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Challenges in measuring fine sediment ingress in gravel-bed rivers using retrievable sediment trap samplers

R. Maltauro[1] | M. Stone[1] | A. L. Collins[2] | B. G. Krishnappan[3]

[1]Department of Geography & Environmental Management, University of Waterloo, Waterloo, Ontario, Canada

[2]Net Zero and Resilient Farming, Rothamsted Research, Okehampton, Devon, UK

[3]Environment Canada, Burlington, Waterloo, Ontario, Canada

Correspondence
R. Maltauro, Department of Geography & Environmental Management, University of Waterloo, Waterloo, Ontario, Canada.
Email: rdefreitasmaltauro@uwaterloo.ca

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Abstract

"Excess" interstitial fine sediment (<2 mm) is known to cause deleterious impacts on streambed ecosystems. Current methodologies available to assess ingress and its vertical and horizontal components still lack standardization, and the accuracy of commonly used assessments is still debatable. Here, we evaluate three fine sediment trap designs that measure only vertical (V), only horizontal (H), and both vertical and horizontal (HV) ingress mechanisms. Sediment traps were deployed in triplicates to: (i) evaluate measurement variability within traps of the same type; (ii) evaluate the effects of trap design on particle size distributions of infiltrated fine sediment and; (iii) assess methodologies used to calculate vertical and horizontal ingress mechanisms. Ingress rates were recorded for each sediment trap during seven deployment periods (lasting from 2 to 10 days) at a range of flow conditions at four sites. A total of 252 traps were deployed. Results from the triplicate assessment of traps with the same design showed that most measurements presented high variability and that particle size distributions were significantly affected by trap design. Here, different sediment traps were able to estimate directional ingress mechanisms. However, direct comparison between HV with either H or V traps led to an overestimation of horizontal or vertical ingress mechanisms, respectively. Better estimations were found when comparing HV observations to half the accumulation in either H or V, due to the proportional trap volume available for each accumulation mechanism according to trap design.

KEYWORDS
cohesive sediment, method comparison, sediment infiltration, sediment intrusion mechanisms

1 | INTRODUCTION

Fine sediment (<2 mm) stored within the interstices of gravel-bed rivers is an important component of catchment fine sediment budgets (Foster et al., 2011). It naturally promotes matrix development (Frostick et al., 1984) and it plays an important role in nutrient cycling and aquatic health (Hauer et al., 2016; Wilkes et al., 2019). However, anthropogenic and natural landscape disturbances (e.g., harvesting, wildfires, droughts, and resource extraction) have increased fine sediment delivery to river systems (Naden et al., 2016; Owens et al., 2005; Walling & Fang, 2003). The subsequent deposition and storage (short- and long-term) of fine sediment within gravel-bed interstices can reduce substrate permeability and conductivity (Brunke, 1999; Schälchli, 1992; Wharton et al., 2017), decrease dissolved oxygen availability (Greig et al., 2005), and degrade benthic habitats used by aquatic organisms for key life stages (Jones et al., 2012; Mathers et al., 2019). Landscape modifications have altered fine sediment deposition and accumulation dynamics, leading to legacy impacts in gravel-bed rivers (Emelko et al., 2016; James, 2013; Stone et al., 2021; Watt et al., 2021), and an improved understanding of the strengths and limitations of assessment methods is required to ensure reliable evidence is generated in support of improved fine sediment management.

In high-energy gravel-bed rivers, fine sediment is known to have a complex interaction with the coarse channel bed framework (Legout et al., 2018). In these river systems, pressure gradients (leading to advective transport) and turbulent mixing (leading to turbulent diffusion) resulting from interactions between the flow and channel roughness elements can induce pore water flow and mass fluxes between the water column and the porous bed (Packman et al., 2004; Reidenbach et al., 2010). These interactions enable fine sediment to infiltrate the gravel interstices under bed shear stresses much higher than the critical shear stress required for fine sediment gravitational deposition (Casas-Mulet et al., 2017; Glasbergen et al., 2015; Krishnappan & Engel, 2006) in a process denoted as fine sediment ingress, but also known elsewhere as entrapment (Krishnappan & Engel, 2006), infiltration (Frostick et al., 1984; Sear, 1993), intrusion (Beschta & Jackson, 1979), or depth filtration (Brunke, 1999). Ingress can occur vertically, through the downward infiltration of suspended particles (Glasbergen et al., 2015; Krishnappan & Engel, 2006; Mooneyham & Strom, 2018) or from finer fractions of the bedload (Frostick et al., 1984; Lisle, 1989), or laterally, through horizontal accumulation driven by pore water flow (Casas-Mulet et al., 2017; Harper et al., 2017; Mathers & Wood, 2016; Petticrew et al., 2007). Interstitial fine sediment can ingress until reaching an impermeable (deeper) layer in a process known as unimpeded static percolation (Gibson et al., 2009; Herrero & Berni, 2016). Alternatively, particles can get trapped at the upper gravel interstices, clogging the framework in a process known as 'bridging' or colmation. (Brunke, 1999; Evans & Wilcox, 2014; Lisle, 1989; Perret et al., 2018; Schälchli, 1992; Wooster et al., 2008). Collectively, these processes make gravel-bed rivers important for the transient storage of fine sediment (Mondon et al., 2021; Owens et al., 2005). Yet, field studies of fine sediment ingress in-situ are still relatively limited, and the methodologies currently available lack standardization to allow direct and easy comparison of field study results.

Several methodologies are used to assess fine sediment ingress in field and laboratory assessments. Within the laboratory setting, flume experiments with gravel beds can indirectly assess fine sediment ingress by comparing initial and final suspended sediment concentrations at each flume run (Glasbergen et al., 2015; Krishnappan & Engel, 2006; Mooneyham & Strom, 2018). Alternatively, flume experiments can also directly measure fine sediment ingress by deploying sediment traps (Carling, 1984). In the field, fine sediment accumulation (channel bed storage) has been assessed through resuspension techniques (Duerdoth et al., 2015; Lambert & Walling, 1988), bulk sampling (McNeil & Ahnell, 1964), and freeze coring (Evans & Wilcox, 2014; Lisle, 1989; Petts, 1988). However, such techniques represent instantaneous snapshots of fine sediment accumulation, failing to provide information on the directional (vertical/horizontal) ingress mechanisms.

Fine sediment ingress rates and mechanisms have been commonly assessed with sediment traps (see Harper et al., 2017). Sediment traps consist of baskets that are filled with locally washed framework gravel (removal of <2 mm sediment), and subsequently inserted within the gravel substrate. A range of ingress trap designs have been deployed in the literature. Lidless impermeable-walled ingress traps (herein denoted as vertical—V traps), which only allow infiltration through the open surface area, have been used to assess the vertical accumulation of fine sediment through either deposition or ingress (Frostick et al., 1984; Wood & Armitage, 1999). Adaptations of these V traps with added open bottoms have also been used to allow and quantify vertical exfiltration of fine sediment (Mathers & Wood, 2016). Lidded permeable-walled ingress traps (herein denoted as horizontal—H traps), which only allow infiltration through the lateral openings but not through the surface, have been used to assess horizontal ingress (Carling, 1984; Casas-Mulet et al., 2017; Petticrew et al., 2007). Lidless permeable-walled traps (herein denoted as horizontal-vertical—HV traps) have been deployed to measure fine sediment accumulation through vertical and horizontal mechanisms simultaneously (Casas-Mulet et al., 2017; Greig et al., 2005; Mathers & Wood, 2016; Petticrew et al., 2007). Paired deployment of sediment traps has been conducted to calculate vertical and horizontal ingress mechanisms. In paired assessments, HV traps are deployed paired with either V (Harper et al., 2017; Mathers & Wood, 2016) or H traps (Casas-Mulet et al., 2017; Petticrew et al., 2007), and differences in fine sediment accumulation between the two trap designs are used to estimate ingress directional mechanisms. Although different sediment trap designs allow the quantification of ingress mechanisms, the accuracy of paired assessments is debatable and has been identified as an important research gap requiring further investigation (Harper et al., 2017). Here, we deployed three trap designs (horizontal-vertical—HV, horizontal—H, and vertical—V) in triplicate to (a) investigate variability in fine sediment ingress measurements within traps of the same design; (b) evaluate the effects of trap design on the accumulation of fine sediment according to particle size and at a range of flow conditions, and; (c) critically discuss the challenges of using different trap designs to measure vertical and horizontal sediment ingress mechanisms.

2 | METHODS

2.1 | Study area

The Crowsnest River, one of three main tributaries of the Oldman Watershed, is a gravel-bed river located on the eastern slopes of the Rocky Mountains in southwestern Alberta, Canada (Figure 1a). Bed elevation over the ~10 km study reach changed from 1314 to 1260 m.a.s.l., and the average bed slope was 0.0041 m/m. The median bed particle size (D_{50}) was 24, 41, 82, and 70 mm at sites one to four, respectively. Baseflow is dominated by groundwater inputs

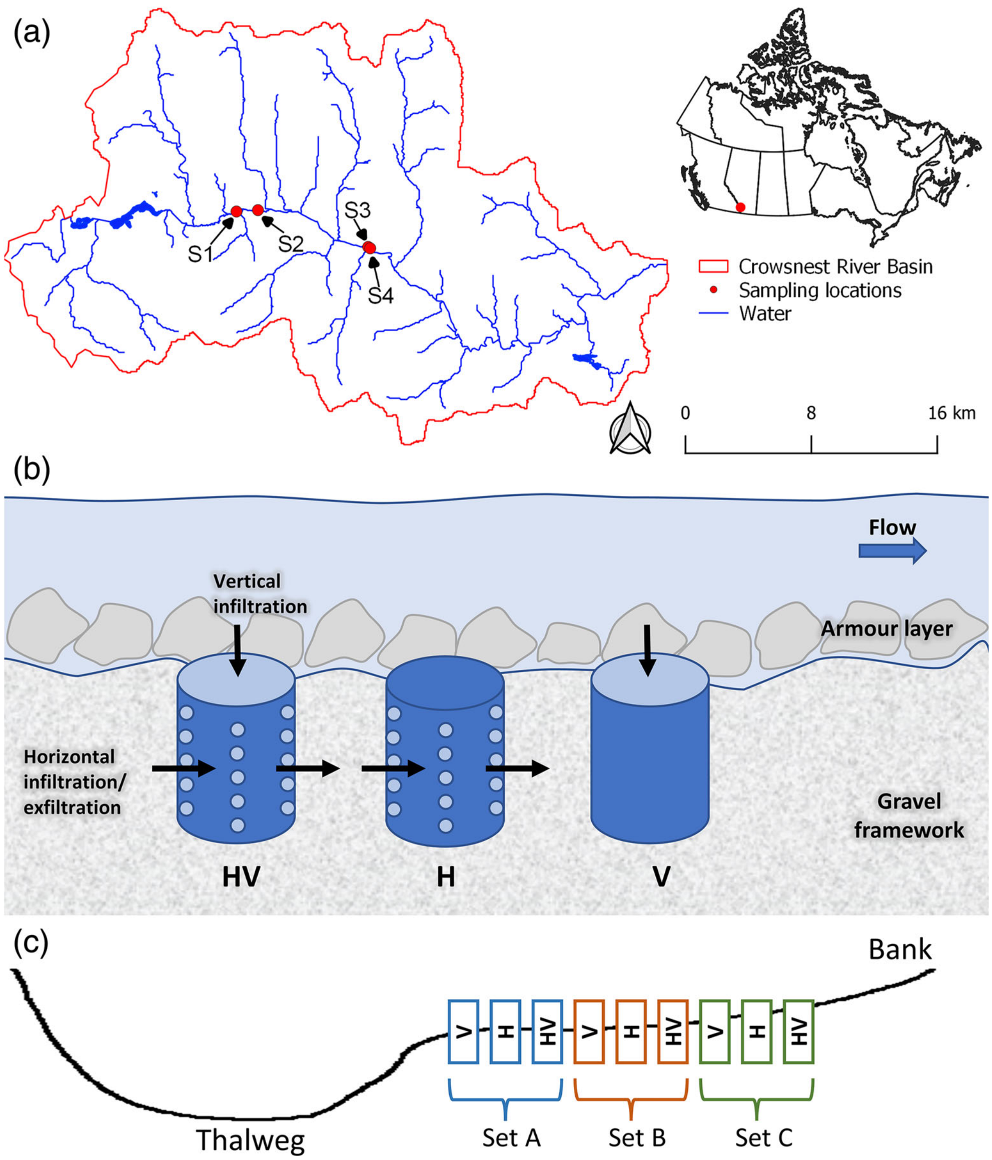

FIGURE 1 Location map (a), retrievable ingress trap designs and conceptualization of the ingress mechanisms being assessed by each trap type (b), and a schematic of the triplicate deployment in situ (c). [Color figure can be viewed at wileyonlinelibrary.com]

from alluvial aquifers in the river valley (Waterline, 2013). Streamflow is strongly controlled by late spring and early summer snowmelt, while peak flows occur due to rain-on-snow or summer storms (Stone et al., 2014; Waterline, 2013). Concentrations of total suspended solids (TSS) in the Crowsnest River are typically low (<5 mg/L), and elevated TSS is commonly associated with higher discharge events and sediment loads from tributary inflows (Silins et al., 2009). Further study site descriptions can be found in Silins et al. (2014) and Watt et al. (2021).

2.2 | Experimental design

Three designs of ingress traps were deployed in this study: HV, H, and V traps. All traps were constructed using 32 oz deli containers (surface diameter of 11.43 cm and height of 13.97 cm). The container walls pertaining to HV and H trap designs were perforated with 1 cm diameter holes (20 holes per trap) (Figure 1b). For HV and H traps, similarly to the samplers deployed by Casas-Mulet et al. (2017), each trap consisted of two tightly aligned containers, allowing for holes to be opened during sampling, and closed during trap retrieval, preventing loss of accumulated fine sediment. Further, to prevent sediment loss upon retrieval, V and HV traps were also lidded before trap removal from the channel. Visually, minimal amounts of fine sediment were observed to leak out of traps during retrieval, and we believe this would not have affected our results. Traps were deployed in triplicates (Figure 1c) in four submerged gravel bars along the Crowsnest River during seven cycles of deployment (3 trap types $\times$ triplicates $\times$ 4 sites $\times$ 7 cycles $=$ 252 traps in total; Figure 2). Sediment traps were deployed side by side, aligned, and laterally centered in the gravel bars to avoid being too close to the thalweg or the bank. Furthermore, trap designs were intercalated to avoid biases in accumulation as a function of their location within the gravel bar (Figure 1). The lengths of cycles were 4, 5, 10, and 6 days, for cycles 1–4, respectively, and 2 days for cycles 5–7 (Figure 3). Each trap was filled with representative framework gravel from each study site (sieve-washed with a 2 mm mesh) and

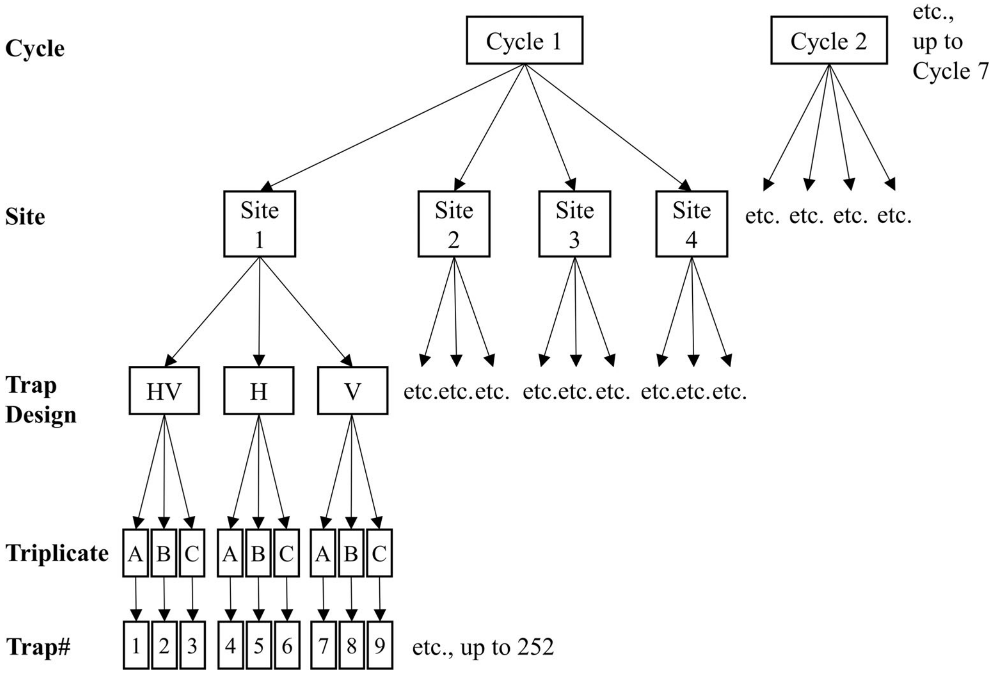

FIGURE 2 Schematic of the sampling design.

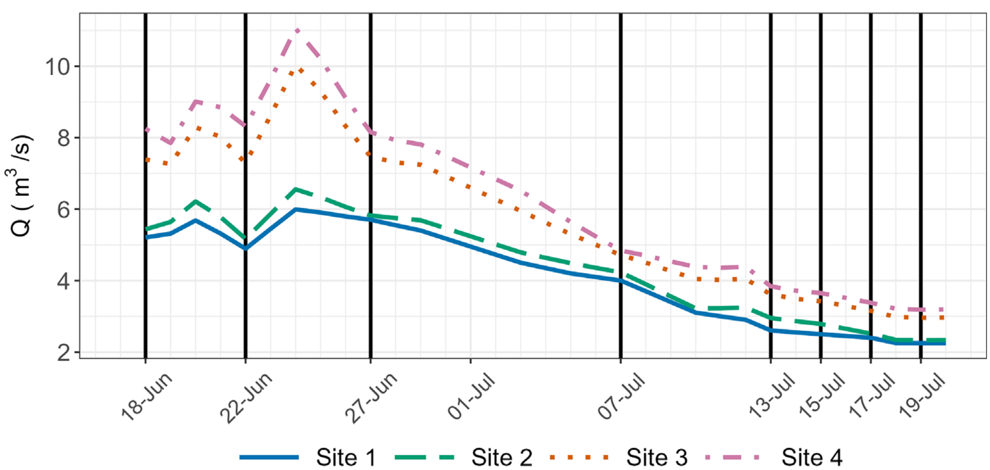

FIGURE 3 Measured discharge at the study sites. Vertical lines indicate the time delimitation of each deployment cycle. [Color figure can be viewed at wileyonlinelibrary.com]

manually shaken to promote a closer-to-natural gravel packing structure. Furthermore, during trap preparation before deployment, care was taken to ensure that no gravels were "clogging" any perforated holes. Six out of the 252 traps were removed from the assessments (traps were found displaced, likely due to vandalism, given the high recreational usage of the study river), leaving a total of 246 traps. For the consistency of pairwise comparisons, the pairs of the damaged traps were also removed (for example, if Cycle 2, Site 2, H-C was damaged, we also removed Cycle 2, Site 2, HV-C, and V-C).

2.3 | Data assessment and statistical analyses

Fine sediment accumulated in each ingress trap (three replicates of each trap design) was wet sieved through 2 mm and 0.5 mm sieves, oven-dried, and weighed, generating mass measurements for total accumulation <2 mm and for two size classes (<0.5 and 0.5–2 mm). Ingress rates were calculated in units of kg.day^{-1} to normalize accumulation according to the deployment period. Discharges (Figure 3) were measured with a FlowTracker2 (SonTek, Yellow Springs, OR, USA), and differences in flow condition were addressed by assessing the statistical effects of each deployment cycle (discussed below). Particle size distributions (effective and absolute) were obtained with a LISST-200x (Sequoia Scientific, Bellevue, WA, USA), which, through a laser diffraction principle, measures volume concentrations (VC) in 36 size bins for particles ranging from 1 to 500 μm. Particle size was measured from sediment-water samples collected while sieve-washing ingressed particles. Absolute particle size distributions were measured after dispersing the samples chemically, with sodium hexametaphosphate (5%), and mechanically, with ultrasonication (Naden et al., 2016; Phillips et al., 2000).

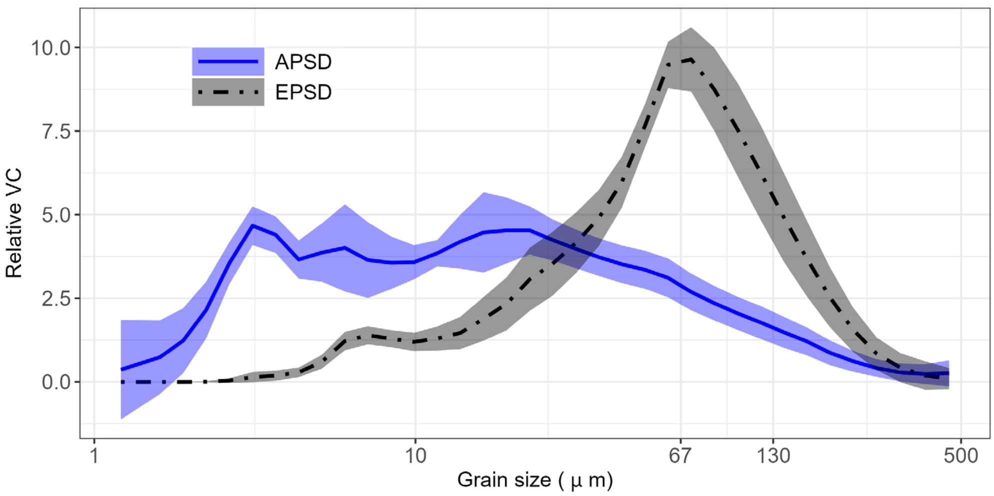

FIGURE 4 Absolute (APSD) and effective particle size distributions (EPSD) of ingressed fine sediment. Curves indicate median of all measurements and shaded areas indicate corresponding ±1 SD. [Color figure can be viewed at wileyonlinelibrary.com]

In order to obtain a mass estimation of ingressed fine sediment according to a range of size classes, while preserving flocculation of particles, effective particle size distributions were grouped into three size classes (< 67, 67–130, and 130–500 μm), defined for comparison with similar studies (Harper et al., 2017; Mathers & Wood, 2016). The relative volume composition per size class in relation to the total VC measured at each sediment trap was calculated and used to estimate their weight composition by multiplying relative volumes with the measured mass of fine sediment <0.5 mm. The mass estimation of size classes <0.5 mm was calculated based on the assumption that these particles are mostly flocculated. Here, comparisons between effective (flocculated) and dispersed particle size distributions have shown the flocculated nature of ingressed fine sediment <0.5 mm (Figure 4), and, as such, their densities were estimated to approach the density of water (1 g. cm^{-3}). This density value agrees with calculations between mass and VC measured in our samples and was adopted for simplicity, as floc density has been observed to change with particle size (Glasbergen et al., 2015; Krishnappan, 2022; Krishnappan & Engel, 2006).

Descriptive statistics, including averages and relative standard deviation (coefficient of variation—CV), were calculated for the triplicate measurements conducted for each trap design. In this study, linear mixed-effects models (LME) were used to assess the relationship between fixed factors (trap design, particle size, and deployment cycle) and ingress rates, by incorporating random factors (study sites) to account for data clustering and improve model fit compared to traditional linear models. The first LME model assessed the dataset pertaining to two size classes (<0.5 and 0.5–2 mm) of fine sediment ($n = 168$), while the following two models assessed size classes separately ($n = 84$ for each size class). For the LME models, ingress rates were log-transformed to improve normality, and values were standardized by centering data around means and scaling with respect to its standard deviation). Beta regression models were applied to evaluate the effects (and interaction effects) of trap design, particle size, and deployment cycle on the proportional content of particles within each size class (< 67 μm, 67–130 μm, 130–500 μm, and 0.5–2 mm). A preliminary assessment of size proportions using a binomial generalized LME, with sites fitted as a random variable, showed that different sites accounted only for little variation in the model, so the beta regression was used for simplicity. Pairwise comparisons were performed with a Wilcoxon signed rank test, using Benjamini-Hochberg correction for multiple comparisons.

To evaluate commonly used paired deployment methods to assess ingress directional mechanisms, we assessed the variability (mean and standard error) in our measurements and used linear regression models to relate direct assessments with estimates of ingress mechanisms. Here, we assumed that the comparison between H and V traps would directly assess solely horizontal and solely vertical measurements, respectively. In contrast, the comparison between HV and H would allow the direct measurement of horizontal mechanisms, while inferring (by their difference) vertical mechanisms, and the comparison between HV and V would allow the direct measurement of vertical mechanisms while inferring horizontal mechanisms. Considering that all three traps had the same control volume, we investigated not only the 1:1 proportion between traps (i.e., comparing the mass accumulated in 1 V or 1 H with the mass accumulated in 1 HV) but also the 2:1 proportion (i.e., assuming that HV accumulated both mechanisms at the same time under the same control volume, its separated ingress mechanisms would have to be increased to be comparable with masses accumulated in either V or H; Hence, when applying the equation $V + H = a(HV)$ for each paired deployment, an average value of ~ 2 was found for the constant a).

All statistical analyses were performed using R Statistical Software (R Core Team, 2022) through the RStudio Integrated Development Environment (RStudio Team, 2022). LME models were fitted using the "lme4" package (Bates et al., 2015) with the restricted maximum likelihood estimation function. Conditional and marginal R^2 values from the LMEs were extracted using the "MuMIn" package (Bartoń, 2023). Beta regression was fitted using the "betareg" package (Zeileis et al., 2021). The significance of predictors was determined using Anova (type 2 with Wald $\chi 2$ statistics) with the "car" package (Fox et al., 2023). Pairwise comparisons were assessed with the "rstatix" package (Kassambara, 2021). All plots were created using the "ggplot2" (Wickham, 2016) and "ggpubr" (Kassambara, 2020) packages.

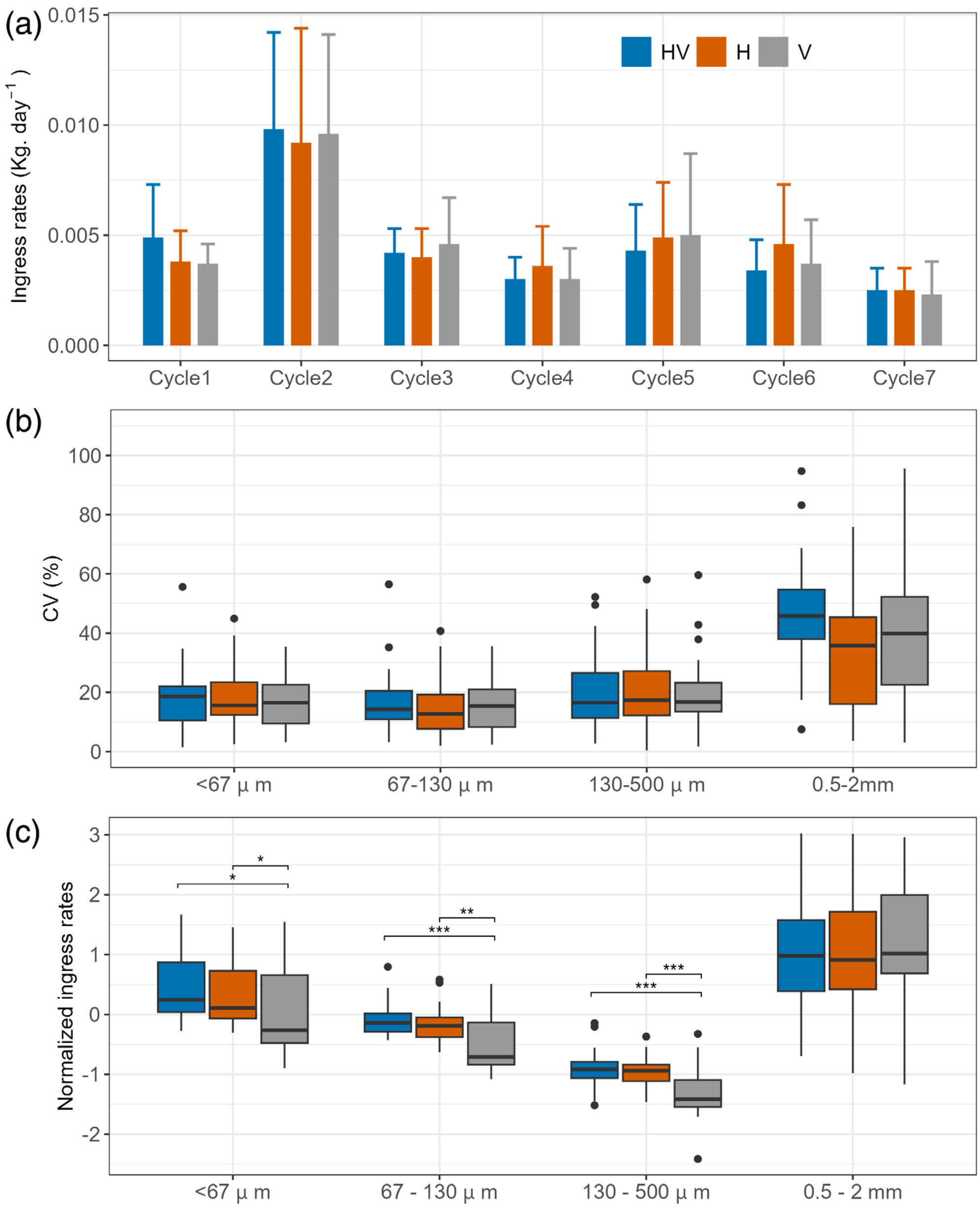

FIGURE 5 Mean (+1 SD) of fine sediment <2 mm accumulation rate ($n = 12$ for each ingress trap design) (a), coefficients of variation from the triplicate measurement of ingress rates (b), and Wilcoxon signed rank test pairwise comparison of ingress rates. In (b) and (c), $n = 28$ for each design of ingress trap. Adjusted (Benjamini–Hochberg) *p*-values: **p* < 0.05, ***p* < 0.01, ****p* < 0.001, and *****p* < 0.0001. Median, upper, and lower quartiles; whisker indicates the range spanning 1.5 times the interquartile range. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Summary of the LME model examining fine sediment ingress rates according to deployment cycle, trap design, and particle size class.

		<0.5 mm and 0.5–2 mm particle sizes ($n = 168$)	
Factor	***df***	χ^2	***p-value***
Trap design	2	2.02	0.365
Trap design: Particle size	3	11.07	**0.011**
Trap design: Particle size: Deployment Cycle	18	105.69	**<0.001**
Marginal R^2		0.343	
Conditional R^2		0.518	

Note: Bold values represent significant results at the 95% confidence level.

3 | RESULTS

Accumulation rates of fine sediment <2 mm, using the three designs of ingress traps deployed, are shown in Figure 5a. However, important differences in ingress rates were observed as a function of particle size through the LME models (Tables 1 and 2). Results from the LME model assessing particles <0.5 and 0.5–2 mm showed that trap design alone did not significantly affect responses in ingress rates, but

TABLE 2 Summary of the LME models examining fine sediment ingress rates according to deployment cycle and trap design, for particle size classes separately.

		<67 µm		67–130 µm		130–500 µm		0.5–2 mm	
		(*n* = 84)		(*n* = 84)		(*n* = 84)		(*n* = 84)	
Factor	***df***	χ^2	***p*-value**	χ^2	***p*-value**	χ^2	***p*-value**	χ^2	***p*-value**
Trap design	2	58.32	**<0.001**	80.91	**<0.001**	45.69	**<0.001**	1.01	0.603
Trap design: Deployment cycle	18	504.47	**<0.001**	208.34	**<0.001**	75.70	**<0.001**	81.85	**<0.001**
Marginal R^2		0.859		0.764		0.494		0.233	
Conditional R^2		0.873		0.781		0.662		0.767	

Note: Bold values represent significant results at the 95% confidence level.

TABLE 3 Summary of the beta regression model examining the proportions of mass accumulation within each size class according to deployment cycle, trap design, and particle size class.

		Four size classes (*n* = 336)	
Factor	***df***	χ^2	***p*-value**
Trap design	2	0.003	0.999
Trap design: Particle size	3	692.76	**<0.001**
Trap design: Particle size: Deployment Cycle	18	141.25	**<0.001**
Pseudo R^2		0.764	

Note: Bold values represent significant results at the 95% confidence level.

significant effects were observed regarding the interactions between trap design, particle size, and deployment cycle (Table 1). The LME model assessing both <0.5 and 0.5–2 mm size classes, however, did not explain substantial model variance (marginal R^2 of 34.3%), with random factors improving the model by 17.5%, resulting in total model variance (conditional R^2) of 51.8% (Table 1). The LME results pertaining to each size class indicated that model fit improved as particle sizes decreased (conditional R^2) and that the clustering effect from sites became significantly more important as particle sizes increased (difference between conditional and marginal R^2) (Table 2). Except for particles 0.5–2 mm, the independent effect of trap design and its interaction with deployment cycle significantly affected responses in ingress rates for all size classes (Table 2). The beta regression model showed the significant effects between the interaction of trap type, particle size, and deployment cycle on the proportional mass of accumulated fine sediment (Table 3).

Variability in ingress rates, regarding the triplicate measurements, was generally high for all size classes (Figure 5b). Over 80% of all measurements presented CVs above 10%, and CVs were particularly higher for coarser particles. CVs were significantly higher for the 0.5–2 mm size class, compared to the smaller particles ($p < 0.001$), and for the 130–500 µm, compared to the 67–130 µm size class ($p < 0.05$) (Figure S1). Variability between trap designs, however, was not significantly different for any size class (Figure 5b). Pairwise comparisons showed significant differences between sediment trap designs for the <0.5 mm size classes, but no differences were observed for 0.5–2 mm particles (Figure 5c). Linear regressions performed considering 1:1 and 2:1 proportions of fine sediment accumulation from H and V traps showed that curves regarding 2:1 proportions were more similar to the measurements from HV traps, in terms of both intercept and slope (Figure 6). As such, the calculation of ingress mechanisms using 2:1 proportions resulted in more realistic estimations, when compared with direct assessments with H and V traps, and reduced the standard errors in both size classes (Figure 7). Furthermore, through the assessment on a 1:1 proportion, we observed that estimates between HV and V, and HV and H traps, overestimated vertical and horizontal mechanisms, respectively (Figure 7). When assessing ingress mechanisms using a 2:1 proportion, this bias was eliminated for estimations between HV and V, although it was only reduced between HV and H (Figure 7).

4 | DISCUSSION

4.1 | Measurement variability

This study sought to examine the variability of fine sediment ingress measurements taken using three designs of sediment traps. High measurement variability was observed across all trap designs, and it was particularly high for 0.5–2 mm particle sizes, demonstrating the importance of size effects (discussed below) on fine sediment ingress measurements. To the authors' best knowledge, triplicate measurements of ingress rates, like the ones performed here, have not been performed elsewhere. Similar studies deploying replicates of traps have also reported high variability within measurements (Casas-Mulet et al., 2017; Harper et al., 2017; Sear, 1993). However, those studies differ from ours in the sense that their replicates were deployed to assess fine sediment ingress variability between channels or within channel features, while our triplicates were deployed close to each other to assess variability within traps of the same design.

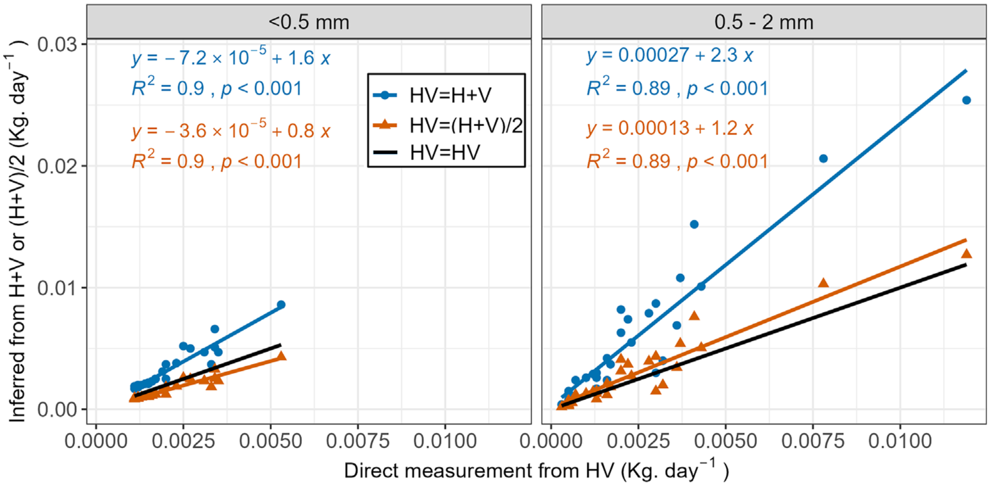

FIGURE 6 Linear regression between fine sediment ingress rates from HV against in H + V traps (1:1 and 2:1 proportions). Black lines correspond to the curve *y* = *x* (HV=HV). Points in the graph represent the mean taken from the triplicate measurements. [Color figure can be viewed at wileyonlinelibrary.com]

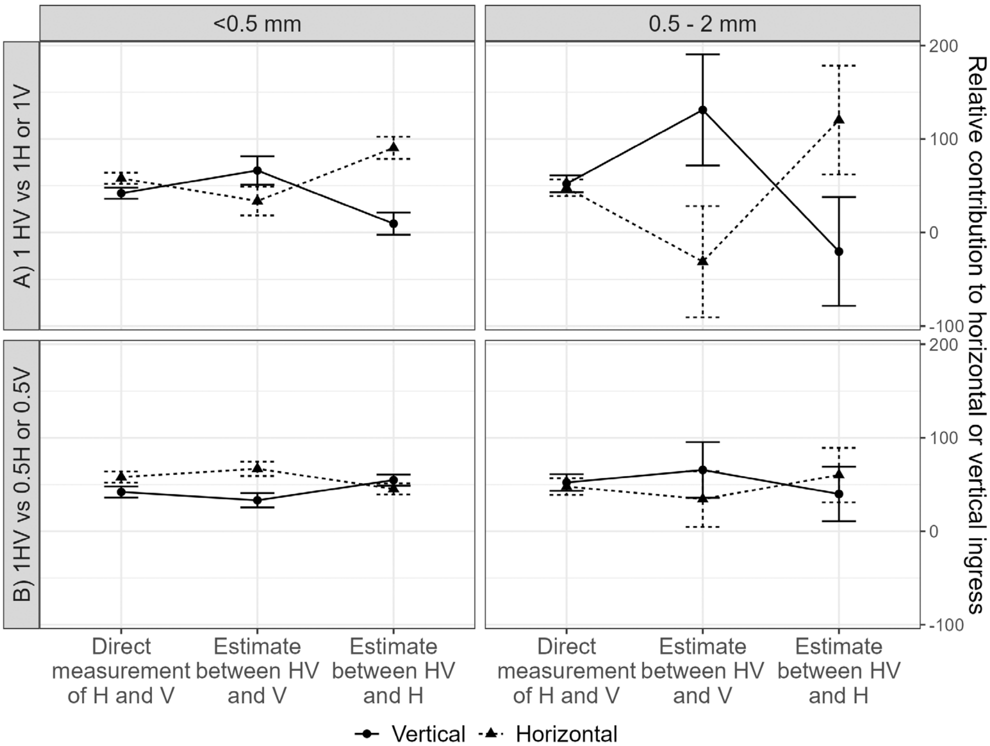

FIGURE 7 Assessment of ingress mechanisms (mean ± 1 SE). Paired estimates obtained by comparing fine sediment accumulation in: HV traps with accumulations in either H or V traps using a 1:1 proportion (a); and HV traps with either H or V traps using a 2:1 proportion (b).

Previous flume studies assessing turbulent flow interactions with gravel beds have shown that small-scale bed topography (such as protruding gravels) can increase turbulent mixing, leading to heterogeneous mass flux exchanges at the sediment–water interface (Reidenbach et al., 2010). As such, the observed high variability in ingress measurements can be partially attributed to the flow-sediment interactions in this gravel-bed river leading to naturally high measurement variability. However, it is also likely that the artificial gravel structure and altered bed roughness created during trap deployment (Casas-Mulet et al., 2017; Harper et al., 2017) have inflated natural variability. Since high variability was also observed in H traps, which were kept lidded, our observations demonstrate that even the slightest differences between gravel organization inside and around the traps were able to affect ingress measurements. The utilization of clean gravels (>2 mm) for the assessments is also an inherent methodological challenge of sediment traps, as it has been observed to replicate unnatural conditions of infiltration, with higher porosity increasing infiltration rates (Petticrew et al., 2007). Accordingly, the length of the deployment cycle can also affect the measured accumulations, given that shorter cycles will have the clean gravel effect inflated, while longer cycles might replicate a closer-to-natural framework setting (Harper et al., 2017). Long deployment periods, however, have been observed to increase interstitial clogging (Harper et al., 2017). Here, we did not observe any significant relationships between ingress measurements and deployment length, and no gravel clogging was observed to develop within our study period. These observations highlight the intrinsic methodological challenges of assessing fine sediment ingress with sediment traps. Our results demonstrate that the deployment of replicates, which are not commonly observed in field assessments, can help improve measurement accuracy, especially regarding sand fractions.

4.2 | The effects of trap design on fine sediment ingress

In this study, we sought to understand the differences between sediment trap designs according to particle size at a range of flow conditions. To the best of our knowledge, no other studies have investigated sediment ingress using three sediment trap designs (HV, H, and V), and the only methodological evaluation of such samplers has been conducted by Harper et al. (2017). As observed in this study and demonstrated elsewhere (Casas-Mulet et al., 2017; Harper et al., 2017; Mathers & Wood, 2016; Petticrew et al., 2007), different trap designs might lead to significantly different ingress rate measurements. These differences in measurements can occur due to the predominance of either vertical or horizontal ingress mechanisms, but they can also occur due to the inherent nature of each design since natural flow pathways are altered differently according to trap design (Harper et al., 2017).

Here, differences between samplers regarding 0.5–2 mm particles were only significant when considering the effects of deployment cycle (Table 2, Figure 7), which we believe might be related to the high variability observed across samplers for this size class. On the other hand, for particles <0.5 mm, differences between trap designs were significant both independently and as a function of deployment cycle (Table 2, Figure 7). In accordance with our observations, Mathers and Wood (2016) found no significant differences between HV and V-like trap designs regarding the accumulation of 1–2 mm particles, while the opposite was true for smaller particles. Conversely, Harper et al. (2017) observed a significantly higher accumulation of particle sizes 0.125–2 mm in HV rather than in V-like traps, but no significant differences were observed for <0.125 mm particles. Although Harper et al. (2017) observed such size effects, they did not observe significant differences between traps according to the proportions of size class, indicating that differences were simply due to the higher mass accumulated in HV traps (a clogging or "bridging" layer developed on their V traps, preventing further ingress). Here, in contrast with their observations, no clogging formed in our samplers, and significant differences between trap types regarding the proportions of size classes were observed (Table 3). The observed proportional differences found in our study indicate that trap type indeed influenced the size distributions of ingressed fine sediment.

Here, differences between traps were observed to change as a function of particle size and deployment cycle, reflecting the hydro-sedimentological regime of the sampling period. In this study, the discussion is focussed on the methodological perspective of observed differences, but further research is required to investigate the effects of hydro-sedimentological drivers on ingress rates and mechanisms.

4.3 | Inferring sediment ingress mechanisms as a function of retrievable trap design

Several studies have relied on the paired deployment of different designs of sediment traps (HV paired with either H or V) to estimate vertical and horizontal contributions of fine sediment (Casas-Mulet et al., 2017; Harper et al., 2017; Mathers & Wood, 2016; Petticrew et al., 2007; Sear, 1993). However, in a methodological evaluation regarding paired deployments, Harper et al. (2017) inquired whether such assessments truly capture directional ingress mechanisms, considering the artificial conditions imposed by ingress traps (altered gravel porosity and interstitial flow pathways according to each trap type). Therefore, this study sought to explore the comparisons between HV with either H or V sediment traps to investigate whether directional ingress mechanisms could be assessed through paired deployment.

Here, we observed higher errors in the estimation of ingress mechanisms when comparing accumulated fine sediment on a 1:1 proportion—especially for the 0.5–2 mm size fraction (Figure 7a). We also observed bias in the estimations of ingress mechanisms using the 1:1 proportion, in which paired deployments between HV and V, and HV and H overestimated vertical and horizontal ingress mechanisms, respectively (Figure 7a). This overestimation, which has also been observed by Casas-Mulet et al. (2017), occurs when HV traps accumulate less fine sediment than H or V traps, leading to estimations of horizontal or vertical mechanisms to be >100%. For instance, if H traps accumulated more than HV, we would infer that >100% of ingress would have occurred due to lateral movements, consequently leading to the inference of zero vertical ingress. However, out of 168 observations (averaged measurements from triplicate sampling), 41 registered higher accumulation in H or V, compared to HV traps. Our observations suggest that H or V traps are not accumulating more fine sediment because those mechanisms are predominant but because HV traps are more susceptible to fine sediment flush due to turbulent mixing since these traps have higher connectivity to both lateral and vertical flows (Casas-Mulet et al., 2017; Harper et al., 2017; Tonina & Buffington, 2009). Furthermore, the 1:1 comparison of HV with either V or H traps might be misleading since HV traps measure two ingress mechanisms under the same control volume, whereas H or V traps measure only one. The errors in ingress mechanisms decreased for both size classes when performing assessments using a 2:1 proportion (Figure 7b). The 2:1 proportion also eliminated the bias through paired deployments between HV and V, although it did not eliminate it in deployments between HV and H (Figure 7b).

4.4 | Standardization of fine sediment ingress measurements and future assessment suggestions

In this study, we observed a good agreement when comparing HV measurements with H + V (on a 2:1 proportion; Figure 6). However, because inferences between HV with either H or V can result in inevitable biases due to the higher flow connectivity in HV traps, direct assessments through H and V traps led us to a better assessment of ingress directional mechanisms. We highlight that no clogging was observed in this study, and its occurrences could have compromised the assessment of directional mechanisms, as observed elsewhere (Harper et al., 2017). As such, in environments where fine sediment regimes might lead to clogging on V-like sediment traps, paired deployments between HV and H traps could be recommended instead. Therefore, the determination of what sediment traps to use in future assessments might rely on a general background understanding of the local fine sediment dynamics including evidence for "bridging." Furthermore, deploying all three types of traps might lead to more thorough investigations, considering the complexity of ingress processes.

Furthermore, ingress rates have been commonly reported in terms of kg.day^{-1}.m^{-2}, as such rates allow for temporal and spatial normalization when comparing fine sediment accumulation. However, other than traps like the V samplers used in this study, the accumulation area of other trap designs might not be limited to their top surface. Accordingly, defining a lateral accumulation area for trap designs such as HV and H, is challenging since the perforated openings on the lateral or the lee sides of the traps might also lead to fine sediment exfiltration. Consequently, ingress comparisons between different studies should consider and regard the methodologies applied elsewhere since accumulation areas can affect normalized ingress rates.

5 | CONCLUSIONS

There has been growing interest in the literature in improving knowledge on fine sediment ingress and its directional infiltration mechanisms. Reliable measurements, which depend on accurate methodologies, are needed to refine fine sediment transport models, which, in turn, are required to inform land use management practices. As such, measurement techniques need to be better understood to reproduce precise and comparable results. To the author's knowledge, this is the first study to measure the variability of ingress using sediment traps with differing designs. All trap designs presented high variability, which could be due to natural variability in ingressing particles, but it is likely being inflated due to the inevitably altered channel bed roughness when deploying samplers. Here, we observed important differences in sediment trap design according to particle size and deployment cycle, and future studies are required to investigate the hydro-sedimentological drivers of such differences in ingress processes. This study demonstrated that ingress mechanisms were well measured with H and V traps, but paired comparisons with HV generated less reliable results. Such paired comparisons might be further compromised in investigations where high ingress rates result in clogging of gravel interstices in V traps.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

R. Maltauro https://orcid.org/0000-0001-8864-3964
M. Stone https://orcid.org/0000-0001-8085-8231
A. L. Collins https://orcid.org/0000-0001-8790-8473
B. G. Krishnappan https://orcid.org/0000-0002-2947-7318

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