prevent lateral movement of fine sediment into the cleaned gravels over the installation period (f)

TABLE 1 VEST and FAST pairs: trap residence time, total sediment collected (accumulated) over the installation period, and rates of sediment infiltration

Site	Trap residence time	Fine sediment collected (kg)		Fine sediment infiltration rate (kg/m²/day)	
		VEST	FAST	VEST	FAST
James Bridge	28	0.017	0.055	0.020	0.062
	61	0.293	0.256	0.153	0.134
	90	0.489	0.082	0.173	0.029
	173	0.672	0.325	0.124	0.060
Sandwell Valley	27	0.205	0.339	0.242	0.399
	35	0.389	0.164	0.354	0.149
	36	0.460	0.465	0.407	0.411
	119	0.465	0.410	0.124	0.110
	124	0.474	0.379	0.122	0.097
	127	0.693	0.696	0.174	0.175
	230	0.677	0.403	0.094	0.056
	401	0.635	0.444	0.050	0.035
Tameside Drive	14	1.385	1.053	3.150	2.393
	30	0.543	0.171	0.576	0.182
	31	0.389	0.416	0.399	0.428
	32	0.122	0.090	0.122	0.089
	37	0.527	0.365	0.453	0.314
	38	1.166	0.398	0.977	0.333
	43	0.109	0.085	0.080	0.063
	54	1.199	1.110	0.707	0.654
	57	0.611	0.245	0.341	0.137
	61	0.640	0.350	0.334	0.183
	66	0.454	0.470	0.219	0.227
	107	0.424	0.657	0.126	0.196
	117	0.683	0.359	0.186	0.098
	117	0.797	0.267	0.217	0.073
	233	1.369	0.816	0.187	0.111

Note. FAST = fixed-area sediment trap; VEST = vertically extending sediment trap.

in VEST and FAST traps and preliminary analysis indicated that sediment accumulation (kg) varied by site (all $p < .05$), mixed effects models were employed in subsequent analyses (Venables & Ripley, 2002).

Application of mixed effects models enables the incorporation of random factors, variables that account for excess variability in the dependent variable. The mass of sediment accumulated was tested via a linear mixed effects (LME) model with the fixed terms of "trap type × particle size × residence time (days)" and site specified as a random factor. Models were fitted using the "nlme" package (Pinheiro et al., 2013) with the restricted maximum likelihood estimation function in R version 3.3.2 (R Development Core Team, 2013). Both marginal R^2 (proportion of variance explained by the fixed factors alone) and conditional R^2 (proportion of variance explained by the fixed and random factors) values were extracted using the "MuMIn" package (Bartoń, 2016). Significant categorical interactions (i.e., particle size and trap type) were investigated further via pairwise comparisons to enable examination of where statistical differences occurred. An LME was also employed to assess whether the rate of sediment accumulation varied as a function of trap residence time (days installed) with site specified as a random factor. Accumulation rates were calculated as the mass of fine sediment filtrating substrates via the surface of the sediment traps, standardized to m^2/day as per other studies (Collins & Walling, 2007; Frostick et al., 1984). To assess whether the proportion of fine sediment in each grain size varied as a function of trap type, a binomial general linear model (GLM) was fitted using a logit error distribution via the "glm" function. Preliminarily analysis via a generalized LME model (GLMM), with site fitted as a random term, indicated that the random effect accounted for little variation, and so, the simplified GLM was employed.

3 | RESULTS

Table 1 summarizes the period of trap installation, the mass of sediment accumulated per trap, and the calculated rate of sediment accumulation in kg/m^2/day for the complete paired dataset. Sediment accumulation varied significantly as a function of trap type with VEST traps collecting 46.16% more fine sediment than the FAST traps (Figure 4). Statistical differences in the mass of fine sediment accumulated were also evident as a function of the independent effect of residence time and particle size and the interaction of the two factors (Table 2). There was also significant interaction between trap type and particle size, indicating that the trap design influenced the total accumulation of certain particle sizes (see below). Examination of the R^2 values indicated that the model accounted for a good proportion of the variability, with fixed factors explaining 49.33% of variance and the random factor of site accounting for an additional 4.7% of the total variance (total model 54%). A summary of model outputs (F, p, and R^2 values) is shown in Table 2. When only vertical surface area was considered, the rate of fine sediment accumulation declined significantly as trap residence time increased ($F_{1,47} = 4.9$ $p = .032$; Figure 6); however, R^2 values indicated a poor fit of the model predictors (marginal $R^2 = 8.62\%$, conditional $R^2 = 11.37\%$).

Pairwise comparisons of the individual particle sizes by trap type indicated that significantly more large particles in the size fractions of 600–2,000 and 125–600 μm were collected in the VEST traps in comparison to the FAST traps (Figure 5; Table 3). Smaller particles (63–125 and <63 μm) demonstrated no statistically significant differences associated with trap type ($p > .5$; Table 3). This is a reflection of the larger mass of sediment collected by VESTs as no significant differences were determined for the proportion of mass within each size fraction as a function of trap type ($p > .05$; GLM), with the model accounting for only a small amount of variability ($R^2 = 10.85\%$; Figure S2).

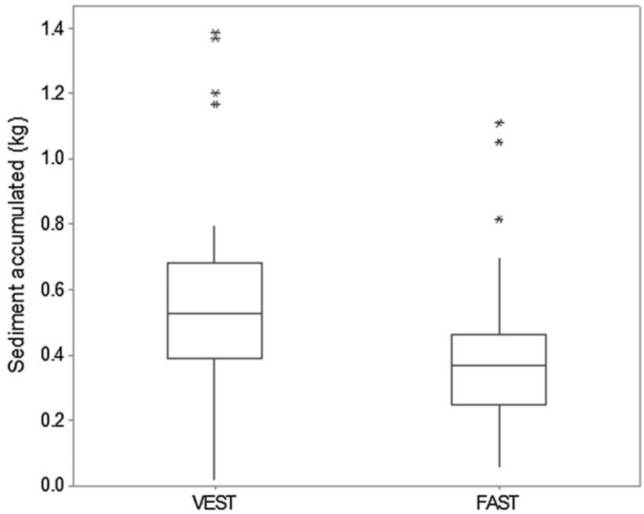

FIGURE 4 Net fine (<2 mm) sediment accumulation (kg) for all traps installed at three sites on the River Tame

TABLE 2 Summary of linear mixed effects model examining the mass of fine sediment accumulated associated with trap type (VEST or FAST), sediment size (n = 4), residence time (days installed), and the interactions between these factors

Factor	df	*F* value	*p* value
Trap type	1	8.46	.004
Particle size	3	64.83	<.001
Residence time	1	6.75	.010
Trap type × particle size	3	3.57	.015
Trap type × residence time	1	0.43	.512
Particle size × residence time	3	3.01	.031
Marginal R^2	49.33		
Conditional R^2	54.04		

Note. FAST = fixed-area sediment trap; VEST = vertically extending sediment trap.

4 | DISCUSSION

4.1 | Sediment accumulation as a function of trap type design

Sediment accumulation per unit surface area was greatest in VESTs, which collected 46% more fine sediment than FAST traps. The higher accumulation of sediment in VESTs suggests that net lateral exchange of fine sediment is an important component of fine sediment accumulation that has been overlooked in many studies to date (Mathers & Wood, 2016; Petticrew et al., 2007). This finding supports a number of other studies that have compared various trap designs—those that permit just vertical exchange and those that permit both lateral and vertical exchange. Within a flume study, Carling (1984), for example, determined that solid-walled traps reduced the trapping efficiency of fines by up to 31%. Sear (1993) and Mathers and Wood (2016) also reported similar findings within field studies with reductions in trapping efficiency of 20–25% and 29%, respectively.

Observations made when excavating the traps showed that the upper layer (~5 cm) of gravel in the FASTs quickly became blocked with fine sediment forming a seal (e.g., Herzig, Leclerc, & Goff, 1970; Huston & Fox, 2015), and fine sediment penetrating less deeply within the FAST traps (to a depth of ~15 cm) compared to the VESTs (~20 cm). This suggests that lateral flushing flows were not possible within the FASTs and this may in part cause the build-up of sediment (and formation of a seal/colmation) in the surface layers of the FASTs. This prevents further sediment accumulation and possibly leads to overestimates of any net lateral sediment accumulation in this study. This observation highlights the importance of vertical and lateral connectivity in maintaining healthy hyporheic habitats. Rivers, which are dominated by the process of vertical fine sediment ingress, may suffer more readily from the formation of fine sediment surface clogs. Colmation can significantly reduce vertical hydrological exchange, limiting the transfer of oxygen and nutrients, and effectively disconnects surface substrates from subsubsurface habitats, thereby potentially reducing stream biodiversity (Bo, Fenoglio, Malacarne, Pessino, & Sgariboldi, 2007; Mathers, Millett, Robertson, Stubbington, & Wood, 2014; Simpson & Meixner, 2012). VEST traps collected a greater mass of larger size fractions, which may be a function of vertical hydrological exchange being maintained, allowing ingress of coarser fines deeper into the substrates. However, there were no differences in the proportional composition of the fine sediment matrix with both trap types representing comparable particle size distributions.

4.2 | Complexities of sediment accumulation measurements associated with time

Within this study, both the vertically extending (permeable) and fixed area (impermeable) traps exhibited rapid filling in the short term (Figure 6). This may be explained by the presence of large void spaces between the cleaned river gravels, which provided maximum connectivity and a high storage volume in which fine sediment could accumulate (Xu, Wang, Pan, & Na, 2012). Hoyal et al. (1997) found that the greatest rates of deposition were in clean gravel beds and that a reduction in deposition occurred long before the bed was filled with sediment, due to an infilling of the surface void space. The rapid trap filling observed in this study is unlikely to be representative of natural sediment deposition rates in undisturbed river channels but may be an artefact of the experimental method used; during trap installation, a significant loss of

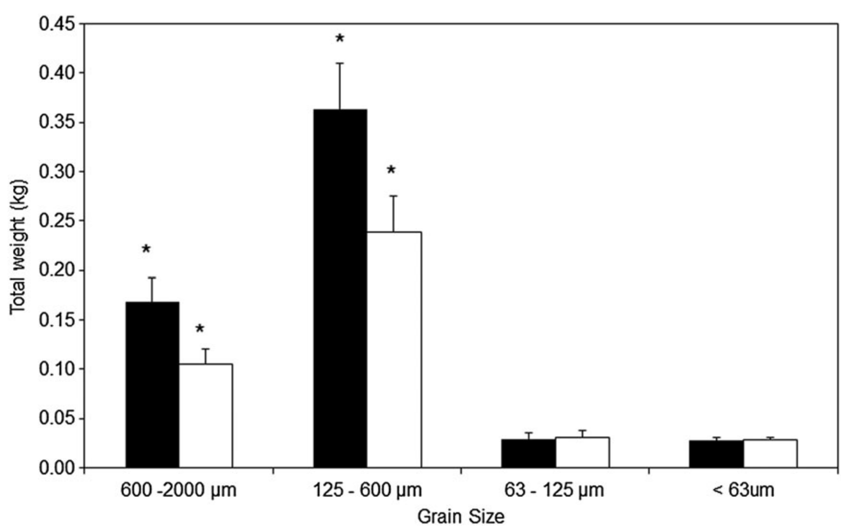

FIGURE 5 Average mass of fine sediment (+1 SE) for grains 600–2,000, 125–600, 63–125, and <63 µm by trap design for all traps installed on the River Tame. Black = vertically extending sediment traps and white = fixed-area sediment traps

TABLE 3 Summary of pairwise comparisons of mass accumulated for each individual substrate sizes as a function of trap type (VEST or FAST)

Grain size	*t* value	*p* value
600–2,000 μm	−2.36	**.022**
125–600 μm	−2.25	**.028**
63–125 μm	0.19	.851
<63 μm	0.11	.914

Note. FAST = fixed-area sediment trap; VEST = vertically extending sediment trap.

bed framework structure, including any surface armouring, will occur. Moreover, screening of gravel for use within sediment traps involves removing all material <2-mm diameter, which represents an unnatural matrix in gravel frameworks and can create a suck or draw for fine sediments. However, this problem is inherent with these methods as it is necessary to start with clean gravel (i.e., zero fine sediment) in order to quantify the mass of fine sediment, which has accumulated during the installation period.

Traps that were removed, sieved, and refilled with clean gravel more frequently (i.e., the traps installed for shorter time periods) collected more fine sediment than traps, which were resident for several months. This may be associated with renewed connectivity of substrates associated with vertical hydrological pathways, an increase in initial storage capacity and the removal of benthic algae (Potamogeton *spp* and Cladophora *spp*) that may inhibit sediment accumulation and ingress (Bo et al., 2007; Fox, Ford, Strom, Villarini, & Meehan, 2014; Papanicolaou, Diplas, Evaggelopoulos, & Fotopoulos, 2002). Hydraulic conductivity, and associated sediment transport, is also strongly linked to the time since the last streambed disturbance (Boano et al., 2007; Stewardson et al., 2016) and, as such, longer trap residence times are able to capture this natural decay in infiltration rates that may be a function of bed turnover (or in this instance trap removal). The results of the study, therefore, suggest that substrate traps installed for short periods may overestimate natural long-term rates of sediment accumulation within gravel frameworks and caution is needed when interpreting the data.

4.3 | Complexities of understanding the processes captured by sediment trap designs

Finally, we consider the accuracy of the two commonly employed sediment traps in the measurement of fine sediment accumulation as a function of the processes they quantify. Solid-walled traps permit only vertical exchange of fine sediment, and therefore, once fine material has infiltrated substrates within the trap, the only direction of transport is vertically through the top of the trap, which can occur through turbulent flows (Detert & Parker, 2010; Kuhnle, Wren, & Langendoen, 2016;) and, in particular, during large flood flows, which are capable of scour events (Harris, Whitehouse, & Moxon, 2016). Permeable traps permit sediment to enter—or leave—the trap by horizontal movement. As a result, the mass of sediment accumulated in both trap designs represents the net accumulation of fine sediment in the gravel bed as trapping efficiencies are not known associated with egress rates varying spatially and temporally. Therefore, when deployed simultaneously, the mass of fine sediment collected in these two traps may enable a comparison between the net accumulation of fine sediment by either isolated vertical exchange or through vertical and lateral exchange.

However, estimates of sediment accumulation rates via commonly employed methods of vertical ingress per m^2/day should be interpreted with care when using two differing types of sediment traps, as the two traps measure different functions of fine sediment accumulation. Consequently, presentation of sediment accumulation rates is a useful tool to help understand the overall trend of fine sediment accumulation over time but should be used with caution when comparing differences associated with trap type directly, as traps may be measuring different processes.

During trap removal, FAST traps accumulated large amounts of fine sediment in the upper gravels, which caused fine sediment clogs; this possibly limited further vertical ingress and potentially reduced total fine sediment accumulation. As a result, it is pertinent to reflect on what processes sediment traps are measuring and, indeed, how accurate the data are. It is possible that by utilizing closed and permeable sediment traps in combination, studies are not measuring differences in sediment transport processes (exclusion of just vertical exchange versus permitting horizontal infiltration and vertical exchange)

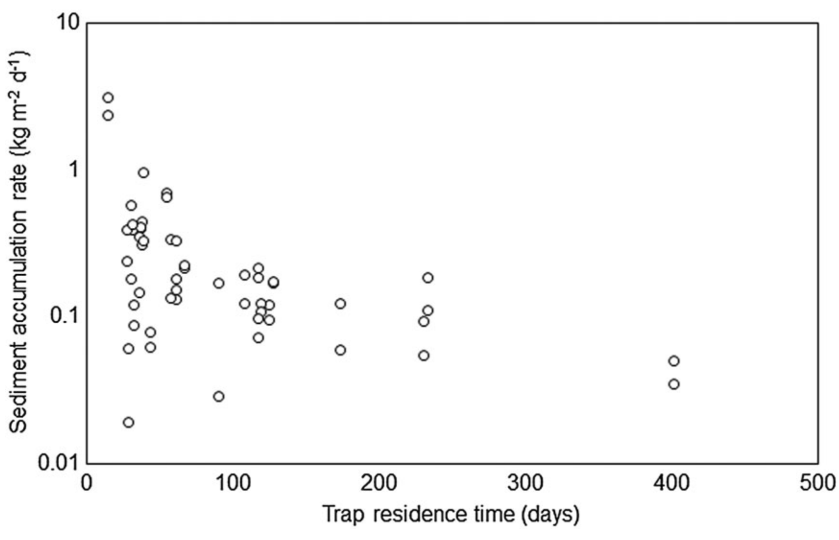

FIGURE 6 Rate of fine sediment accumulation (kg/m^2/day) as a function of trap residence time

but may be recording an inherent design feature of the trap itself. By limiting flushing horizontal flow pathways, do sediment traps truly capture the contribution of the different directions of fine sediment infiltration in gravel beds?

5 | CONCLUSION

The results of this study indicate that the application of two differing designs of sediment traps provides differing accumulation rates when a range of sediment trap residence times are examined. However, there are notable and inherent issues with the application of sediment traps, which raise questions of how accurate the measurements are as a function of the processes they are employed to measure and therefore for what purpose should sediment traps be used. First, both sediment trap designs represent artificial substrate conditions and, therefore, only provide information on the accumulation of fine sediment under initially clean gravel scenarios, which are not common. Second, the two methods measure different processes (vertical exchange versus vertical and lateral exchange), but the extent to which they accurately do this is debatable, with FAST traps being highly susceptible to the formation of fine sediment seals. Sediment traps are, however, likely to represent useful tools for comparing corresponding trap designs under different flow conditions and between sites. However, we suggest that trap studies using different designs of sediment traps should do so with caution and should reflect on the processes, which are being measured in the context of their results.

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