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RESEARCH ARTICLE

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The HydroEcoSedimentary tool: An integrated approach to characterise interstitial hydro-sedimentary and associated ecological processes

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Abstract

Increased deposition of fine sediments in rivers and streams affects a range of key ecosystem processes across the sediment–water interface, and it is a critical aspect of river habitat degradation and restoration. Understanding the mechanisms leading to fine sediment accumulation along and across streambeds and their effect on ecological processes is essential for comprehending human impacts on river ecosystems and informing river restoration. Here, we introduce the HydroEcoSedimentary tool (HEST) as an integrated approach to assess hydro-sedimentary and ecologically relevant processes together. The HEST integrates the estimation of sedimentary processes in the interstitial zone, as well as hydraulic, geochemical and ecological assessments, with a focus on brown trout early life stages. Compared to other methods, the HEST expands the possibilities to monitor and quantify fine sediment deposition in streambeds by differentiating between vertical, lateral and longitudinal infiltration pathways, and distinguishing between the depth (upper vs. lower layers) at which interstitial processes occur within the sediment column. By testing the method in two rivers with different degrees of morphological degradation, we detail the possible measurements and uses of the HEST, demonstrate its feasibility and discuss its reliability.

KEYWORDS

aquatic conservation, fine sediment infiltration, fish egg survival, freshwater biomonitoring, hyporheic flow, river restoration, streambed deposition, water–sediment interface

1 | INTRODUCTION

The increased deposition of fine sediments in streambeds is a critical aspect of river habitat degradation, exacerbated by anthropogenic activities and posing severe threats to freshwater ecosystem biodiversity (Knott, Mueller, Pander, & Geist, 2019; Lummer, Auerswald, & Geist, 2016; Reid et al., 2019; Sear, 1993; Wood & Armitage, 1997). Although transport and deposition of fines into gravels are natural processes facilitating streambed development (Frostick, Lucas, & Reid, 1984; Naden et al., 2016; Packman & MacKay, 2003), activities such as river regulation, channelization and land-use change modify the natural longitudinal connectivity of rivers, the lateral connection to their floodplains and the vertical exchange between the surface and adjacent groundwater (Allan, 2004; Auerswald & Geist, 2018; Petts & Gurnell, 2005; Prosser et al., 2001; Wilkes et al., 2019; Wohl et al., 2015).

High fine sediment deposition affects a range of key ecosystem processes across the sediment–water interface, including water,

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oxygen and nutrient exchange (Findlay, 1995; Soulsby, Youngson, Moir, & Malcolm, 2001), microbial activity (Nogaro, Datry, Mermillod-Blondin, Descloux, & Montuelle, 2010), primary production (Jones, Duerdoth, Collins, Naden, & Sear, 2014), as well as the integrity of macroinvertebrate (Buendia, Gibbins, Vericat, Batalla, & Douglas, 2013; Descloux, Datry, & Marmonier, 2013), and fish communities (Duerregger et al., 2018; Greig, Sear, & Carling, 2005; Kemp, Sear, Collins, Naden, & Jones, 2011; Sternecker, Denic, & Geist, 2014). Understanding the mechanisms leading to fine sediment deposition along and across streambeds and their effects on ecological processes are therefore essential for comprehending human impacts on river ecosystems and inform river management (Denic & Geist, 2015; Haimann et al., 2018; Owens et al., 2005; Pander, Mueller, & Geist, 2015a; Ward, Tockner, Uehlinger, & Malard, 2001).

Local accumulation of fines in streambeds results mostly from gravitational deposition of the suspended load (Boano, Revelli, & Ridolfi, 2011; Frostick et al., 1984). Depending on the surface hydraulic conditions, such deposited fines can be settled, stored, infiltrated into the streambed or resuspended back to the water column (Casas-Mulet, Alfredsen, McCluskey, & Stewardson, 2017; Stewardson et al., 2016; Wharton, Mohajeri, & Righetti, 2017). Pressure gradients at the sediment–water interface may promote vertical and horizontal (lateral and longitudinal) interstitial hydrological exchange and transport along and across the upper and lower sediment layers of the streambed (Boudreau & Jorgensen, 2001; Brunke, 1999; Casas-Mulet, Lakhanpal, & Stewardson, 2018; Hassan, Tonina, Beckie, & Kinnear, 2015).

Among all available field methods to monitor sediment deposition in rivers (see detailed reviews in Akoumianaki, Cooksley, & Dodd, 2016; Naden et al., 2003; Rex & Carmichael, 2002), streambed traps are the most commonly used method to quantify accumulation rates over a known time interval (Franssen, Lapointe, & Magnan, 2014; Frostick et al., 1984; Greig et al., 2005; Lachance & Dubé, 2004; Petticrew, Krein, & Walling, 2007; Schindler Wildhaber, Michel, Burkhardt-Holm, Bänninger, & Alewell, 2012; Sear, 1993; Soulsby et al., 2001; Zimmermann & Lapointe, 2005). However, despite the growing evidence that lateral transport is an important component contributing to fine sediment deposition, few trap designs differentiate between vertical and horizontal (lateral and longitudinal) infiltration pathways (Casas-Mulet et al., 2017; Harper et al., 2017; Mathers & Wood, 2016). The depth at which interstitial processes occur along the sediment column (e.g., upper or lower sediment layers) has also shown to be very relevant for vital ecological processes (e.g., Casas-Mulet et al., 2018; Casas-Mulet, Alfredsen, Brabrand, & Saltveit, 2015; Casas-Mulet, Saltveit, & Alfredsen, 2015). Still, it is not usually taken into account in field assessments. In addition, it is rare to find a field method that incorporates the measurement of both ecologically relevant and sedimentary processes together (but see Duerregger et al., 2018; Mathers & Wood, 2016; Pander, Schnell, Sternecker, & Geist, 2009).

To help address these gaps in field assessment methods, here, we introduce the HydroEcoSedimentary tool (HEST). This field tool provides an integrated estimation of sedimentary processes in the interstitial zone, combined with hydraulic, geochemical and ecological assessments. The sedimentary evaluation focuses on the infiltration of fines (<2 mm) across the sediment column depth (upper and lower sediment layers), and from both the vertical (top-down from the water column) and horizontal (including each longitudinal and lateral subsurface transport of fines) directions. The hydraulic assessment focuses on hydraulic conductivity and includes continuous monitoring of temperature and point measurement of key physico-chemical parameters known to be crucial for aquatic organisms' survival and development. Finally, the ecological assessment targets brown trout (*Salmo trutta*) embryo survival as a key biological indicator of streambed quality (e.g., Acornley & Sear, 1999; Kondolf, 2000; Malcolm & Youngson, 2003; Pander et al., 2009; Soulsby et al., 2001).

By carrying out the first assessment in two morphologically different rivers in Germany, in this study, we detail the HEST methodology illustrating all the possible measurements and uses of the tool, discussing its feasibility and reliability. Specifically, we aim at testing the following hypotheses:

1. A clear difference in fine sediment input will be detected between:
   a. Lateral, longitudinal and vertical HESTs, with higher sediment inputs expected in the vertical HESTs given the dominance of gravitational deposition,
   b. Top and bottom compartments, with higher inputs expected in the upper layers, given the greater influence of surface hydraulics.
2. A minimum number of replicates for each HEST types should suffice to detect differences in fine sediment input.
3. Higher sediment deposition will lead to greater brown trout embryo mortality through reduced water quality.

2 | MATERIAL AND METHODS

2.1 | HEST approach and technical details

The HEST was designed to enable the differentiation of sediment layers (top and bottom) while ensuring minimal fine sediment loss during retrieval. We used three interlocked containers made of AUER Packaging® (AUER Packaging GmbH, Amerang, Germany) lightweight and impermeable plastic with solid construction to achieve this goal. Each HEST consisted of a shorter container (H: 15 cm, D: 22.6 cm) for the upper compartment, and two taller containers (H: 19 cm, D: 22.6 cm) for the lower compartment and for the cover enabling opening and closing procedures that warranted minimal fine sediment loss upon retrieval (Figure 1). The HESTs integrate elements from the tools tested in Lachance and Dubé (2004) and Casas-Mulet et al. (2017), specially purposed to avoid the loss of fines during collection and retrieval, and provide a step towards the integral assessment of multiple pathways of sediment exchange, respectively.

We constructed two types of HEST, one focussed on horizontal (longitudinal, L and lateral, X) and the other on vertical (V) fines infiltration direction. For the horizontal HESTs, we cut two rectangular

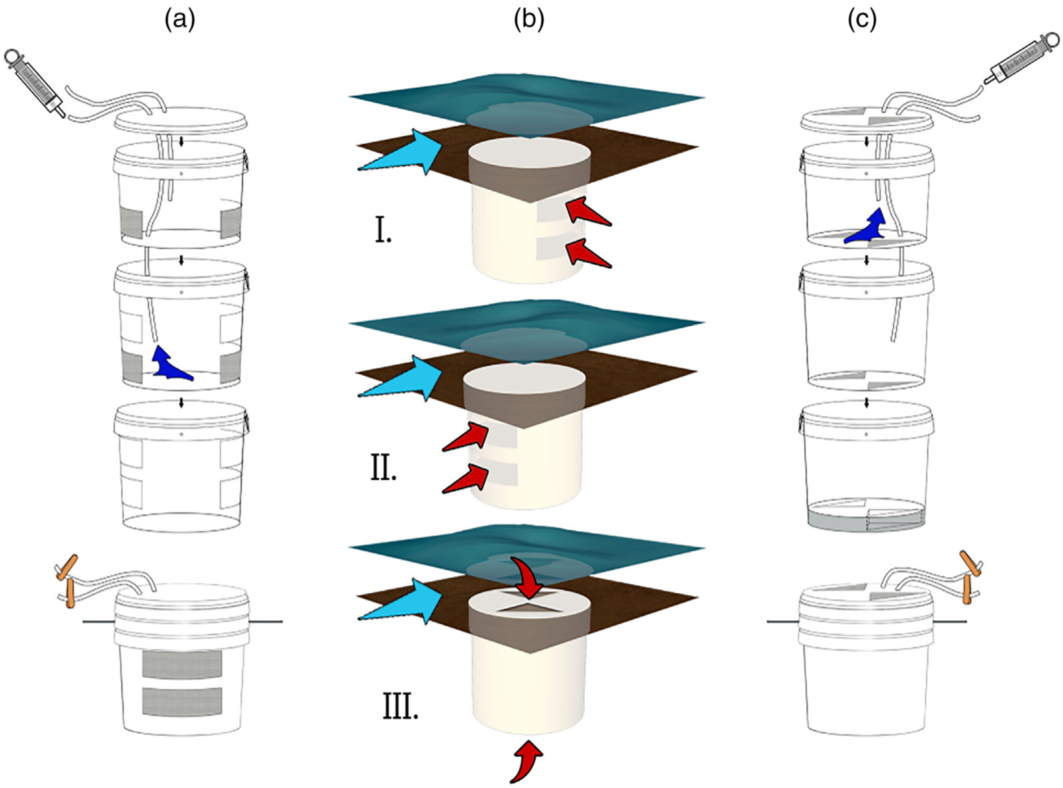

FIGURE 1 HEST structure and components for the lateral, X, and longitudinal, L (a) and vertical, V (c) designs. Operation of each of the designs and positions (lateral [X], I; longitudinal [L], II; and vertical [V], III) once installed at streambed level (b). Light blue arrows indicate the flow direction and red arrows indicate the infiltration direction. Dark blue arrows indicate the water inside the trap suctioned by the syringe [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Measurements used for the construction of the HEST

Infiltration	Compartment	Height (m)	Lower diameter (m)	Opening shape	Opening dimensions (cm)	Infiltration area (m^2)
Vertical	Top	0.15	0.199	Triangle	12.7S × 5.66H	0.0072
	Bottom	0.19	0.195	Triangle	15.5S × 5.76H	0.0072
Horizontal	Top	0.15	0.199	Rectangle	15.4W × 4.7H	0.0072
	Bottom	0.19	0.195	Rectangle	15.4W × 4.7H	0.0072

Note: Note on opening dimensions: S: side, H: height, W: width.

apertures of 15.4 × 4.7 cm^2 dimensions in the upper and lower compartments. For the vertical HESTs, we cut triangular apertures in the cover and bottom of each cylinder, which were the same area as the rectangular apertures used in the horizontal HESTs (Table 1). We covered each of the apertures with Jaera® perforated metallic plates (2 mm diameter round holes, JAERA GmbH & Co. KG, Laatzen, Germany) glued from the inside of the containers to allow the infiltration of fines, here defined as inorganic and organic material <2 mm.

In order to extract water samples from the HESTs upon installation, we inserted a 1.5 m long Sahleberg® TubeTec silicon tubing of 4.5 and 6 mm inner and outer diameter, respectively (Sahleberg GmbH, Feldkirchen, Germany) in each of the top and bottom components of the HEST. A sturdy plastic tube fitting the soft silicon was inserted at the inner end to keep the silicon tube in place. The outer end of the silicon tubing was sealed with labelled IKEA® kitchen bag clips to prevent the intrusion of surface water upon installation. The tubes allowed the suction of multi-level interstitial water with the aid of a syringe (Figure 1).

2.2 | Study sites

We tested the HEST in two Bavarian rivers in south Germany, the pre-alpine river Moosach, a tributary of the river Isar in Freising and the secondary floodplain Zeller channel, located on the right bank of the Danube floodplain, near Ingolstadt (Figure 2a). The river Moosach is characterised by dominant groundwater flowing through an entirely artificial bed of almost rectangular cross-section due to persistent

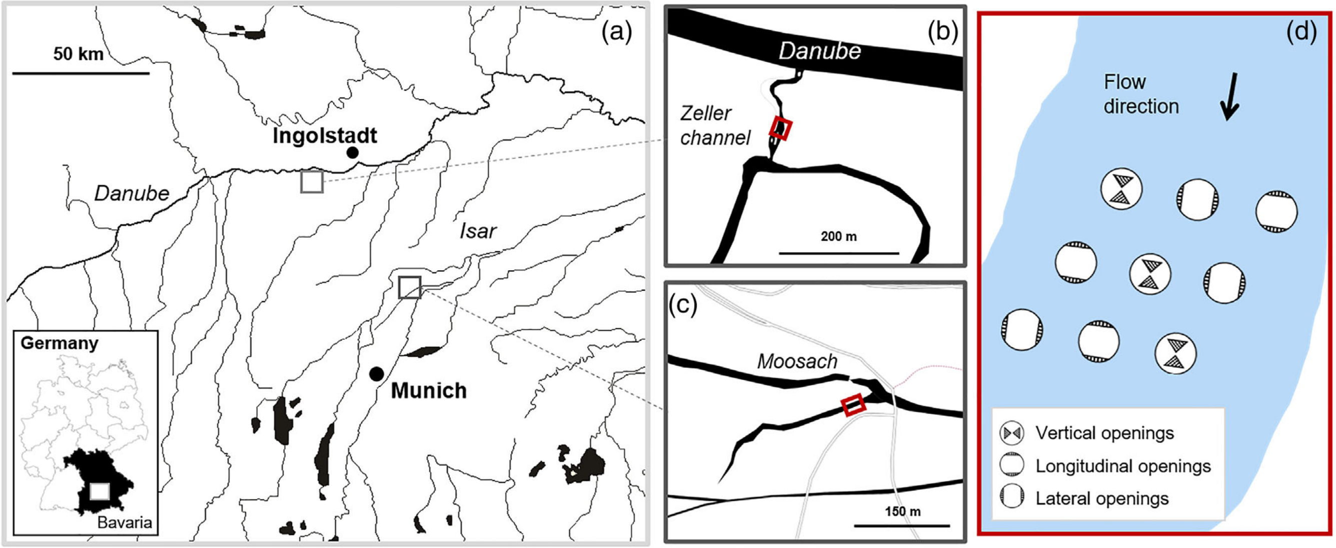

FIGURE 2 Geographic location of the study sites in the context of Germany, Bavaria (a); in relation to the Danube (b) and the Moosach (c) rivers, and configuration of the samples at the site taking the Zeller channel as the example (d) [Color figure can be viewed at wileyonlinelibrary.com]

anthropogenic activities leading to heavy siltation (Auerswald & Geist, 2018; Sternecker, Wild, & Geist, 2013). At the experimental site, the Moosach presents a ca. 5 m width gravel streambed exposed to high amounts of fines (Figure 2c). The Zeller channel, in contrast, lies in one of the largest remaining alluvial forests in the Danube system (Stammel et al., 2012). It is part of a floodplain restoration program started in 2010, aiming at reconnecting the main Danube with its historical floodplain, increasing groundwater dynamics and providing additional habitat for keystone organisms (Pander, Mueller, & Geist, 2015b; Pander, Knott, Mueller, & Geist, 2019; Stammel, Fischer, Gelhaus, & Cyffka, 2016, Stammel et al., 2012). The Zeller channel is 10 m wide, dominated by gravel and characterised by a highly dynamic morphology resulting in the formation of small islands and emergent side bars (Figure 2b). Nine HESTs, including three replicates of each V, L and X infiltration directions, were installed at each of the two sites, along and across a riffle section, over an approximate area of 5 m width by 10 m length. The installation setup allowed an extensive separation between HESTs, as recommended in Braun, Auerswald, and Geist (2012), to ensure each was independent of one another (Figure 2d).

2.3 | Preparation, field installation and operation

Before field installation, each HEST was pre-filled with non-homogeneous fine-free gravel, ranging from >2 to <63 mm in particle size. We followed granulometry curves from each river's natural streambed material, described in Pander et al. (2015a) for the Moosach; and in Pander et al. (2015b) for the Danube, to mimic the corresponding sediment fractions at each site. We used commercial fine-free gravel that mimicked preferred spawning grounds for brown trout.

For the Zeller channel samples only, we inserted eye-point stage brown trout eggs from a nearby fish farm (Forellenhof Nadler, Eching, Germany) in the HESTs to assess their survival (Figure 3). Eggs were stripped from the parental fish on November 14, 2018. After receiving the eggs, they were acclimatised, dead eggs were removed and the remaining live eggs were distributed into the HESTs. A small pit was formed in the sediment inside each HEST compartment into which 30 eggs were placed and carefully covered with the remaining sediment in the compartment. In addition, we installed one HOBO® temperature logger inside each HEST compartment to assess thermal changes in the streambed. Once ready, the full HESTs were kept submerged in a tank with aerated water, so the quality of the eggs was preserved during transport and until their installation 12 hr later. A reference HEST carrying 100 eggs in each compartment was used to assess the potential impact of transport on the eggs. We handled and transported the reference in the same way as the rest of the samples and checked it upon return on the same day. The reference showed 100% survival for all eggs, with no signs of negative impacts. The results of the test support the literature in that mechanical stress caused by this step has no or very little adverse effect on egg survival (Barlaup & Moen, 2001; Sternecker & Geist, 2010).

At each site, we installed the HESTs into the streambed following the composition indicated in Figure 2d. A hole big enough to fit each of the HESTs was dug, keeping disturbance of the surrounding streambed to a minimum. We inserted each HEST with their top at the surface gravel level, and coarse sediment was used to fill the gap between the hole and the HEST walls. The HESTs were installed in closed mode to avoid unstable fines infiltrating during the process and were opened to start the experiment after all fines were settled (Figure 3). The lateral and longitudinal HEST had covers sealing the top of the container. They were installed in a manner that, upon opening the meshed apertures, the exchange from the river to inside the

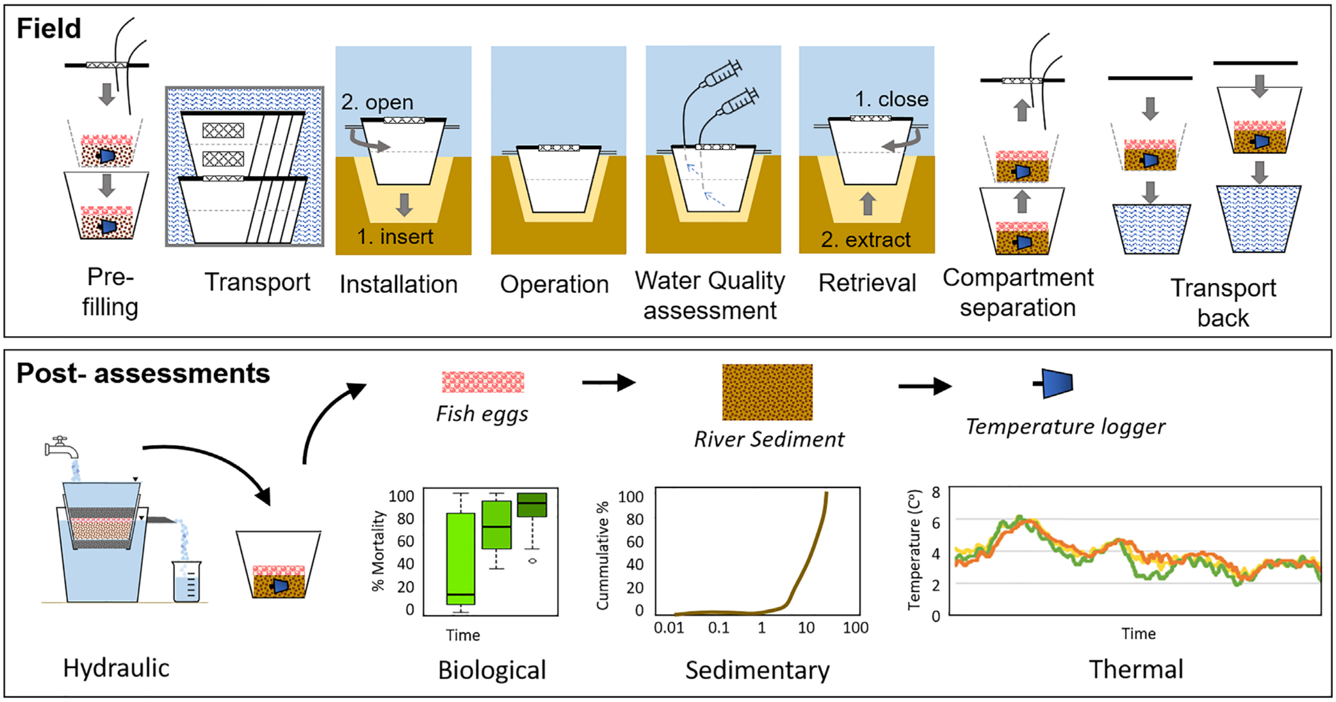

FIGURE 3 Installation, operation and assessment of the data obtained using the HydroEcoSedimentary tool (HEST) [Color figure can be viewed at wileyonlinelibrary.com]

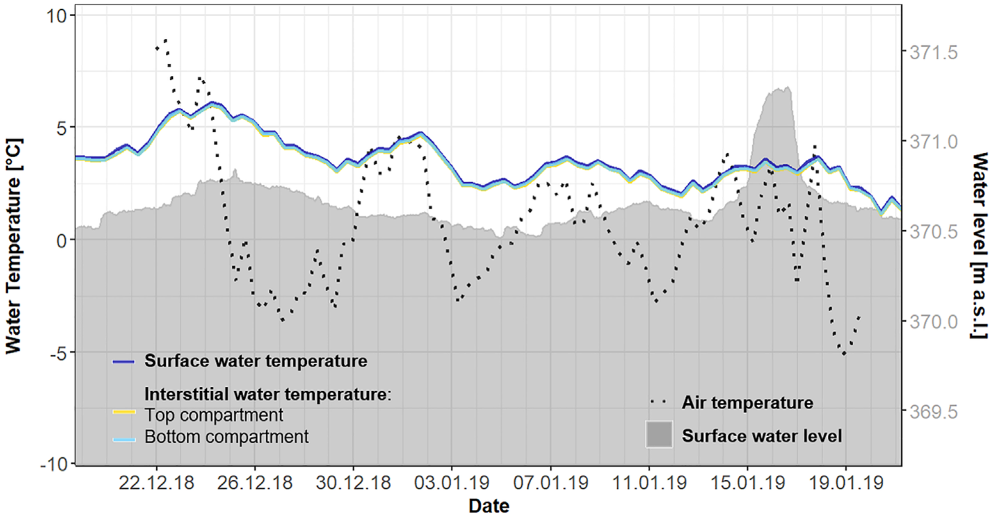

FIGURE 4 Illustration of air and water temperatures and water levels in the Zeller channel. Water temperatures are illustrated both for surface and interstitial the interstitial and surface waters of the Zeller channel, against air temperature (obtained from the weather station at the AuenZentrum Neuburg-Ingolstadt), during the study duration. *Note:* One single sample of longitudinal HEST has taken as an example, for summary data, see Table 3 [Color figure can be viewed at wileyonlinelibrary.com]

HEST could only happen in the lateral and longitudinal direction, respectively (Figure 1b).

We installed the HESTs on September 14, 2018 in the Moosach, and December 18 the same year, in the Zeller channel, and they remained there for 33 and 34 days, respectively. Upon retrieval, the openings of each HEST were closed by turning the collectors' covers (Figure 3). We retrieved all HESTs successfully. Detailed hydrology and water temperatures during the study period in the Zeller channel site are illustrated in Figure 4, while water depth and river bed velocity data at each HEST at the time of installation and retrieval are summarised in Table 2.

2.4 | Hydro-sedimentary assessment

2.4.1 | Hydraulic conductivity

Hydraulic conductivity describes the flow of water through a saturated porous medium such as the streambed. It indirectly assesses its permeability, and it is an important indicator of exchange processes between groundwater and surface water in gravel beds (Freeze & Cherry, 1979). We estimated hydraulic conductivity for the 18 HEST compartments (nine tops, nine bottoms), retrieved from the Zeller channel site. We carried out the assessment immediately upon

TABLE 2 Hydraulic boundaries measured at the top of each HEST

		Depth (m)			Velocity ($m.s^{-1}$)		
		Min	Mean	Max	Min	Mean	Max
Zeller channel	Vertical HEST	0.10	0.12	0.13	0.28	0.39	0.47
	Longitudinal HEST	0.13	0.15	0.17	0.57	0.59	0.61
	Lateral HEST	0.14	0.16	0.18	0.28	0.41	0.50

Note: Note that the presented values are the average of the replicates for each treatment ($n = 3$).

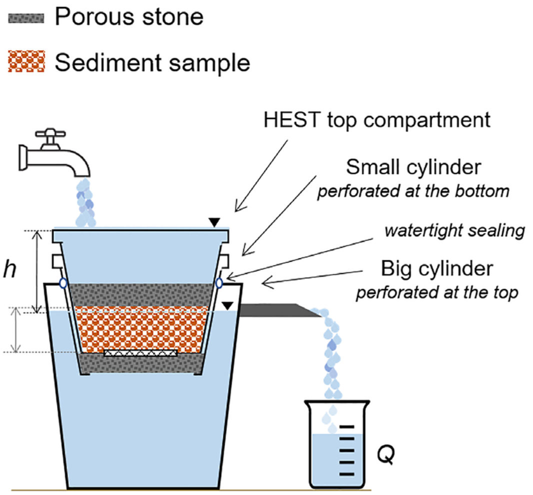

FIGURE 5 Illustration of the hydraulic conductivity measurement for the top compartment of the vertical infiltration HEST. The constant-head method is based on Darcy's law, with a continuous water level being maintained over an undisturbed sample and detecting the volume of water flowing through it in a given time. *Note:* Q refers to the volume of water collected at the outlet in cm^3, L is the height (cm) of the sediment sample (in brown) between the top and bottom porous stones (in grey), and h (cm) is the head difference between the inlet and outlet water levels (indicated by small black triangles at the small and big cylinders, respectively) [Color figure can be viewed at wileyonlinelibrary.com]

retrieval on undisturbed samples before they were sorted for sedimentary and ecological assessments. We used a tailor-made setup for each of the vertical and horizontal infiltration HESTs, and the upper and lower compartments. The setup was based on the constant-head method described in Das and Sobhan (2014). It consisted of a 20 L plastic container with a hole in the lid to fit a perforated smaller container watertight sealed with silicone halfway through the hole, designed to insert the sediment compartment subject to assessment. The small container was of the exact size of the compartment to be assessed, and the big container had a small outlet installed at the level of the sediment sample to enable water to flow out (Figure 5). Each sediment sample was to be kept in their respective compartments and placed inside the corresponding top or bottom setup before the start of the assessment. In order to create an even distribution of the water flowing through the sediment sample and to help prevent the loss of fines during the procedure, two perfectly fitting porous stones, providing solid support at both ends of the sediment sample while allowing free passage of water, were inserted into the space between the sediment sample and the sealed small container and on top of the sediment sample (Figure 5). The water supply at the inlet was adjusted in such a way that the difference of head between the inlet and the outlet remained constant during the test period. After a constant flow rate was established, the water from the big container outlet was collected in a graduated flask for a duration of 30 seconds on three occasions to ensure results between runs were of the same order of magnitude (Figure 5). The hydraulic conductivity was then calculated for each sediment sample using the following equation:

$$k = \frac{QL}{Aht} \tag{1}$$

where k is the hydraulic conductivity in $cm.s^{-1}$, Q is the volume of water collected in cm^3, A is the area of cross-section of the sediment sample in cm^2, L is the length of the sediment sample in cm, h is the head difference between the inlet and outlet in cm, and t is the duration of water collection in seconds.

We determined the hydraulic conductivity of each sediment sample (top and bottom compartments) exposed to vertical infiltration both before field site installation and immediately after retrieval (Figure 3). Especially during the after retrieval assessments, we visually assessed whether any fines were lost in the process. The absence of any recorded visual turbidity in the withdrawn water during each experimental run illustrated a negligible loss of material and demonstrated the porous stones' efficiency to hold the sample.

To enable the contextualisation of the experimental results, we compared them to the computed results obtained by applying the Hazen Method as used in previous studies (e.g., Casas-Mulet et al., 2017; Franssen et al., 2014). The method calculates hydraulic conductivity (k) based on the grain-size composition of a given sediment sample:

$$k = 100(D_{10})^2 \tag{2}$$

where D_{10} refers to the diameter that corresponds to 10% of the sample material weight, and 100 is a constant used for gravel beds.

We compared the hydraulic conductivity values measured in the HESTs before installation and after field retrieval in the Zeller channel site, and they were both also compared to the calculated values obtained with the Hazen method.

2.4.2 | Fine sediment deposition

For each sediment sample retrieved from the field, the grain-size distribution of the entire material was determined through wet sieving (DIN, 1990), using an AS 200 Retsch sieving machine (Retsch, Haan, Germany) and fabric sieves ISO 3310-1. The sieves were of screen sizes 20, 6.3 and 2 mm, and a tank was placed under the sieves to allow finer fractions to settle before collection. The coarse fractions (>20 mm, >6.3 mm, 2 mm) were dried at air temperature for 24 hr, and the finer fractions (< 2 mm) were oven-dried at 100°C for 24 hr. Each fraction was then weighed using Dini Argeo (Dini Argeo S.r.l., Modena, Italy) scales, measured to the nearest 0.1 g.

Fine sediment (< 2 mm) deposition rates in each HEST were calculated in kilograms per day (kg.d^{-1}), and at each site, they were compared between infiltration directions (V, L and X), and compartments (top and bottom). The loss of fines sediments attributed to the HESTs retrieval process was tested and found not to be a major concern (see Appendix A for further details).

2.5 | Physico-chemical assessment

We assessed ecologically relevant physico-chemical parameters in situ for the interstitial water obtained from each HEST and the river surface water on two occasions: after installation and before retrieval. The interstitial water of each of the top and bottom compartments was extracted using a 100 mL, Omnifix Solo plastic syringe (B. Braun Melsungen AG, Melsungen, Germany). The syringe was connected to the silicone tubing with a tight closing, leading to a vacuum that enabled the water sampling by suctioning. The first 20 ml of water were discarded for the potential surface water influence. The next ca 50 ml of true interstitial water were immediately transferred to a clean 100 ml container in which several measuring heads of a WTW® Multimeter 340i (WTW GmbH, Weilheim, Germany) were inserted to assess temperature (°C), dissolved oxygen (mg.L^{-1}), electrical conductivity (μS.cm^{1}), and pH. In addition, turbidity (NTU) was assessed using some 10 ml sample water and a WTW® Turb 355 IR measuring set. All measuring heads, sets and bottles were rinsed with distilled water between data measurements to avoid cross-contamination.

The loggers installed inside each of the top and bottom compartments of the HESTs and the Zeller channel's water column allowed to record continuous (at 30 min intervals) temperature data.

Water quality values obtained for each HEST compartment were compared to surface water and known water quality thresholds for brown trout (Elliott, 1994; Jonsson & Jonsson, 2011). Interstitial and stream water temperature data obtained from the continuous logging devices in each of the HEST compartments were visually and analytically compared through basic statistic indicators.

2.6 | Ecological assessment: Brown trout embryo survival

After field retrieval and after hydraulic conductivity estimation, all HESTs were immediately assessed in the laboratory for egg and larvae survival. Each of the HEST compartments were opened carefully, data loggers and larger stones were removed, and the sediment contents were emptied into a tray, rinsed with water and examined for larvae and eggs. A distinction was made between live and dead eggs as well as between live and dead larvae, as described in Pander et al. (2009). Subsequently, the tray containing the sediment was rinsed with water several times and poured through a sieve to find any neglected embryo. All samples were preserved in a solution of 70% ethanol. All remaining sediment was then assessed, as indicated in Section 2.4.2.

Total mortality (%) was calculated as the difference between the surviving eggs or larvae, and the initially loaded eggs in each of the HESTs retrieved from the Zeller channel site. The results were compared between infiltration directions and compartments.

2.7 | Data analysis

Two-group comparisons were made via t-tests after using Shapiro–Wilk normality test and Levene test for homoscedasticity. For data that did not meet the requirements for parametric analysis, we used the non-parametric Wilcoxon test. For multiple-group comparisons, we first tested each dataset for normal distribution (Shapiro–Wilk test) and homoscedasticity (Levene test). If the data did not correspond to the assumptions to perform parametric ANOVA, the non-parametric Kruskal–Wallis test was applied to determine whether there were significant differences within the data sets. The subsequent *post-hoc* Wilcoxon test was used to determine whether samples differed significantly between compartments and/or infiltration directions.

To visualise differences in abiotic habitat conditions inside each HEST compartment (top and bottom) and for each infiltration direction (V, L and X), a principal component analysis (PCA) based on Euclidian distances was computed. The PCA allowed an overlay with the measured variables indicating the strength of correlation to the arrangement of HEST compartments in the ordination plot. The abiotic conditions in each compartment were linked to the detected mortality using a bubble plot with the size of the bubbles indicating the detected mortality in percentage (%). To test for statistically significant differences between compartments and infiltration directions, we carried out an analysis of similarity (ANOSIM).

For all data analyses, a significance level of $p \leq .05$ (=95% probability) was assumed. Data analysis was carried out in R (R Core Team, 2020) and in Primer v7 (Plymouth Marine Laboratory, Plymouth, United Kingdom).

3 | RESULTS

3.1 | Hydraulic conductivity

As expected, in both compartments, hydraulic conductivities before field installation were higher than after retrieval. Such results were significant for both the experimental and analytical comparisons. Experimental outcomes presented consistently lower hydraulic

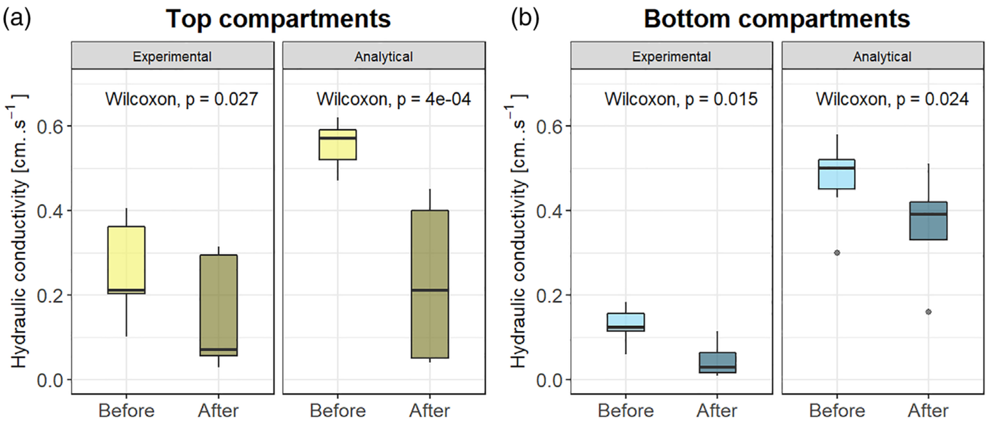

FIGURE 6 Comparison of experimentally measured and analytical computation of hydraulic conductivity (*k*) before installation and after retrieval at the Zeller channel site for (a) top, and (b) bottom compartments. Note that each boxplot combines the results of the tests carried out for all V, L and X HESTs (n = 9). For the experimental assessment, the resulting k of each n represents the average of the three runs [Color figure can be viewed at wileyonlinelibrary.com]

conductivity values than those calculated using the Hazen Method (Figure 6) but fell in the same order of magnitude. Differences between compartments were similar, illustrating a broader range of values in the top versus bottom. Analytical hydraulic conductivity values after retrieval were positively correlated with maximum river bed velocities ($R^2 = 0.8$, $p > .1$) and maximum depths ($R^2 = 0.5$, $p > .1$) at each HEST.

3.2 | Fines deposition

Fine sediment deposition rates were twice as high in the Moosach as they were in the Zeller channel (0.81 kg.m^{-2}.day^{-1} vs. 0.4 kg.m^{-2}.day^{-1}, on average). In terms of infiltration direction, although no significant differences were found in fine sediment deposition between HEST types, accumulation rates were higher in the six vertical compartments compared to the longitudinal and lateral ones (Figure 7a,b). Higher deposition rates were found in the nine top compared to the nine bottom compartments; however, such differences were only significant in the Moosach, and not in the Zeller channel site (Figure 7c, d). Overall, given the limited dataset, interpretation of the results needs to be made with care despite the shown trend.

3.3 | Interstitial water physico-chemistry

Water quality parameters measured through the silicone tubing installed in the HESTs illustrated values within thresholds of water quality requirements for brown trout. Between-site differences in water quality reflected the different natures of both sites, as expected. Within-site comparisons illustrate similar values between interstitial water extracted from the HESTs and surface water. Differences were minimal between temperature, pH and electric conductivity values. The greater differences were found in dissolved oxygen concentration and turbidity values, with no apparent patterns depending on infiltration direction or compartment location (Table 3). Continuous water temperature monitoring illustrated minimal differences between surface and interstitial (top and bottom compartments) water (Table 4, Figure 4).

3.4 | Brown trout eggs and larvae mortality

Mean mortality rates of brown trout eggs and larvae ranged between 38% and 70%. We found no significant difference at $p = .05$ in brown trout mortality rates between the top and bottom compartments, or between the three different infiltration direction treatments (Figure 8a,b). However, both mortality and sediment infiltration rates were higher in vertical HESTs compared to lateral and longitudinal, and such differences would have been significant at $p = 0.1$ (Figures 7b and 8a).

3.5 | Multivariate analysis of abiotic factors in relation to mortality

The PCA of all abiotic parameters measured in the HEST explained 91.4% (PC1 = 70.3% and PC2 = 21.1%) of the cumulative variation in the dataset using fines, turbidity, temperature, pH, electric conductivity, oxygen content and hydraulic conductivity as explanatory variables. Samples were clustered by compartment depths (top and bottom) and infiltration directions (V, L, X). Fine sediment content and turbidity correlated the strongest with the arrangement of samples in the plot (Figure 9). However, the ANOSIM test detected no statistically significant differences between the top and bottom compartments nor between infiltration directions V, L and X. Although not

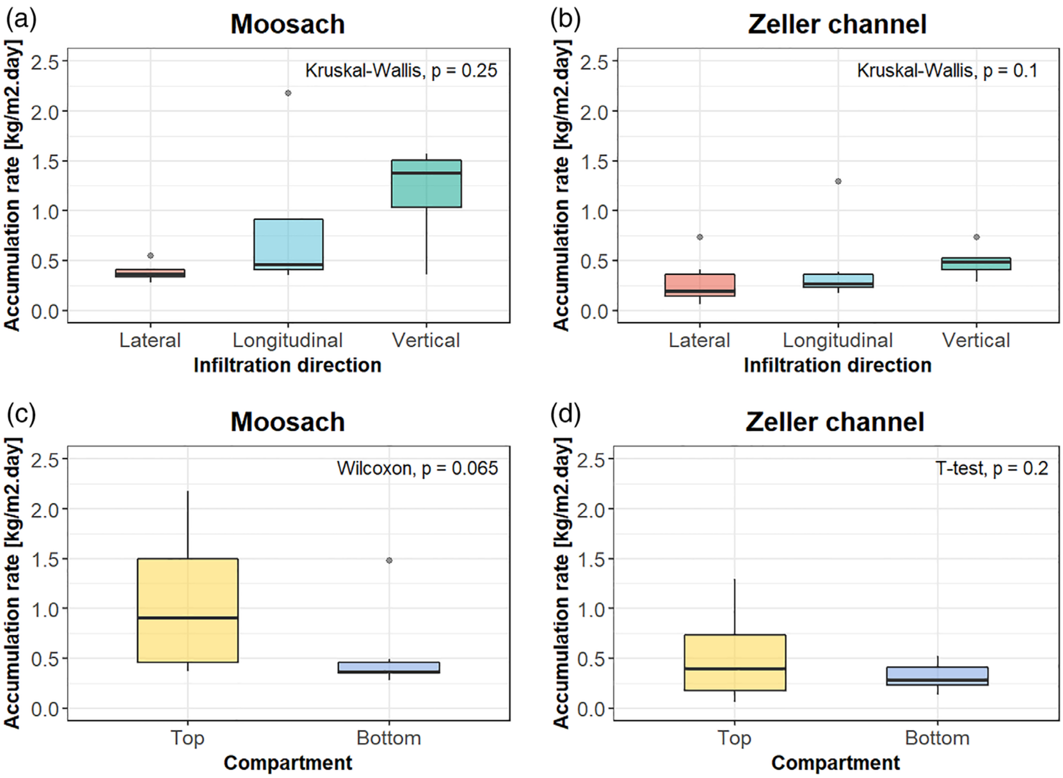

FIGURE 7 Accumulated fine sediment rates in the HESTs at each of the two sites. Panels a and b illustrate the three different infiltration directions lateral (X), longitudinal (L) and vertical (V), with each boxplot *n* = 6; and panels c and d present the top (T) versus bottom (B) compartments, with each boxplot *n* = 9 [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Ecologically relevant water quality parameters assessed at each of the sites, and include each HEST type and the surface flowing water

		Compartment	pH	Temperature (°C)	Conductivity (µS.cm^{-1})	O$_2$ (mg.L^{-1})	Turbidity (NTU)
Moosach	Vertical HEST	Top	8.0	12.4	765.0	8.5	510.6
		Bottom	n.d.	n.d.	n.d.	n.d.	n.d.
	Longitudinal HEST	Top	8.0	12.2	787.0	8.5	579.2
		Bottom	7.9	12.6	780.0	7.2	24.3
	Lateral HEST	Top	8.1	12.2	768.5	8.5	124.4
		Bottom	8.1	12.9	773.5	7.8	173.1
	Surface water	–	8.0	12.3	772.3	8.5	10.2
Zeller channel	Vertical HEST	Top	8.1	2.5	630.3	12.4	677.8
		Bottom	8.1	2.5	608.7	12.3	334.9
	Longitudinal HEST	Top	8.1	2.5	622.0	12.5	574.4
		Bottom	8.2	2.6	629.3	12.5	862.1
	Lateral HEST	Top	8.2	2.2	664.7	12.2	725.2
		Bottom	8.2	2.3	659.7	12.4	691.8
	Surface water	–	8.2	3.0	665.0	12.4	19.9

Note: The values presented for each HEST type are an average of the values obtained for each set of samples for each compartment (top and bottom) of each vertical, longitudinal and lateral HESTs. n.d., indicates no data as it was not possible to extract any water from these containers.

exclusively, higher mortality (70–100%) also seemed to occur in samples of high turbidity and fine sediment content, which align with the positive correlations found between these factors and mortality. However, only turbidity presented a significant ($p = .03$) positive correlation, and none of the factors illustrated a strong correlation ($R^2 = 0.2$ for fine sediment and $R^2 = 0.3$ for turbidity) with mortality.

TABLE 4 Water temperature differences derived from continuous monitoring in the Zeller channel for each temperature differences in the compartments

		Compartment	Min (°C)	Mean (°C)	Max (°C)
Zeller channel	Vertical HEST	Top	0.86	2.48	4.19
		Bottom	0.69	2.34	4.03
	Longitudinal HEST	Top	−0.51	1.12	2.82
		Bottom	−0.17	1.47	3.16
	Lateral HEST	Top	1.16	3.51	6.16
		Bottom	0.59	2.24	3.93
	Surface water	–	1.10	3.57	6.26

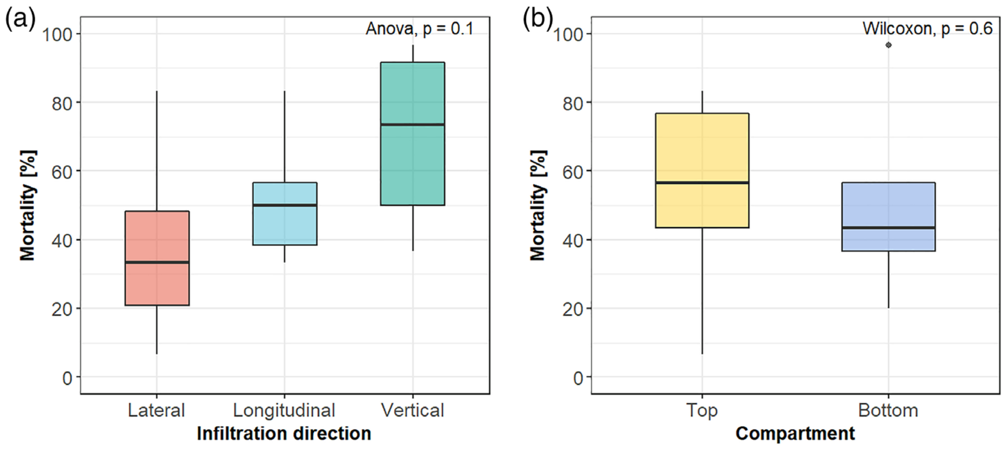

FIGURE 8 Brown trout eggs and larvae survival by HEST compartment (T and B) and infiltration direction (X, L and V), for the Zeller channel site [Color figure can be viewed at wileyonlinelibrary.com]

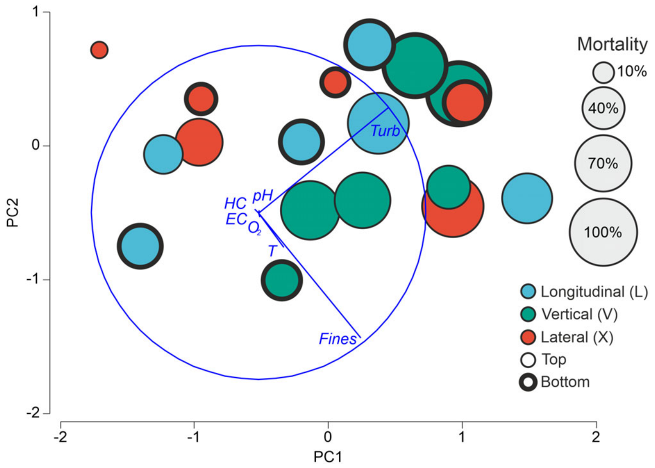

FIGURE 9 Principal component analysis (PCA) for the measured variables in each of the HEST compartments at the Zeller channel site. Variables include total weight of sediment content in grams (Fines), turbidity (Turb), temperature (T), pH value (pH), electric conductivity (EC), oxygen content (O_2) and hydraulic conductivity after field retrieval (HC). The measured variables are displayed as vectors in the graph. The length of the vectors corresponds to the strength of correlation, and the blue lined circle indicates 100% correlation. Mortality for each compartment is overlayed and expressed as a bubble plot. Note that the top and bottom compartments are differentiated with a bold line surrounding each circle representing a bottom compartment. The three fine sediment infiltration pathways of the HEST are indicated in blue (longitudinal, L), green (vertical, V) and red (lateral, X) [Color figure can be viewed at wileyonlinelibrary.com]

4 | DISCUSSION

Understanding fine sediment infiltration pathways leading to accumulation in streambeds is key to restoring dynamic processes in rivers (Auerswald & Geist, 2018; Knott et al., 2019; Sear, 1993). Given the indisputable links between physical habitat and ecological processes in rivers (Humphries, Keckeis, & Finlayson, 2014; Thorp, Thoms, & Delong, 2006; Vannote, Minshall, Cummins, Sedell, & Cushing, 1980) and the proven effects of fine sediments on biology (e.g., Jones et al., 2014; Jones, Collins, Naden, & Sear, 2012; Kemp et al., 2011), it is crucial to provide methods for an integrated sedimentary, hydrological and ecologically relevant assessment of streambed function. Here, we provide the HEST as an integrative tool to assess hydroecosedimentary processes in streambeds with a special focus on the infiltration depths and directions of fines, and the linkage to biological indicators, using brown trout eggs as a highly relevant example. The development of this tool has been driven by the need for understanding in-situ processes and mechanisms in streambeds. It presents a potentially powerful assessment tool to inform restoration projects in the way that it can help and detect sites in need of restoration, as well as provide objective monitoring of restoration success, both of which are crucial in evidence-based conservation and restoration (Geist & Hawkins, 2016; Palmer, Hondula, & Koch, 2014). In this paper, we illustrate the application benefit of the tool in two sites with different degrees of morphological degradation in Germany.

Overall, the installation, use and retrieval of the HESTs in both field sites were feasible. The tool was successful in simultaneously recording a set of key hydrosedimentary and ecologically relevant factors, illustrating its potential usability and reliability. A list of the most important features of the HESTs design and their up and downsides are discussed below:

The HESTs differentiate from the most traditional sediment trap designs focused on top-down or vertical infiltration (e.g., Hoess & Geist, 2020; Lachance & Dubé, 2004; Sear, 1993; Soulsby et al., 2001; Zimmermann & Lapointe, 2005) and provide an opportunity to differentiate it from horizontal (lateral and longitudinal) infiltration, which has recently been recognised as an important component contributing to fine sediment deposition (Casas-Mulet et al., 2017; Harper et al., 2017; Mathers & Wood, 2016). In addition, the inclusion of top and bottom compartments in the HEST design provides an additional insight to experimentally test the importance of near-bed versus depth infiltration and deposition processes (Casas-Mulet et al., 2017, 2018).

The experimental estimation of hydraulic conductivity in the HESTs before installation and after retrieval offers a promising approach to assess undisturbed sediment samples that can be considered a realistic hydraulic indicator. The results were aligned with the hydraulic conductivity values estimated with the Hazen method, and those were positively correlated with in-situ measurements of bottom velocities and water depths, suggesting slow local flows may lead to more deposition and, in turn, decrease the hydraulic conductivity. Acknowledging the simplicity and coarseness compared to other experimental methods (Diminescu, Dumitran, & Vuta, 2019), our estimation of hydraulic conductivity of field retrieved undisturbed sediment samples offers a valuable approach that can be perfected in the future.

The possibility of accounting for the loss of fines during retrieval failure and estimating hydrological factors with the HEST illustrates its additional usefulness and reliability. Although careful retrieval is always important (Lachance & Dubé, 2004), the consistent low difference in sediment loss between close and open HESTs showed that, in case of faulty retrieval, the loss of the fines could be easily accounted for by applying a correction ranging between 0.7 and 1.6% of fines loss (see details in Appendix A).

The extraction of water samples from the HESTs at different points in time allows to monitor water quality and test whether the conditions in the compartments are within ecological thresholds and/or whether they differ from surface water quality. Between-site water quality responded to expected patchiness in each stream subject to their distinctive geology, fluvial geomorphology and ecology (Auerswald & Geist, 2018; Braun et al., 2012; Stammel et al., 2012). In the Zeller channel, although interstitial water quality was within ecological thresholds and did not show significant differences with surface water and between samples, it was still useful to monitor key quality variables and to rule out any effect on mortality. The inclusion of a temperature logger inside each HEST compartment, for example, could be extremely important to detect local groundwater input over time, which has been demonstrated to have a significant effect on embryo salmonids elsewhere (e.g., Malcolm et al., 2009).

In this study, the use of the ecological part of the HEST assessment was focused on brown trout egg survival. However, other target species or life stages of organisms living in the interstitial could be targeted. Moreover, the HEST can also be used as a standalone hydrosedimentary or sedimentary assessment, focusing on sediment infiltration, illustrating the flexible use of the tool and its applicability and possible broad use.

Regarding the specific hypotheses tested in this study with the use of the HESTs, the following discussion points should be highlighted:

Higher sediment inputs were found in the vertical HESTs and top compartments, compared to horizontal (longitudinal and lateral) HESTs and bottom compartments, respectively. Although these differences may potentially demonstrate that surface hydraulic processes dominate sediment accumulation via gravitational deposition (Casas-Mulet et al., 2017, 2018), the results were not statistically significant in neither of the cases. Although the first hypothesis cannot be confirmed for our experimental site, the HESTs design and approach can provide valuable information on hyporheic exchange in sites with high groundwater inputs. For example, it could be used as a screening approach to identify specific assessment locations in systems that have complex groundwater–surface interactions.

The minimum number of replicates for each HEST type and compartment ($n = 3$) was sufficient as a proof of concept to illustrate general patterns of sedimentary processes occurring in two highly contrasting streams, and to illustrate differences between treatments. However, we recommend increasing the number of HEST replicates to allow a statistically reliable interpretation of the results. Specifically, the minimum number of replicates could be used as a test in a specific stream before deciding if a broader resolution is necessary.

Our study did not provide significant evidence that salmonid embryo mortality could be linked to high fine deposition in gravel beds via reduced water quality (Crisp, 1996; Greig et al., 2005; Pander et al., 2009; Soulsby et al., 2001); or that such mortality is explicitly linked to interstitial depths (e.g., Casas-Mulet, Saltveit et al., 2015; Casas-Mulet, Alfredsen, et al., 2015), and/or to different infiltration pathways for fines (e.g., vertical vs. horizontal). However, the small dataset used in this study provided an initial indication of these links, and it suggests our method as a promising approach to illustrate hydroecosedimentary processes. In addition, the expected correlations between turbidity, fine sediment and mortality were confirmed, indicating the HESTs can be used to better understand sediment effects of biota mechanistically.

5 | CONCLUSIONS

Overall, the HEST is a promising tool to assess hydrosedimentary and ecologically relevant processes in gravel streambeds with high enough sensitivity to detect patterns and differences relevant to inform potential restoration measures. The HEST is an advancement in interdisciplinary research applicable to different environments as well as to other target species in the interstitial. Although, here, we present a test of the HEST based on a small dataset, we see it as a promising tool that can be perfected over time, helping improve our process understanding of fine sediments and their effects on biota. The development of integrated methods and tools facilitating the assessment of multiple pathways of sediment exchange and integrating ecologically relevant processes are the way forward to developing a mechanistic knowledge of streambed processes that can inform relevant and targeted restoration and mitigation measures in river systems.

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DATA AVAILABILITY STATEMENT

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

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APPENDIX: FINE SEDIMENT LOSS TEST A.

The loss of fines during sediment trap retrieval is a risk that needs to be considered, and fines are more prone to escape from sediment collectors when totally or partially open (Casas-Mulet et al., 2017; Lachance & Dubé, 2004). Although the HEST is designed to ensure the sediment traps close during retrieval, there is always a risk of failure. In order to assess how much fine sediment is lost in the event of the HESTs not closing properly upon retrieval, we set a laboratory test to quantify and compare the loss of sediments between closed and open collectors. We used six sets of each horizontal and vertical collectors filled in with non-homogenous gravel with a grain size of 2 to 63 mm, and we then added 250 g of fine sediment <2 mm to each. Three pairs of vertical and horizontal collectors were closed and inserted into a larger bucket filled with water for 5 min. They were then retrieved, and the fines remaining in the big bucket were sieved, dried and weighed and compared to the initially 250 g of added fines. We repeated the same procedure with the remaining three pairs of vertical and horizontal collectors, but left them fully open upon insertion and retrieval, to enable comparison with the previous sets (Figure A1).

The setup design prioritised static versus flowing testing conditions. Although not mimicking the exact natural field conditions, the setup provided a stable environment to replicate and quantify the sediment loss in a reliable manner. In addition, the low flow conditions at both sites at the time of installation and retrieval ensured a close representation of the lab experiment to natural conditions.

The loss of fines was computed by comparing the weight of <2 mm fractions lost during the test between open versus closed HESTs. The fine sediment loss test illustrated differences between HESTs in the open and closed retrieval modes. However, differences between open and close retrieval were low and relatively constant with mean difference values ranging between 0.9 and 1.6% (Table A1).

Given the non-flowing experimental terms of the test, the results from this exercise could potentially slightly different results than those expected in natural flowing conditions. However, the low flow conditions in both sites at the time of installation and retrieval supports the comparability and validity of this test.

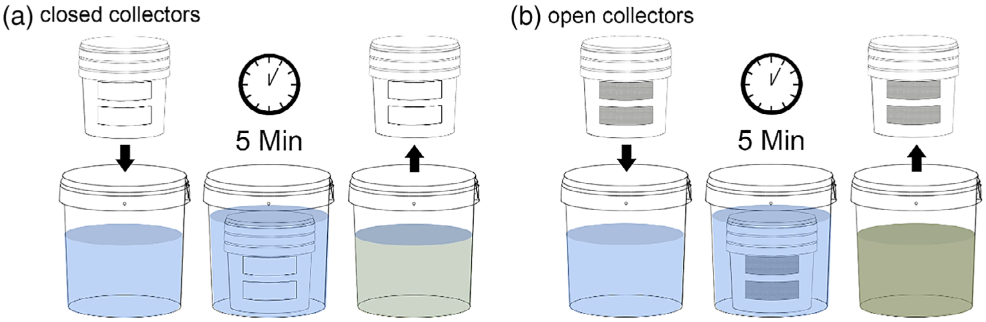

FIGURE A1 Illustration of the fine sediment loss assessment using the horizontal HEST as an example, during closed (a) and open (b) collectors retrieval, respectively [Color figure can be viewed at wileyonlinelibrary.com]

TABLE A1 Percentages of fine sediment retrieved during the fine sediment loss assessment from the vertical and horizontal HESTs, differentiating between top and bottom compartments, and open and closed modes

Infiltration	Compartment	Mode	Range (%)	Mean (%)	O-C mean difference (%)	*p-value*
Vertical	Top	Open	1.2–1.6	1.3	0.9	0.059
		Closed	0.4–0.4	0.4		
	Bottom	Open	2.4–2.8	2.7	1.6	0.072
		Closed	0.8–1.2	1.1		
Horizontal	Top	Open	0.8–1.2	0.9	0.7	0.072
		Closed	0.0–0.4	0.3		
	Bottom	Open	2.0–2.8	2.4	1.6	0.001
		Closed	0.4–1.2	0.8		

Note: p-values denote the significance assessment of the difference in loss between open and closed compartments.