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Impacts of gravel jetting on the composition of fish spawning substrates: implications for river restoration and fisheries management

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Abstract

Fine sediments can impact river biota, with egg and larval stages of lithophilic fish particularly sensitive to deposition of sand- and clay-sized particles (‘fines’) in spawning gravels. Mitigation and restoration methods include jetting to cleanse gravels of fines. Despite wide application, impacts of jetting on gravel composition and quality have rarely been quantified. Here, gravel jetting impacts on sediment composition in the River Great Ouse (UK), were tested during an *in-situ* experiment completed at riffle (55.6 ± 13.4 m^2) and patch (0.3 m^2) scales to determine its magnitude and persistence on surface and subsurface substrate conditions. Before-after (riffle) and control-impact (patch) designs were used, with bedload sediment traps installed downstream of experimental patches to investigate the sediments mobilised during jetting. At the riffle scale, surface grain size was significantly altered; fines were removed resulting in coarser and better-sorted sediments. Similar patterns were detected at the patch scale, although sediment sorting was not significantly altered. Despite reduced fine sediment content of subsurface gravels at the riffle scale, the overall grain size composition was not significantly altered. At the patch scale, no subsurface improvements were detected. Temporally, at the riffle scale, no changes in surface or subsurface sediments lasted more than 12 months; patch scale changes generally persisted for less than 3 months. Thus, whilst gravel jetting could improve spawning gravel quality for surface spawning fishes, including European barbel *Barbus barbus*, its effects are short-term. However, because subsurface sediments are not affected by gravel jetting, the benefits are limited for redd-building fishes, such as salmonids. Consequently, reducing fine sediment delivery to rivers, such as by changes in agricultural practices, would be more sustainable for managing excessive river sedimentation.

1. Introduction

In-stream degradation of river functional habitats is amongst the most-studied of all forms of freshwater degradation (Morandi et al. 2014), with deterioration in substrate quality associated with global declines in freshwater biodiversity (Hancock 2002). The importance of river substrata includes its provision as functional habitat for the development of many taxa (Geist 2011; Hancock 2002; Palmer et al. 1997; Sternecker at al. 2013a). Processes and activities that impact bed sediment composition, such as delivery of excess fine sediment (≤ 2 mm; 'fines'), can negatively impact riverine biota (Dudgeon et al. 2006; Kemp et al. 2011; Wood and Armitage 1997). For example, reproductive success and recruitment of lithophilic fishes can be influenced by fine sediment ingress that alters the composition of spawning gravels (Kemp et al. 2011). Fines content in spawning gravels affects interstitial flows and so impacts oxygen permeation, metabolic waste removal and fry emergence (e.g. Kemp et al. 2011; Pattison et al. 2015; Sear et al. 2016). Consequently, river restoration methods often focus on reducing fines content in spawning gravels with the aim of improving reproductive success to enhance fish populations (Bernhardt et al. 2005; Giller 2005; Wood and Armitage 1997).

A variety of methods have been used to reduce the fines content of spawning gravels, including gravel augmentation, placement of in-stream structures (e.g. woody debris, boulders etc.) and gravel cleaning (Wheaton et al. 2004a; Wheaton et al. 2004b). Gravel augmentation involves replenishing depleted or replacing degraded sediments, increasing spawning substrate availability (McManamay et al. 2010; Merz and Chan 2005) and/or suitability (Pander et al. 2015; Pulg et al. 2013; Sarriquet et al. 2007).

Hydraulics, and so substrate conditions, can be manipulated using in-stream structures such as artificial log steps, boulders and woody debris (Michel et al. 2014; Palm et al. 2007; Pander et al. 2015). These measures can mitigate some of the negative effects resulting from fine sedimentation by increasing hyporheic water exchange (Michel et al. 2014). In addition, gravel cleaning techniques, such as substrate raking, typically involve the mechanical bioturbation of sediments to promote fine sediment mobilisation (Meyer et al. 2008) and can help restore spawning gravels of lithophilic fishes (Pander et al. 2015; Pulg et al. 2013; Sternecker et al. 2013b).

Despite wide application, in practice many mitigation projects are inhibited by scientifically weak approaches, without specific objectives, post-monitoring evaluations and consideration of landscape processes that provide the context for specific sedimentation problems (Bond and Lake 2003; Wheaton et al. 2004a; Wheaton et al. 2004b). Most studies also report results from reach-scale (< 1 km restored river section) projects that lack a temporal component (Palmer et al. 2010; Pander and Geist 2013). Equally, some projects lack pre-restoration assessments, a component crucial to understanding the longevity of effects through time and/or space (Morandi et al. 2014; Wheaton et al. 2004a; Wheaton et al. 2004b). Thus, studies that utilise robust experimental designs are integral for understanding the factors that contribute to successful restoration (Palmer et al. 2007).

Gravel jetting, a technique to remove fines from gravels and provide enhanced spawning substrates for fish, has been widely applied in British rivers (Hendry et al. 2003). Despite this, only two studies report the impacts of gravel jetting on spawning substrates (Shackle et al. 1999; Twine 2013). Both studies found gravel jetting decreased percentage fines within subsurface sediments (Shackle et al. 1999; Twine 2013). However, both lacked replication and temporal perspectives. Whilst gravel jetting might improve local spawning substrate conditions, the process could potentially have negative consequences for downstream habitats and biota by releasing fine sediments (Kemp et al. 2011; Sternecker et al. 2013b). Also, gravel jetting loosens fluvial substrates, removing naturally developed stabilising sediment structures that might reduce critical entrainment thresholds and increase bed mobility under ambient and high flows. This has potential implications for egg-to-emergence survival if excess scour exposes egg pockets (Buffington et al. 2004; Hassan et al. 2015). Shackle et al. (1999) observed increased rates of sedimentation downstream of restored areas, but failed to quantify some potential negative impacts of different gravel cleaning methods on downstream habitats. Other studies have reported increased sedimentation downstream of restoration works (Pander et al. 2015; Sternecker et al. 2013b). Specifically, fine sediment accrual was observed in close proximity to restored sections and it could be assumed that this would create problems for downstream habitats by, for example, causing siltation of gravels. Therefore, while there is some evidence to suggest that jetting can be of local value, its benefits are not unequivocally established and the activity is not risk-free, such that jetting practices require careful assessment.

Consequently, this study utilised an experimental approach under field conditions to quantify the effects of gravel jetting on fish spawning grounds. Given the paucity of knowledge on gravel improvement schemes for non-salmonid fishes (Kemp et al. 2011), the focus was on the enhancement of gravels utilised for spawning by the cyprinid

European barbel *Barbus barbus* in the middle reaches of the Great Ouse River, Eastern England. *Barbus barbus* was used as the focal species as it is a typical non-salmonid lithophile that is a flag species for indicating good ecological status (Britton and Pegg 2011). It is also a potentially powerful zoogeomorphological agent (Pledger et al. 2014, 2016) in rivers. Their fisheries also have relatively high socio-economical value (Britton and Pegg 2011) and so there is a management requirement for their populations to be sustainable. In addition, by restoring *B. barbus* spawning areas, other fishes should also benefit through improved spawning substrata (e.g. *S. cephalus*; Arlinghaus and Wolter 2003; Balon 1975; Pinder 1997) and foraging habitats (Merz and Chan 2005; Mueller et al. 2014).

The experiment was completed at two spatial scales; riffle (55.55 ± 13.35 m^{22}) and patch (approximately 0.25 m^2: i.e. small areas within a riffle), to quantify how jetted area influences the magnitude and temporal persistence of restoration effects. The Environment Agency, the fisheries regulatory authority of England, typically restore 0.5 x 0.5 m patches of riffles during jetting. Therefore, patches always retained the same size of 0.25 m^2, whereas the size ranges of riffles utilised in the experiment varied from 26.88 m^2 to 98.04 m^2. The objective was to determine changes in sediment condition and mobility caused by gravel jetting, by measuring (1) surface sediment composition at riffle and patch scales (D5, D50 and D95 percentiles, mean, sorting (grain size distribution variance), skewness (measure of asymmetry of the grain size distribution curve), kurtosis (shape of the curve); Bunte and Abt 2001); (2) subsurface sediment composition at riffle and patch scales (D5, D50, D95, mean, sorting, skewness, kurtosis and sand and silt contents) and percentage of organic matter at patch scale; (3) longevity of gravel jetting effects: composition of surface and subsurface sediments after 12 months (riffle scale) and after 3 and 9 months (patch scale); and (4) quantity and composition of any sediment washed from the bed during patch-scale jetting.

2. Materials and Methods

2.1 Study sites

In the summer (August-September) of 2014 and 2015, experimental work was conducted on cyprinid fish spawning gravels in the middle River Great Ouse, eastern England (Figure 1). The Great Ouse has a catchment area of 8600 km^2 (Pinder et al. 1997), receives low mean annual rainfall (< 63 cm y^{-1}; Pinder et al. 1997) and is predominately groundwater-fed (Neal et al. 2000). It is highly regulated in its lower reaches for the purposes of flood and land management (Garner 2010; Pinder 1997; Pinder et al. 1997) and is impacted generally by agricultural inputs (Neal et al. 2000). In the last 20 years, to improve fish populations and the fisheries they support, the Environment Agency have used a combination of stocking with hatchery-reared *B. barbus* (Bašić and Britton 2016) and habitat improvement schemes, primarily gravel jetting of spawning gravels.

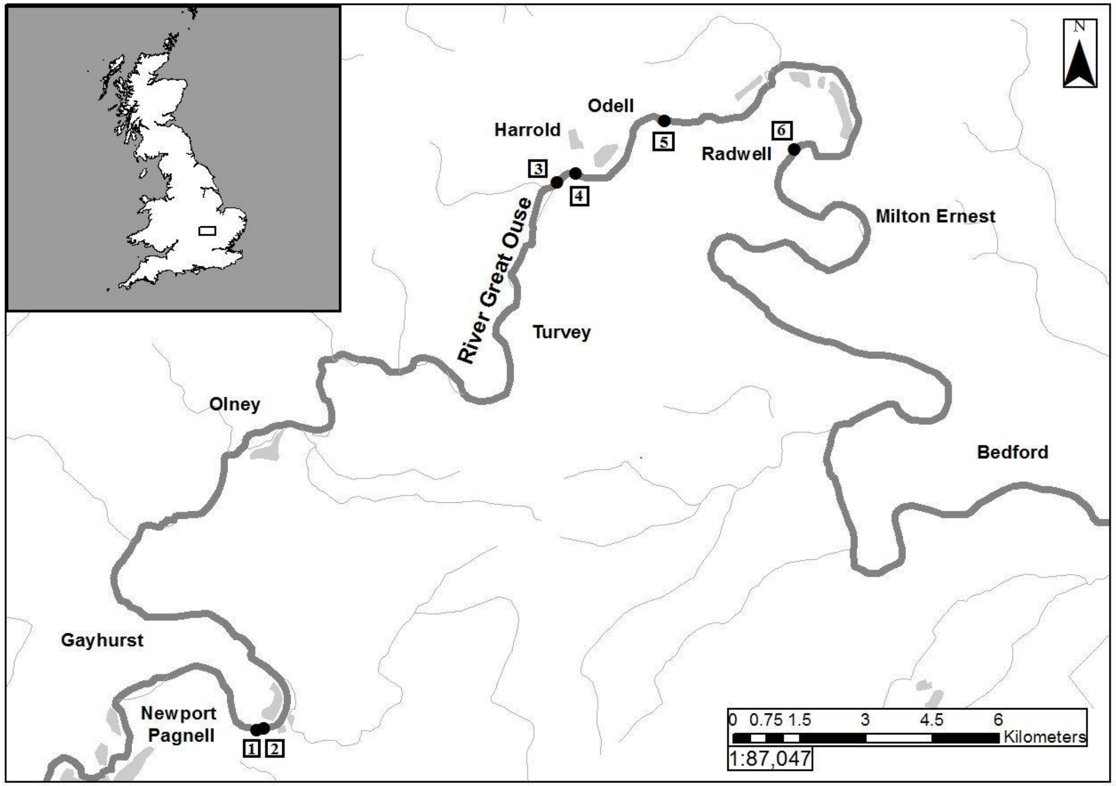

Figure 1. Approximate location of the study reach in the UK, highlighting sampled riffles in the River Great Ouse between Newport Pagnell and Bedford. Labelled black dots correspond to the locations of sites at: 1 - U/S Newport Pagnell 2, 2 - D/S Newport Pagnell, 3 – Harrold weir, 4 – U/S Harrold bridge, 5 - U/S Odell, 6 - Radwell bridge, sampled during riffle-scale (n = 5; sites 1-5; riffle scale) and patch-scale (n = 3; sites 3, 5 and 6; patch scale) experiments (Ordnance survey 2005; Ordnance survey 2015).

Experimental sites were selected using a strict set of criteria; they needed to be wade-able under base-flow conditions and be either natural spawning sites of target cyprinid lithophiles like *B. barbus* (*cf*. Twine 2013), or be representative of spawning sites in terms of their hydraulic (water depth: 0.12 - 0.88 m; near-bed flow velocity: 0.16 - 0.96 ms^{-1}; mean flow velocity: 0.2 - 1.07 ms^{-1}) and substrate conditions (surface grain size: 2 - 60 mm) (Banarescu and Bogutskaya 2003; Melcher and Schmutz 2010). In 2014, five of these sites were selected at random and samples of surface and subsurface sediments were taken pre- and post-gravel jetting at the riffle scale (Figure 2a). A before-after experimental design was selected due to confined riffle sizes, preventing bisection of riffles into spatially independent control and treated areas. This ensured jetting activities would not influence quantitative results from control sections of riffles.

The patch scale experiment in 2015 adopted a control impact design with post treatment sampling at three of the riffle sites and utilised 0.5 x 0.5 m areas which were either jetted (treatment) or not jetted (control) (Figure 2b). This allowed for monitoring of temporal changes during the post-restoration period, while controlling for the different environmental impacts. The three sites used for the patch scale experiments were Harrold weir, U/S Odell and Radwell (Figure 2a,b), selected on the basis of their size and similarity in flow, depth and surface sediment characteristics. This was to ensure quantitative findings were not influenced either by the proximity of control and treated patches or substantial difference in flow/sediment conditions. Before-after design was not utilised at the patch scale, as collecting a core sample before jetting at a smaller scale would influence bed stability during patch-scale jetting, hence outcomes of the procedure.

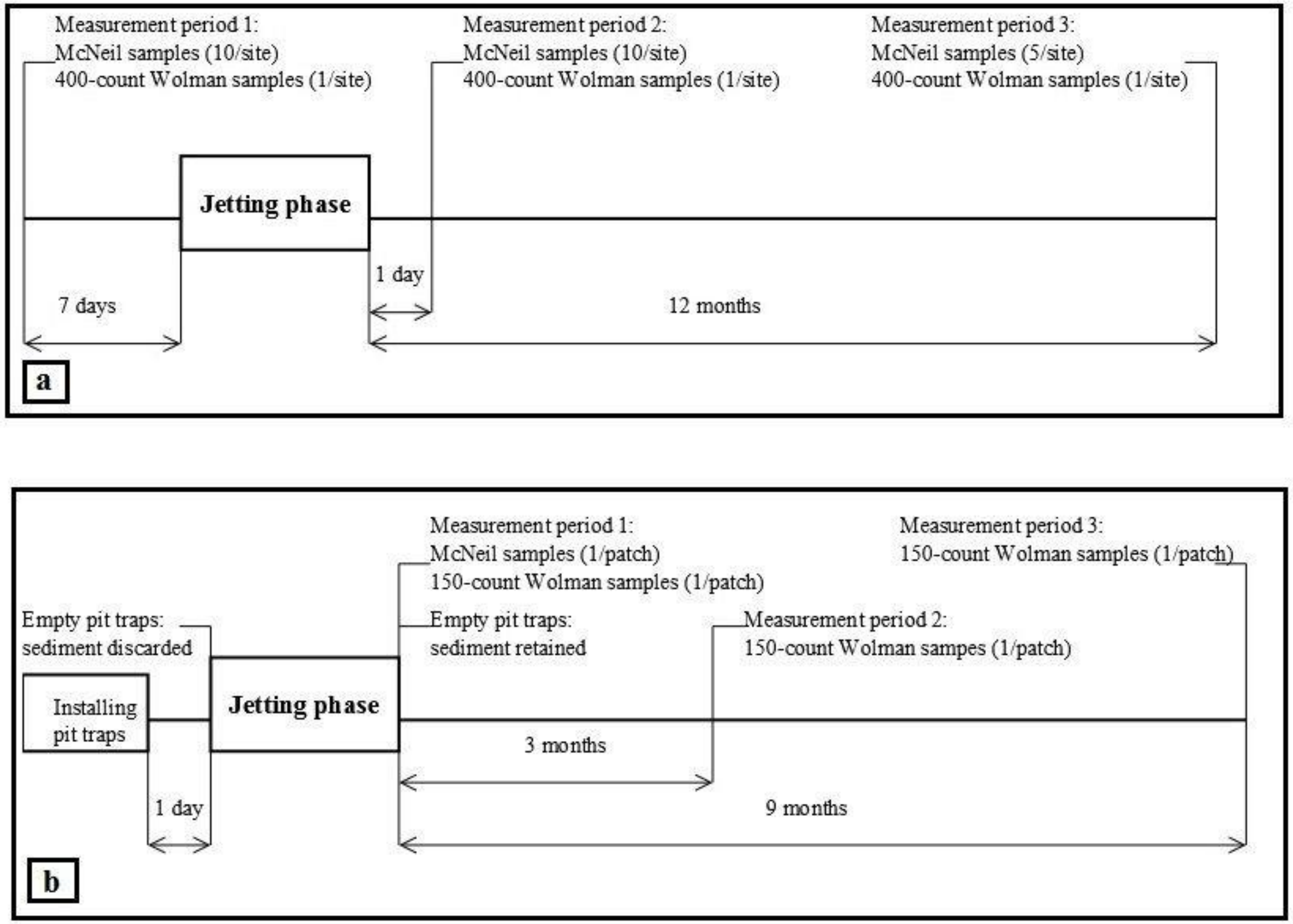

Figure 2. Schematic diagrams presenting the experimental procedure for a) riffle-scale and b) patch-scale experiments, performed in 2014/2015 and 2015/2016, respectively.

2.2 Substrate jetting

Riffle-scale jetting took different lengths of time depending on riffle size (range = 45 - 180 min), but effort per person and unit area was consistently applied across all sites. For consistency, each site was jetted by three operators, who started at the upstream end of the riffle and worked downstream. During the experimental period, no flood events were recorded and in each case, pre- and post-treatment sampling was conducted 7 days before and 1 day after gravel jetting, respectively (Figure 2a). It was thus assumed that measured differences between conditions before and after the jetting phase were the direct result of gravel jetting.

One year later, during patch-scale jetting, three control and three treatment patches were selected that were located upstream (control) and downstream (treatment) of each other, at each of the three sites. This was to ensure an adequate degree of replication. Patches were spaced 3 m apart in each direction to ensure spatial independence. Prior to jetting the treatment patches, two plastic bedload slot samplers (0.28 x 0.18 x 0.15 m) were installed downstream of each patch so they were flush and level with the bed surface, and were used to assess the quantity and composition of sediment (> 0.064 mm) released from the bed and transported as bedload during jetting. The treatment patches were then exposed to jetting by a single operator for a fixed 15-minute time period (Figure 2b). Rigid plastic inserts, placed within each of the slot samplers, were emptied during and after the jetting phase and any collected sediment was retained for laboratory analysis (Figure 2b).

2.3 Impacts of gravel jetting on surface sediment composition at different temporal scales

At the riffle scale, surface grain-size distributions were determined before and after gravel jetting using 400-count Wolman samples (Rice and Church 1996), with a lower truncation limit set at < 2 mm. To investigate the persistence of gravel jetting effects, measurements of surface sediment characteristics were made at four of the sites (excluding U/S Newport Pagnell, due to limited access), approximately 12 months after jetting in August 2015. Again, 400-count Wolman samples were used to assess surface grain size distributions (Figure 2a).

At the patch scale, a 150-count Wolman sample was collected post-jetting from each of the treatment and control patches (Figure 2b). During patch-scale assessments, grains were carefully selected, sized and returned to their original locations. A systematic approach was adopted when selecting grains that ensured clasts were not reselected. All control and treatment patches were monitored after 3 and 9 months (Figure 2b) using 150-count Wolman samples. This was to specify the longevity of gravel jetting impacts within one year, based on the results derived from the riffle scale experiment (*cf. Results*). Monitoring patches 6 months post jetting was not feasible due to high flows and so dangerous working conditions. The experiment was terminated after 9 months as no significant change was observed between pre- and post-jetting conditions for any of the parameters (*cf. Results*).

From surface samples collected at both spatial scales, *D*5, *D*50, *D*95 percentiles and mean, sorting, skewness and kurtosis were obtained using Trask's (1932) graphic mixed approach (Bunte and Abt 2001). These data were used to address objectives (1) and (3).

2.4 Impacts of gravel jetting on subsurface sediment composition at different temporal scales

At the riffle scale, 10 samples of subsurface sediments were collected per site using a McNeil sampler (core volume ≈ 0.005 m^3; McNeil and Ahnell, 1964) and Koski plunger before and immediately after gravel jetting. The McNeil sampler provides a robust sample of bed material, including fine sediments, at inundated, but shallow sites. Twelve months later, an additional 5 McNeil samples were collected from each of the sites. Each subsurface sample was dried and sieved into whole-phi size fractions separately, using an electronic shaker and sieve stack before weighing.

At the patch scale, one McNeil sample was collected from each of the treatment and control patches post-jetting (Figure 2b). Longevity of jetting effects at the patch scale was monitored for surface sediments alone because no significant changes to subsurface properties were detected and so expected, immediately and 3 months after jetting, respectively..

*D*5, *D*50, *D*95 percentiles and mean, sorting, skewness and kurtosis were calculated as described in Section 2.3. Additionally, fine sand (0.063 mm - 2 mm) and silt (≤ 0.063 mm) contents were determined, as these size fractions are recognised as having significant detrimental impacts on bed permeability, oxygen supply and thus *in-situ* egg survival and larval emergence (Bryce et al. 2010; Franssen et al. 2014; Lapointe et al. 2005; Meyer 2003; Sear et al. 2016). Percentage organic matter was measured only for patch-scale subsurface sediments via Loss on Ignition (LOI hereafter; CEN 2007), where a 10 g subsample of fine sediment (≤ 2 mm) was taken from each dried and sieved sample and further dried in an oven for 24 h at 100 °C. Each sample was then weighed to measure the pre-ignition mass (m_{pre}). Samples were subsequently placed in a furnace for 3 h at 550 °C before determining their post-ignition mass (m_{post}). The percentage of organic matter in each sample was determined using the equation (1).

$$\% \text{ organic matter} = \left(\frac{\text{mpre} - \text{mpost}}{\text{mpre}}\right) * 100 \quad (1)$$

Subsurface sediments data were used to address objectives (2) and (3).

2.5 Impact of gravel jetting on the size distribution and mass of transported bedload at the patch scale

Bedload samples collected downstream of treatment and control patches during the jetting phase were dried and sieved into whole-phi size fractions using an electronic shaker and sieve stack before weighing. Data derived from these samples were compared to identify the immediate impacts of jetting on bedload transport (Figure 2b).

D5, *D50*, *D95* percentiles and statistical parameters (mean, sorting, skewness, kurtosis) were derived from bedload sediments, along with fine sand, silt and organic matter content. Also, total transported mass data were extrapolated to the riffle scale, providing an estimate of the total mass of sediment purged from each riffle during the jetting phase. Bedload sediment data were used to address objective (4).

2.6 Data analysis

At the riffle scale, changes in surface and subsurface sediment composition in time due to gravel jetting were assessed using linear (LMM) and generalized linear mixed models (GLMMs, package lme4; Bates et al. 2015). This approach accounted for the random effect of site for surface and subsurface sediments and pseudoreplication of subsurface sediments (5 or 10 samples per site). Prior to any analyses, residuals from each data set were tested for normality using the MASS package (Venables, and Ripley 2002) in R 3.2.2 (R Development Core Team 2011). In the case of normally distributed residuals, model parameters were estimated using restricted maximum likelihood in linear mixed models to account for crossed random effects, small sample sizes and unbalanced design. In the case of log normal distributions, data were analysed using the flexible, penalised, quasi-likelihood method (family-Gaussian; link-log) that is suitable for over-dispersed data, crossed random effects and unbalanced design. However, where the mean of the response variable was below 5, the estimate was biased (Bates 2010; Bolker et al. 2009), so a Laplace approximation (family-Gaussian; link-log) was used (Bates 2010; Bolker et al. 2009). To test for differences in sand and silt content at the riffle scale, Laplace approximation with binomial logistic regression models (family-binomial; link-logit) was used, with weight argument specified as the total mass of sediment analysed for each sample.

At the patch scale, changes in surface sediment composition in time as a result of gravel jetting were analysed using linear (LMM) and generalized linear mixed models (GLM-family-Gaussian; link-log and family-binomial; link-logit) to account for temporal dependency of the data by using repeated measure as a random effect on the intercept. Changes in subsurface sediment composition through gravel jetting were assessed using linear (LM) and generalized linear models (GLM-family-Gaussian; link-log and family-binomial; link-logit), as no spatial or temporal dependency was assumed between patches. However, in cases of data over-dispersion, each sample was classed as a random effect on the intercept in mixed models.

At both spatial scales, where significant effects were detected, pairwise comparisons of covariate adjusted means were performed using least-squares means with Dunnett adjustment for *P* values for multiple independent comparisons of treatments with the control.

3. Results

3.1 Impacts of gravel jetting on surface sediment composition at different temporal scales

At the riffle scale, gravel jetting had a significant impact on the *D*5 (LMM; $P < 0.01$), *D*95 (GLMM; $P < 0.01$), mean (LMM; $P < 0.01$) and degree of sediment sorting (LMM; $P < 0.01$) (Table 1a). As a function of gravel jetting, mean *D*5, *D*50 and *D*95 values for surface sediments increased significantly (Table 1b; Figure 3) indicating a coarsening of the sediment surface (Table 1b; Figure 3). Even though sediments were already well sorted prior to jetting, sediment sorting was increased significantly by jetting (Table 1b; Figure 3). However, kurtosis (LMM; *P* > 0.05) and skewness (LMM; *P* > 0.05) did not change (Table 1a). Specifically, sediments derived before and after the jetting phase maintained nearly symmetrical and leptokurtic grain size distributions, characterised by clustering around the means and small standard deviations (Figure 3).

There were no significant differences in any of the surface percentiles when comparing conditions before and 12 months after the jetting phase (Table 1b; Figure 3). A similar pattern was observed for mean, sorting, skewness and kurtosis values, with no significant differences found between before jetting and 12 months after jetting (Figure 3).

Table 1 Outputs from linear mixed models testing for differences at the riffle scale in surface sediment parameters: a) final models; and b) pairwise comparisons; where: 1) pre- and 24 hours post-jetting; and 2) pre- and 12 month post-jetting. Site was specified as a random effect on the intercept. Mean differences are from estimated least-square means (difference significant at * $P < 0.05$ and ** $P < 0.01$).

a)

Final models

D5 ~ Treatment + (1|Site) (AIC = 71.20; log likelihood = - 30.60; $P < 0.05$)*

D50 ~ Treatment + (1|Site) (AIC = 61.22; log likelihood = - 24.01; $P < 0.01$**)

D95 ~ Treatment + (1|Site) (family – Gaussian (link-log); penalized quasilikelihood; AIC = NA; log likelihood = NA; $P < 0.01$**)

Mean ~ Treatment + (1|Site) (AIC = 56.31; log likelihood = - 23.15; $P < 0.01$**)

Sorting ~ Treatment + (1|Site) (AIC = -47.26; log likelihood = 28.63; $P < 0.01$**)

Skewness ~ Treatment + (1|Site) (AIC = - 35.42; log likelihood = 22.71; $P > 0.05$)

Kurtosis ~ Treatment + (1|Site) (AIC = -62.93; log likelihood = 36.46; $P > 0.05$)

b)

Metric	**Mean difference**	
	1	**2**
D5	- 3.28 ± 1.15, $P < 0.05^{*}$	- 0.11 ± 1.26, $P > 0.05$
D50	- 7.24 ± 0.64, $P < 0.01^{**}$	- 0.60 ± 0.69, $P > 0.05$
D95	- 0.12 ± 0.04, $P < 0.05^{*}$	0.02 ± 0.05, $P > 0.05$
Mean	- 6.66 ± 0.62, $P < 0.01^{**}$	- 0.56 ± 0.67, $P > 0.05$
Sorting	- 0.06 ± 0.02, $P < 0.05^{*}$	0.01 ± 0.02, $P > 0.05$

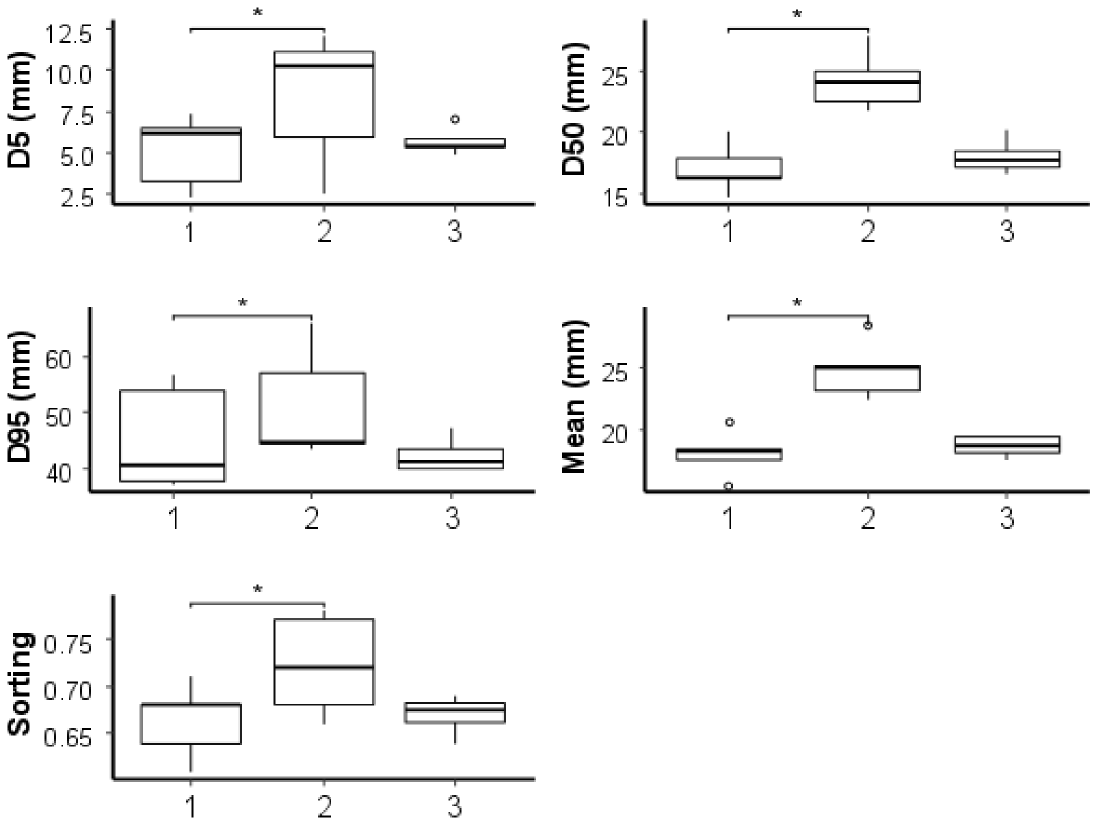

Figure 3 Surface percentiles and statistical parameters significantly affected by treatment, pre-jetting (1), 24 hours post-jetting (2) and 12 months post-jetting (3) at the riffle scale. Thin horizontal lines represent 10, 25, 85 and 90 percentiles. Thick black horizontal lines, circles and asterisks represent medians, outliers and significant relationships, respectively

At the patch scale, there was a significant effect of treatment and time interaction on *D*5 (GLMM; $P < 0.01$), *D*50 (LMM; $P < 0.01$), *D*95 (GLMM; $P < 0.05$), mean (LMM; $P < 0.01$) and sorting parameters (LMM; $P < 0.01$) (Table 2a). Compared to control patches, the sediments of jetted patches one hour after jetting had significantly higher *D*5, *D*50, *D*95 and mean values, although differences in sorting, skewness and kurtosis values were not significantly different (Table 2b; Figure 4). After 3 months, only the *D*5 significantly differed from the control patches, while other percentiles showed no significant differences between control and treated patches (Table 2b; Figure 4). Furthermore, none of the percentiles or statistical parameters were significantly different after 9 months when comparing data derived from control and treatment patches (Figure 4).

Table 2 Outputs from linear mixed models testing for differences in surface sediment parameters between control and jetted patches: a) final models; and b) pairwise comparisons; where: 1) 1 hour post-jetting; 2) 3 months post-jetting; and 3) 9 months post-jetting. Each repeated sample was specified as a random effect on the intercept. Mean differences are from estimated least-square means (difference significant at * $P < 0.05$ and ** $P < 0.01$).

a)

Final models:

D5 ~ Treatment x Time + (1|Sample) (family – Gaussian (link-log); Laplace approximation, AIC = -251.84; log likelihood = - 117.92; $P < 0.01$**)

D50 ~ Treatment x Time + (1|Sample) (AIC = 303.31; log likelihood = - 143.66; $P < 0.01$**)

D95 ~ Treatment x Time + (1|Sample) (family – Gaussian (link-log); penalized quasilikelihood; AIC = NA; log likelihood = NA; $P < 0.05$*)

Mean ~ Treatment x Time + (1|Sample) (AIC = 301.99; log likelihood = - 143.00; $P < 0.01$**)

Sorting ~ Treatment x Time + (1|Sample) (AIC = -142.47; log likelihood = 79.14; $P < 0.01$**)

Skewness ~ Treatment x Time + (1|Sample) (AIC = -68.92; log likelihood = 42.46; $P > 0.05$)

Kurtosis ~ Treatment x Time + (1|Sample) (AIC = -220.28; log likelihood = 118.14; $P > 0.05$)

b)

Metric	**Mean difference**		
	1	**2**	**3**
D5	- 0.45 ± 0.13, $P < 0.01$**	- 0.81 ± 0.32, $P < 0.05$*	- 0.41 ± 0.61, $P > 0.05$
D50	- 4.23 ± 1.89, $P < 0.05$*	- 0.78 ± 1.89, $P > 0.05$	- 0.002 ± 1.89, $P > 0.05$
D95	- 0.20 ± 0.06, $P < 0.01$**	- 0.01 ± 0.09, $P > 0.05$	0.03 ± 0.08, $P > 0.05$
Mean	- 5.15 ± 1.77, $P < 0.01$**	- 0.97 ± 1.77, $P > 0.05$	- 0.16 ± 1.77, $P > 0.05$
Sorting	- 0.03 ± 0.03, $P > 0.05$	- 0.02 ± 0.03, $P > 0.05$	- 0.03 ± 0.03, $P > 0.05$

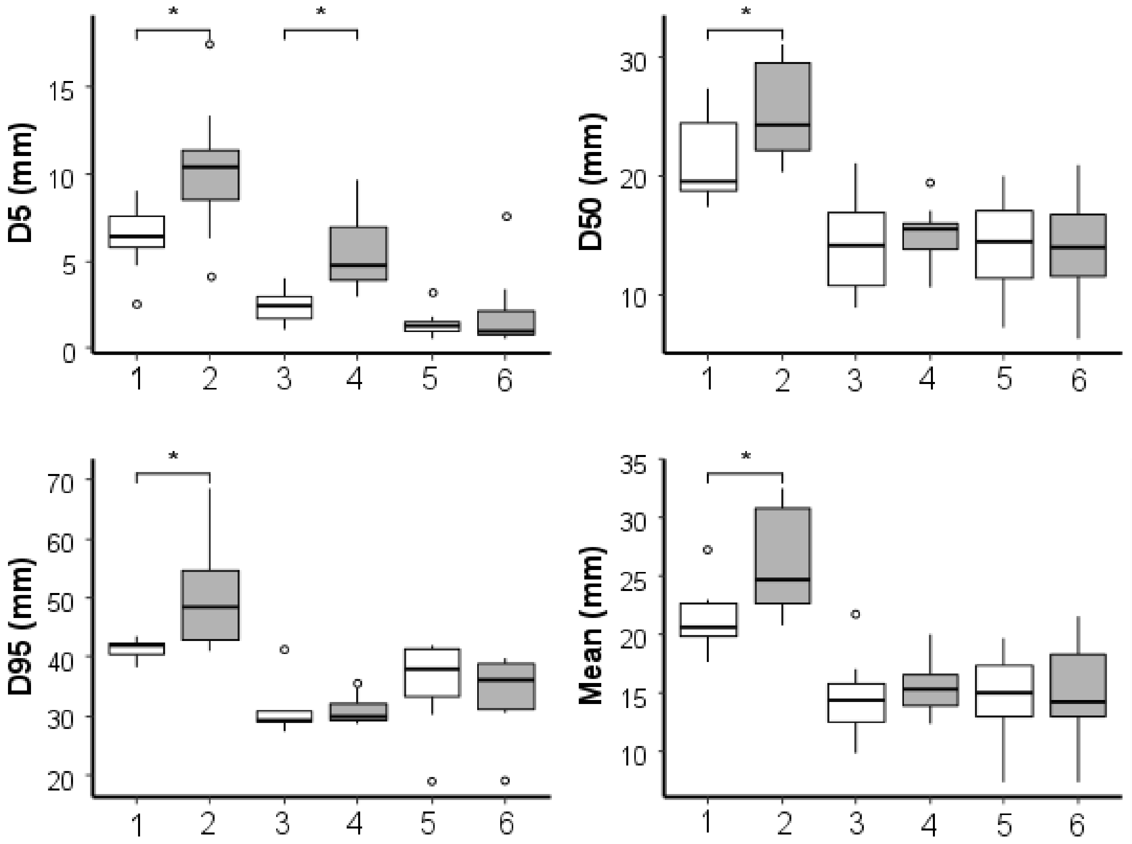

Figure 4 Surface percentiles and statistical parameters significantly affected by treatment, 1 hour post-jetting (1, 2), 3 months post-jetting (3, 4) and 9 months post-jetting (5, 6) at control (white boxes) and treated patches (grey boxes). Thin horizontal lines represent 10, 25, , 85 and 90 percentiles. Thick black horizontal lines, circles and asterisks represent medians, outliers and significant relationships, respectively.

3.2 Impact of gravel jetting on subsurface sediment composition at different temporal scales

At the riffle scale, gravel jetting only significantly affected the subsurface *D*5 (GLMM; $P < 0.05$), sand content (GLMM; $P < 0.05$) and silt content (GLMM; $P < 0.01$) (Table 3a). In contrast, *D*50 (LMM; $P > 0.05$), *D*95 (GLMM; $P > 0.05$) mean (LMM; $P > 0.05$), sorting (LMM; $P > 0.05$), skewness (LMM; $P > 0.05$) and kurtosis (LMM; $P > 0.05$) values were not significantly altered by gravel jetting (Table 3a; Figure 5).

Riffle-scale assessments of substrate condition 24 hours after the jetting phase showed an increase in *D5* and decreases in subsurface sand and silt content, which indicate a reduction in the fine sediment content of the bed material (Table 3b; Figure 5). The longevity of this impact was short-lived, and conditions after 12 months were not significantly different from pre-jetting conditions (Table 3b; Figure 5).

At the patch scale, gravel jetting did not significantly impact upon subsurface sediment composition; there were no differences in grain size distribution parameters between treatment and control patches 1 hour after the jetting phase (Table 4).

Table 3 Outputs from linear mixed models testing for differences at the riffle scale in subsurface sediment parameters: a) final models; and b) pairwise comparisons, where: 1) pre- and 24 hours post-jetting; and 2) pre- and 12 month post-jetting. Site and sample were random effects on the intercept. Mean differences are from estimated least-square means (difference significant at * $P < 0.05$ and ** $P < 0.01$).

a)

Final models:

D5 ~ Treatment + (1|Site) + (1|Sample) (family – Gaussian (link-log); Laplace approximation, AIC = - 14.0; log likelihood = 13.0; $P < 0.05$*)

D50 ~ Treatment + (1|Site) + (1|Sample) (AIC = 656.84; log likelihood = - 322.42; $P > 0.05$)

D95 ~ Treatment + (1|Site) + (1|Sample) (family – Gaussian (link-log); penalized quasilikelihood; AIC = NA; log likelihood = NA; $P > 0.05$)

Mean ~ Treatment + (1|Site) + (1|Sample) (AIC = 612.23; log likelihood = - 300.12; $P > 0.05$)

Sorting ~ Treatment + (1|Site) + (1|Sample) (AIC = 226.74; log likelihood = 119.37; $P > 0.05$)

Skewness ~ Treatment + (1|Site) + (1|Sample) (AIC = 149.03; log likelihood = - 68.52; $P > 0.05$)

Kurtosis ~ Treatment + (1|Site) + (1|Sample) (AIC =- 529.82; log likelihood = 270.91; $P > 0.05$)

Sand content ~ Treatment + (1|Site) + (1|Sample) + (1|Sample_ID) (family – binomial (link-logit); AIC = 1930.60; log likelihood = -959.30; $P < 0.05$*)

Silt content ~ Treatment + (1|Site) + (1|Sample) + (1|Sample_ID) (family – binomial (link-logit); AIC = 782.30; log likelihood = -385.10; $P < 0.01$**)

b)

Metric	**Mean difference**	
	1	**2**
D5	-0.32 ± 0.11, $P < 0.01^{**}$	0.21 ± 0.13, $P > 0.05$
Sand content	0.43 ± 0.16, $P < 0.05^{*}$	0.28 ± 0.18, $P > 0.05$
Silt content	0.73 ± 0.15, $P < 0.01^{**}$	0.33 ± 0.18, $P > 0.05$

Table 4 Outputs from linear and mixed linear models testing for differences in subsurface sediment parameters between control and jetted patches 1 hour post-jetting. Mean differences are from estimated least-square means (difference significant at * $P < 0.05$ and ** $P < 0.01$).

Final models:

D5 ~ Treatment (family – Gaussian (link-log); $\chi^2 = 1.93$; $P > 0.05$)

D50 ~ Treatment (F (16) = 0.67; $R^2 = 0.04$; $P > 0.05$)

D95 ~ Treatment + (1|Sample_ID) (family – Gaussian (link-log); penalized quasilikelihood; AIC = NA; log likelihood = NA; $P > 0.05$)

Mean ~ Treatment (F (16) = 1.11; $R^2 = 0.06$; $P > 0.05$)

Sorting ~ Treatment (F (16) = 3.89; $R^2 = 0.20$; $P > 0.05$)

Skewness ~ Treatment (F (16) = 3.76; $R^2 = 0.19$; $P > 0.05$)

Kurtosis ~ Treatment (F (16) = 4.02; $R^2 = 0.20$; $P > 0.05$)

Sand content ~ Treatment + (1|Sample_ID) (family – binomial (link-logit); AIC = 280.70; log likelihood = -137.40; $P > 0.05$)

Silt content ~ Treatment + (1|Sample_ID) (family – binomial (link-logit); AIC = 113.40; log likelihood = -53.70; $P > 0.05$)

Organic matter content ~ Treatment (family – binomial (link-logit); $\chi^2 = 2.20$; $P > 0.05$)

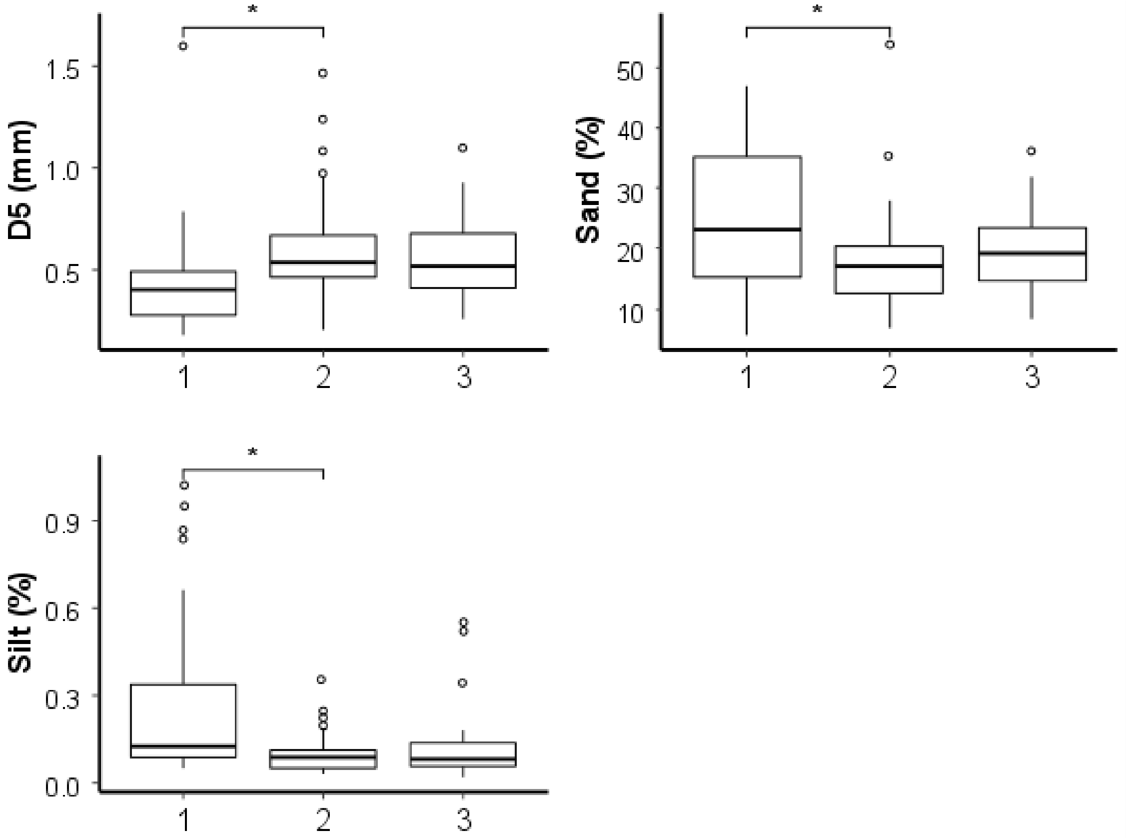

Figure 5 Subsurface percentiles, statistical parameters and sand and silt content significantly affected by treatment, pre-jetting (1), 24 hours post-jetting (2) and 12 months post-jetting (3) at the riffle scale. Thin horizontal lines represent 10, 25, 85 and 90 percentiles. Thick black horizontal lines, circles and asterisks represent medians, outliers and significant relationships, respectively.

3.3 Impact of gravel jetting on the size distribution and mass of transported bedload at the patch scale

Data derived from bedload samples revealed that gravel jetting mobilised bed material. The mean mass of displaced sediment from each treated patch was 7.04 ± 2.37 kg, with no mobility observed or quantified under control conditions (Table 5). In general, displaced sediments predominately consisted of poorly-sorted gravels and sand, with leptokurtic distributions that were strongly skewed towards finer grain sizes (Table 5). The majority of sediment mobilised from the bed during jetting was sand (60.31 ± 2.91 %; Table 5).

Table 5 Quantity and composition of mobile sediment, washed from the bed during patch-scale jetting. Patch mean values (n = 9; ± SE).

Metric	**Value**
*D*5 (mm)	0.29 ± 0.02
*D*50 (mm)	1.68 ± 0.47
*D*95 (mm)	30.05 ± 8.33
Mean (mm)	3.51 ± 0.41
Sorting	0.36 ± 0.03
Skewness	1.72 ± 0.36
Kurtosis	0.17 ± 0.02
Sand (%)	60.31 ± 2.91
Silt (%)	0.14 ± 0.02
Organic matter content (%)	1.59 ± 0.20
Amount of sediment/patch (kg)	7.04 ± 2.37

4. Discussion

Results from this *in-situ* experiment revealed that gravel jetting had a significant coarsening effect on the surface gravels of the river at riffle and patch scales. However, despite some reduction of fine sediment content, most subsurface grain size characteristics were not affected by gravel jetting at the riffle scale. When applied at patch scales, there were no impacts of jetting on the subsurface bed material. These quantified effects in both surface and subsurface sediments diminished at the riffle scale 12 months after gravel jetting. Additionally, no significant differences were detected for most assessed properties of surface sediments 3 months post-jetting at the patch scale. Significant quantities of fine sediments, largely consisting of sand, were purged from the bed during jetting and transported downstream.

Analysis of surface grain-size distributions during both riffle and patch scale assessments indicated that gravel jetting had a significant impact on the composition of surface spawning gravels by displacing finer sediments, which resulted in coarser, better-sorted sediments (significantly increased percentiles, mean and sorting). In comparison, Sepulveda et al. (2015) quantified fewer significant alterations in surface percentiles (D50, D84) as a function of gravel restoration via modified suction dredging in North America, with a decrease in surface particle sizes following restoration. However, the investigated systems were snowmelt-driven streams of second order, with faster flows, and suction dredging is a more invasive technique, which could explain observed reductions in particle sizes in that study.

Subsurface grain-size distributions at riffle and patch scales were not affected as strongly as the surface, with no change in *D*50 and *D*95, and no significant change in the mean grain size at both scales. In contrast, Pulg et al. (2013) measured significant change in the mean grain size following restoration via bucket excavators in Germany, while Pander et al. (2015) reported an increase in the geometric mean particle diameter of subsurface sediments at 4 out of 6 sites following gravel-cleaning operations in Germany, with an overall non-significant effect. Impacts of increased subsurface grain sizes on lithophilic fish species during incubation vary between studies. While some report increased survival rates related to decreased fine sediment content and increased oxygen concentration (Pulg et al. 2013), others find limited benefits of increased grain sizes for egg survival of lithophilic fish species (Mueller et al. 2014). As our study implied no change in subsurface mean grain size or *D*50, benefits for lithophilic species dependent on the subsurface zone are expected to be minor following gravel jetting, at least based on the quantitative evidence presented here. For subsurface sediments, fines content was the only parameter influenced by gravel jetting at the riffle scale, as indicated by significant increases in the *D*5 and decreases in sand and silt content. Other studies of gravel cleaning have recorded similar decreases in fine sediment content (e.g. Meyer et al. 2008; Pulg et al. 2013; Sepulveda et al. 2015) and similar success has also been associated with gravel additions (Sarriquet et al. 2007). However, despite the reduction in fines caused by jetting, the amount of subsurface sand in our study riffles on the River Great Ouse (17.7 %) remained above recommended levels; for example, they were above the 15 % threshold thought to detrimentally affect the early development of salmonid fishes (Kemp et al. 2011; Kondolf 2000; O’Connor and Andrew 1998).

The detected difference between riffle and patch-scale jetting effects on the subsurface sediments is potentially the result of either variability in pre-treatment site conditions between two experiments or the size of the treated areas. Firstly, while every effort was made to select comparable sites at the patch scale, sites at the riffle scale contained substrates with different fines contents that could have impacted upon our results (Pander et al. 2015). For example, the different sites used during the riffle-based work each maintained substrates with high sand and silt contents, whereas substrates at sites utilised during the patch-scale component had, in general, lower silt and sand contents. High standard deviations for fines content prior to gravel jetting at the riffle, relative to patch scale, further support this reasoning and imply high variability between the sites selected for riffle-scale experimentation. This confirms the importance of local site dynamics in shaping natural grain-size distributions that would therefore impact upon the efficacy of investigated restoration techniques (Pander et al 2015; Pulg et al. 2013).

Importantly, measured changes in surface and subsurface sediments at the riffle scale persisted for less than a year, which is consistent with previous studies (e.g. Meyer et al. 2008; Pander et al. 2015; Rubin et al. 2004). For example, dredging and redistribution of gravels was found successful at removing fines from sediments in the River Sieg, Germany, but the effects lasted only five months (Meyer et al. 2008). Sternecker et al. (2013b) reported improvements in hyporheic water conditions and subsurface sediments lasting for at least three months following restoration via substratum excavation in the River Moosach, Germany, but the limited duration of the study prohibited further assessment. Effects of gravel replenishment and fine sediment removal, using flow deflectors and sediment traps on egg-to-emergence survival rates in a small stream in

Gotland, Sweden, were positive and significant but lasted less than a year (Rubin et al. 2004). Different methods of substratum restoration assessed by Pander et al. (2015) in Germany only impacted upon physicochemical substratum quality for less than one year. However, as none of the investigated techniques were gravel jetting, this study is the first to quantify the longevity of effects for this method and confirm that its impact is equally short-lived.

The amount of sediment removed from the bed during patch-scale jetting was significant and extrapolation to the riffle scale suggests that on average, almost 1 tonne of sediment per site, consisting mainly of sand, would have been mobilised during riffle-scale jetting. This could benefit subsequent rates of egg-to-emergence and larval survival, as high concentrations of sand within sediments can trap fines and therefore detrimentally impact upon life within the egg pocket (Levasseur et al. 2006; Pulg et al. 2013; Sear et al. 2016). Additionally, gravel jetting loosens fluvial substrates, likely reorganising stable, water-worked grains into random arrangements and positions of relative instability. It is reasonable to assume these structural changes, alongside reductions in consolidating fine sediments, could reduce critical entrainment thresholds and increase bed mobility, particularly under high flow conditions (Buffington et al. 2004; Powell 1998; Wilcock and McArdell 1997). This is then likely to influence scour depths (Montgomery el al. 1996; Montgomery et al. 1999) and so, potentially, the reproductive success of shallow-spawning lithophils. Additionally, jetting of substrata with high proportions of sand led to increased sedimentation downstream of treated areas, with potential negative implications for downstream habitats (Pander et al. 2015). Although quantification of suspended sediment fluxes were beyond the scope of the study, significant reductions in sand and silt contents of subsurface sediments were detected (Figure 5) and observations of suspended sediment plumes during jetting suggested the release of sand- and silt- sized particles (0.064 - 2 mm and ≤ 0.064 mm, respectively) from the bed, and their downstream displacement under baseflow conditions. Mobilisation of these particles could have significant consequences, particularly when restoring large areas of river bed or fines-rich sediments.

It is well established that low fines content in spawning gravels are a prerequisite for successful salmonid spawning, given their construction of redds in which eggs are buried for relatively extended periods during winter and spring (e.g. Kemp et al. 2011). In contrast, there is limited knowledge on how gravel-spawning, non-salmonid fishes are impacted by elevated fines content in spawning substrates. Inferences that the detected impacts for salmonid fishes might be similar for other fishes are complicated due to differing phenology and spawning strategies. For example, the spawning times of riverine cyprinid fishes tend to be late spring and/ or early summer, when river flows are reduced and thus impacts of fines in spawning gravels could be magnified due to ambient oxygen levels being relatively low. However, unlike salmonid fishes, these species rarely build extensive nests, instead using shallow depressions or depositing eggs within surface gravel interstices (Balon 1975; Kottelat and Freyhof 2007). This results in eggs and larvae spending less time within gravels, especially as the warmer temperatures help minimise the time between egg deposition and emergence, thus impacts of fines might be limited. This also suggests that gravel jetting could potentially be beneficial for these non-salmonid fishes, provided it is completed just prior to spawning aggregations and activities. This would need balancing against the potential for damage to downstream habitats caused by fine sediment displacement. Moreover, spawning of cyprinid fishes is asynchronous, thus jetting activities to benefit a late-spawning species, such as *B. barbus,* could coincide with reproductive activities of an earlier spawning species, such as *Leuciscus leuciscus* (Maitland and Linsell 2006). Thus, careful planning around the phenology of the fishes within the community would be required to deliver optimal benefits.

Local interventions, such as gravel jetting, therefore do not deliver long-term or straightforward solutions to fine sediment ingress, with potential negative implications for downstream habitats and biota. Transferability of these data to other systems should be considered with care, given differences in geomorphological conditions and so, responses to restoration in diverse rivers. Nevertheless, there remains some potential for applying gravel jetting to restore habitats of shallow spawners, particularly if completed just prior to spawning over riffle scales at fines-rich sites, where only a short-term impact (lasting less than 3 months) is required. To increase longevity of jetting effects, flow deflectors could be immediately utilised post-jetting that increase flows over restored areas, limiting fines ingress and potentially maintaining post-jetting conditions for longer periods. However, without quantitative evidence, these assertions are speculative but provide areas for future studies to explore. As an alternative, modified suction dredges could be used to remove rather than mobilise fine sediments from the river bed, avoiding potentially detrimental ecological impacts of jetting and fines mobilisation (Sepulveda et al. 2015). Other, potentially more sustainable localised actions are also suggested, such as creation of off-channel settling reservoirs and buffer zones to protect river banks from erosion and livestock (Hendry et al. 2003), but these typically influence ambient conditions across broad spatial scales, and can rarely be used to target localised issues. Catchment scale changes in land management practices remain the most effective solutions for dealing with excessive sedimentation in freshwater systems (Hendry et al. 2003; Honea et al. 2009; Pulg et al. 2013), as they address the cause of sedimentation in rivers, rather than treat the ‘symptoms’ at the local scale. To be effective, determination of fine sediment sources within catchments and their overall contributions to sediment fluxes are required (Collins and Walling 2007a, b; Naura et al. 2016). However, these actions are often costly, time-consuming and not feasible without substantial policy changes. Of particular importance for freshwater fisheries management is the need to investigate the specific fine-sediment tolerances of eggs and larvae of fishes other than salmonids, in both field and controlled conditions. Such investigations should provide benchmark data for river managers to assess whether changes in sediment composition are a function of restoration interventions and would deliver spawning and recruitment benefits for the target fish species.

This then raises the issue of how restoration techniques can be better utilised in the conservation of fish spawning habitats. Approximately 5-70 USD/m^2 is spent on substrate improvements (e.g. gravel addition and cleaning), while placement of in-stream structures costs between 119 and 190 USD/m^2 or around 20 000 USD per project (Ajres et al. 2014). Despite this expenditure, knowledge on the efficacy and impacts of the methods remain poorly quantified.. Correspondingly, it is recommended that future research has a focus on two areas. Firstly, there is a need to investigate the impacts of a wide range of gravel restoration methods, utilising appropriate experimental designs, degrees of replication and post-restoration monitoring, that aim to build a more complete picture of the net effects of different restoration techniques through time and space. A current lack of quantitative evidence on the efficacy of restoration techniques makes selection of impactful methods difficult. Secondly, cost-benefit analyses of restoration projects are required that cover a range of freshwater habitats and biota, and incorporate environmental impact and resource requirements. Collectively, these will assist selection of the optimal restoration methods to be applied in specific rivers..

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6. References

Ayres, A., Gerdes, H., Goeller, B., Lago, M., Brouwer, O.S., IVM, J.V., Angelopoulos, N., Cowx, I., 2014. Restoring rivers for effective catchment management. European Commission.

Arlinghaus, R., Wolter, C., 2003. Amplitude of ecological potential: chub *Leuciscus cephalus* (L.) spawning in an artificial lowland canal. J. Appl. Ichthyol. 19 (1), 52–54. doi: 10.1046/j.1439-0426.2003.00343.x.

Balon, E.K., 1975. Reproductive guilds of fishes: a proposal and definition. J. Fish. Res. Board. Can. 32 (6), 821-864. doi: 10.1139/f75-110.

Banarescu, P.M., Bogutskaya, N.G., 2003. The Freshwater Fishes of Europe; Cyprinidae 2, part II: Barbus. AULA-Verlag GmbH, Wiebelsheim.

Bašić, T., Britton, J.R., 2016. Characterising the trophic niches of stocked and resident cyprinid fishes: consistency in partitioning over time, space and body sizes. Ecol. Evol. 6 (14), 5093-5104. doi: 10.1002/ece3.2272.

Bates, D.M., 2010. lme4: Mixed-effects modelling with R. Springer, USA.

Bates, D.M., Maechler, M., Bolker, B., Walker, S., 2015. Fitting Linear Mixed-Effects Models Using lme4. J. Stat. Softw. 67 (1), 1-48.

Bernhardt, E.S., Palmer, M., Allan, J.D., Alexander, G., Barnas, K., Brooks, S., Carr, J., Clayton, S., Dahm, C., Follstad-Shah, J., Galat, D., 2005. Synthesizing U. S. river restoration efforts. Science. 308 (5722), 636-637. doi: 10.1126/science.1109769.

Bolker, B.M., Brooks, M.E., Clark, C.J., Geange, S.W., Poulsen, J.R., Stevens, M.H. H., White, J.-S.S. (2009). Generalized linear mixed models: a practical guide for ecology and evolution. Trends Ecol. Evol. 24 (3), 127-135. doi: 10.1016/j.tree.2008.10.008.

Bond, N.R., Lake, P.S., 2003. Characterizing fish–habitat associations in streams as the first step in ecological restoration. Austral. Ecol. 28 (6), 611-621. doi: 10.1046/j.1442-9993.2003.t01-1-01317.x.

Britton, J. R., Pegg, J., 2011. Ecology of European Barbel *B. barbus*: Implications for river, fishery, and conservation management. Rev. Fish. Sci. 19, 321-330. doi: 10.1080/10641262.2011.599886.

Bryce, S.A., Lomnicky, G. A., Kaufmann, P.R., 2010. Protecting sediment-sensitive aquatic species in mountain streams through the application of biologically based streambed sediment criteria. J. N. Am. Benthol. Soc. 29 (2), 657-672.

Buffington, J.M., Montgomery, D.R., Greenberg, H.M., 2004. Basin-scale availability of salmonid spawning gravel as influenced by channel type and hydraulic roughness in mountain catchments. Can. J. Fish. Aquat. Sci. 61 (11), 2085-2096. doi: 10.1139/f04-141.

Bunte, K., Abt, S. R., 2001. Sampling surface and subsurface particle-size distributions in wadable gravel-and cobble-bed streams for analyses in sediment transport, hydraulics, and streambed monitoring. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, USA.

CEN, 2007. Characterization of waste - Determination of loss on ignition in waste, sludge and sediments. CEN, Brussels.

Collins, A.L., Walling, D.E., 2007a. Sources of fine sediment recovered from the channel bed of lowland groundwater-fed catchments in the UK. Geomorphology 88 (1), 120-138. doi: 10.1016/j.geomorph.2006.10.018.

Collins, A.L., Walling, D.E., 2007b. The storage and provenance of fine sediment on the channel bed of two contrasting lowland permeable catchments, UK. River Res. Appl. 23 (4), 429-450. doi: 10.1002/rra.992.

Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z.I., Knowler, D.J., Lévêque, C., Naiman, R.J., Prieur-Richard, A.H., Soto, D., Stiassny, M.L., Sullivan, C.A., 2006. Freshwater biodiversity: importance, threats, status and conservation challenges. Biol. Rev. 81 (2), 163-182. doi: 10.1017/S1464793105006950.

Franssen, J., Lapointe, M., Magnan, P., 2014. Geomorphic controls on fine sediment reinfiltration into salmonid spawning gravels and the implications for spawning habitat rehabilitation. Geomorphology. 211, 11-21. doi: 10.1016/j.geomorph.2013.12.019.

Garner, P., 2010. Habitat use by 0+ cyprinid fish in the River Great Ouse, East Anglia. Freshwater Forum. 8 (1), 2-27.

Geist, J., 2011. Integrative freshwater ecology and biodiversity conservation. Ecol. Indic. 11 (6), 1507-1516. doi: 10.1016/j.ecolind.2011.04.002.

Giller, P.S., 2005. River restoration: seeking ecological standards. Editor's introduction. J. Appl. Ecol. 42 (2), 201-207. doi: 10.1111/j.1365-2664.2005.01020.x.

Hancock, P.J., 2002. Human impacts on the stream–groundwater exchange zone. Environ. Manage. 29 (6), 763-781. doi: 10.1007/s00267-001-0064-5.

Hassan, M.A., Tonina, D., Buxton, T.H., 2015. Does small-bodied salmon spawning activity enhance streambed mobility? Water Resour. Res. 51 (9), 7467-7484. doi: 10.1002/2015WR017079.

Hendry, K., Cragg-Hine, D., O’Grady, M., Sambrook, H., Stephen, A., 2003. Management of habitat for rehabilitation and enhancement of salmonid stocks. Fish. Res. 62, 171-192. doi: 10.1016/S0165-7836(02)00161-3.

Honea, J.M., Jorgensen, J.C., McClure, M.M., Cooney, T.D., Engie, K., Holzer, D.M. and Hilborn, R., 2009. Evaluating habitat effects on population status: influence of habitat restoration on spring-run Chinook salmon. Freshwater Biol. 54 (7), 1576-1592. doi: 10.1111/j.1365-2427.2009.02208.x.

Kemp, P., Sear, D., Collins, A., Naden, P., Jones, I., 2011. The impacts of fine sediment on riverine fish. Hydrol. Process. 25 (11), 1800-1821. doi: 10.1002/hyp.7940.

Kondolf, G.M., 2000. Assessing Salmonid Spawning Gravel Quality. T. Am. Fish. Soc. 129 (1), 262-281. doi: 10.1577/1548-8659(2000)129<0262:ASSGQ>2.0.CO;2.

Kottelat, M., Freyhof, J., 2007. Handbook of European freshwater fishes. Publications Kottelat, Switzerland.

Lapointe, M., Bergeron, N., Berube, F., Pouliot, M., Johnston, P., 2005. Interactive effects of substrate sand and silt contents, redd-scale hydraulic gradients, and interstitial velocities on egg-to-emergence survival of Atlantic salmon (*Salmo salar*). Can. J. Fish. Aquat. Sci. 61 (12), 2271-2277. doi: 10.1139/f04-236.

Levasseur, M., Bergeron, N.E., Lapointe, M.F., Bérubé, F., 2006. Effects of silt and very fine sand dynamics in Atlantic salmon (*Salmo salar*) redds on embryo hatching success. Can. J. Fish. Aquat. Sci. 63 (7), 1450-1459. doi: 10.1139/f06-050.

Maitland, P.S, Linsell, K., 2006. Guide to freshwater fish of Britain and Europe. Philip's, London.

McManamay, R.A., Orth, D.J., Dolloff, C.A., Cantrell, M.A., 2010. Gravel addition as a habitat restoration technique for tailwaters. N. Am. J. Fish. Manage. 30 (5), 1238-1257. doi: 10.1577/M10-007.1.

McNeil, W.J., Ahnell, W.H., 1964. Success of pink salmon spawning relative to size of spawning bed materials. US Department of Interior, Fish and Wildlife Service, Washington. Report no. 157.

Melcher, A.H. and Schmutz, S., 2010. The importance of structural features for spawning habitat of nase *Chondrostoma nasus* (L.) and barbel *Barbus barbus* (L.) in a pre-Alpine river. River Systems, 19 (1), 33-42. doi: 10.1127/1868-5749/2010/019-0033.

Merz, J.E., Ochikubo Chan, L.K., 2005. Effects of gravel augmentation on macro-invertebrate assemblages in a regulated California river. River Res. Appl. 21 (1), 61-74. doi: 10.1002/rra.819. Meyer, C.B., 2003. The importance of measuring biotic and abiotic factors in the lower egg pocket to predict coho salmon egg survival. J. Fish. Biol. 62 (3), 534-548. doi: 10.1046/j.1095-8649.2003.00039.x.

Meyer, E.I., Niepagenkemper, O., Molls, F., Spänhoff, B., 2008. An experimental assessment of the effectiveness of gravel cleaning operations in improving hyporheic water quality in potential salmonid spawning areas. River Res. Appl. 24 (2), 119-131. doi: 10.1002/rra.1051.

Michel, C., Schindler Wildhaber, Y., Epting, J., Thorpe, K.L., Huggenberger, P., Alewell, C., Burkhardt-Holm, P., 2014. Artificial steps mitigate the effect of fine sediment on the survival of brown trout embryos in a heavily modified river. Freshwater Biol. 59 (3), 544-556. doi: 10.1111/fwb.12284.

Montgomery, D.R., Beamer, E.M., Pess, G.R., Quinn, T.P., 1999. Channel type and salmonid spawning distribution and abundance. Can. J. Fish. Aquat. Sci. 6 (3), 377-387. doi: 10.1139/f98-181.

Montgomery, D.R., Buffington, J.M., Peterson, N.P., Schuett-Hames, D., Quinn, T. P., 1996. Stream-bed scour, egg burial depths, and the influence of salmonid spawning on bed surface mobility and embryo survival. Can. J. Fish. Aquat. Sci. 53, 1061-1070. doi: 10.1139/f96-028.

Morandi, B., Piégay, H., Lamouroux, N., Vaudor, L., 2014. How is success or failure in river restoration projects evaluated? Feedback from French restoration projects. J. Environ. Manage. 137, 178-188. doi: 10.1016/j.jenvman.2014.02.010.

Mueller, M., Pander, J., Geist, J., 2014. The ecological value of stream restoration measures: an evaluation on ecosystem and target species scales. Ecol. Eng. 62, 129-139. doi: 10.1016/j.ecoleng.2013.10.030.

Naura, M., Hornby, D.D., Collins, A.L., Sear, D.A., Hill, C., Jones, J.I., Naden, P.S., 2016. Mapping the combined risk of agricultural fine sediment input and accumulation for riverine ecosystems across England and Wales. Ecol. Indic. 70, 209-221. doi: 10.1016/j.ecolind.2016.03.055.

Neal, C., Jarvie, H.P., Williams, R.J., Pinder, L.C.V., Collett, G.D., Neal, M., Bhardwaj, L., 2000. The water quality of the Great Ouse. Sci. Total Environ. 251, 423-440. doi: 10.1016/S0048-9697(00)00420-4.

O'Connor, W.C.K., Andrew, T.E., 1998. The effects of siltation on Atlantic salmon, *Salmo salar* L., embryos in the River Bush. Fisheries Manag. Ecol. 5 (5), 393-401. doi: 10.1046/j.1365-2400.1998.550393.x.

Ordnance survey, 2005. GB National Outlines, Scale 1:250000 [online map]. Available from: http://digimap.edina.ac.uk [Accessed 29 April 2016].

Ordnance survey, 2015. Strategi® Map, Upper part of the River Great Ouse, GB, Scale 1:250000 [online map]. Available from: http://digimap.edina.ac.uk [Accessed 29 April 2016].

Palm, D., Brännäs, E., Lepori, F., Nilsson, K., Stridsman, S., 2007. The influence of spawning habitat restoration on juvenile brown trout (*Salmo trutta*) density. Can. J. Fish. Aquat. Sci 64 (3), 509-515. doi: 10.1139/f07-027.

Palmer, M.A., Allan, J. D., Meyer, J., Bernhardt, E.S., 2007. River restoration in the twenty-first century: data and experiential knowledge to inform future efforts. Restor. Ecol. 15(3), 472-481. doi: 10.1111/j.1526-100X.2007.00243.x.

Palmer, M.A., Covich, A., Finlay, B., Gilbert, J., Hyde, K., Johnson, R., Kairesala, T., Lake, P., Lovell, C., Naiman, R., Ricci, C., 1997. Biodiversity and ecosystem processes in freshwater sediments. Ambio, 571-577.

Palmer, M.A., Menninger, H.L., Bernhardt, E., 2010. River restoration, habitat heterogeneity and biodiversity: a failure of theory or practice? Freshwater Biol. 55 (s1), 205-222. doi: 10.1111/j.1365-2427.2009.02372.x.

Pander, J., Geist, J., 2013. Ecological indicators for stream restoration success. Ecol. Indic. 30, 106-118. doi: 10.1016/j.ecolind.2013.01.039.

Pander, J., Mueller, M., Geist, J., 2015. A comparison of four stream substratum restoration techniques concerning interstitial conditions and downstream effects. River Res. Appl. 31 (2), 239-255. doi: 10.1002/rra.2732.

Pattison, I., Sear, D.A., Collins, A.L., Jones, J.I., Naden, P.S., 2015. Interactions between fine-grained sediment delivery, river bed deposition and salmonid spawning success. PIAHS. 367, 199-206.

Pinder, L.C.V., 1997. Research on the Great Ouse: overview and implications for management. Regul. Rivers: Res. Manage. 13 (3), 309-315. doi: 10.1002/(SICI)1099-1646(199705)13:3<309::AID-RRR460>3.0.CO;2-J.

Pinder, L.C.V., Marker, A.F.H., Mann, R.H.K., Bass, J.A.B., Copp, G.H., 1997. The River Great Ouse, a highly eutrophic, slow-flowing, regulated, lowland river in eastern England. Regul. Rivers: Res. Manage. 13 (3), 203-218. doi: 10.1002/(SICI)1099-1646(199705)13:3<203::AID-RRR449>3.0.CO;2-F.

Pledger, A.G., Rice, S.P., Millett, J., 2014. Reduced bed material stability and increased bedload transport caused by foraging fish: a flume study with juvenile Barbel (*Barbus barbus*). Earth Surf. Process. Landf. 39, 1500-1513. doi: 10.1002/esp.3592 .

Pledger, A.G., Rice, S.P., Millett, J., 2016. Bed disturbance via foraging fish increases bedload transport during subsequent high flows and is controlled by fish size and species. Geomorphology, 253, 83-93. doi: 10.1016/j.geomorph.2015.09.021.

Powell, D.M., 1998. Patterns and processes of sediment sorting in gravel-bed rivers. Prog. Phys. Geogr. 22 (1), 1-32.

Pulg, U., Barlaup, B.T., Sternecker, K., Trepl, L., Unfer, G., 2013. Restoration of spawning habitats of brown trout (*Salmo trutta*) in a regulated chalk stream. River Res. Appl. 29, 172-182. doi: 10.1002/rra.1594.

R Development Core Team, 2011. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/.

Rice, S.P., Church, M., 1996. Sampling surficial fluvial gravels: The precision of size distribution percentile estimates. J. Sediment. Res. A. Sediment. Petrol. Process. 66 (3), 654-665. doi: 10.2110/jsr.66.654.

Rubin, J.F., Glimsäter, C., Jarvi, T., 2004. Characteristics and rehabilitation of the spawning habitats of the sea trout, *Salmo trutta*, in Gotland (Sweden). Fisheries Manag. Ecol. 11 (1), 15-22. doi: 10.1111/j.1365-2400.2004.00349.x.

Sarriquet, P.E., Bordenave, P., Marmonier, P., 2007. Effects of bottom sediment restoration on interstitial habitat characteristics and benthic macro-invertebrate assemblages in a headwater stream. River Res. Appl. 23 (8), 815-828. doi: 0.1002/rra.1013.

Sear, D.A., Burke, N., Bateman, S., Jones, J.I., Collins, A.L., Hulin, A., Pattison, I., Naden, P.S., 2016. Does fine sediment source as well as quantity affect salmonid embryo mortality and development? Sci. Total Environ. 541, 957-968. doi: 10.1016/j.scitotenv.2015.09.155.

Sepulveda, A.J., Layhee, M., Sutphin, Z.A., Sechrist, J. D., 2015. Evaluation of a Fine Sediment Removal Tool in Spring-fed and Snowmelt Driven Streams. Ecological Rest. 33 (3), 303-315. doi: 10.3368/er.33.3.303.

Shackle, V.J., Hughes, S., Lewis, V.T., 1999. The influence of three methods of gravel cleaning on brown trout, *Salmo trutta*, egg survival. Hydrol. Process. 13 (3), 477-486. doi: 10.1002/(SICI)1099-1085(19990228)13:3<477::AID-HYP751>3.0.CO;2-#.

Sternecker, K., Cowley, D.E., Geist, J., 2013a. Factors influencing the success of salmonid egg development in river substratum. Ecol. Freshw. Fish. 22 (2), 322-333. doi: 10.1111/eff.12020.

Sternecker, K., Wild, R., Geist, J., 2013b. Effects of substratum restoration on salmonid habitat quality in a subalpine stream. Environ. Biol. Fish. 96 (12), 1341-1351. doi: 10.1007/s10641-013-0111-0.

Trask, P.D., 1932. Origin and Environment of Source Sediments of Petroleum. Gulf Publishing Co, Houston, Texas.

Twine, K.G., 2013. Conservation of barbel (*Barbus barbus*) in the River Great Ouse. Thesis (PhD). Univeristy of Hull.

Venables, W.N., Ripley, B.D., 2002. Modern Applied Statistics with S, fourth ed. Springer, New York.

Wheaton, J.M., Pasternack, G.B., Merz, J.E., 2004a. Spawning habitat rehabilitation -I. Conceptual approach and methods. Intl. J. River Basin Management. 2 (1), 3-20.

Wheaton, J.M., Pasternack, G.B., Merz, J. E., 2004b. Spawning habitat rehabilitation – II. Using hypothesis development and testing in design, Mokelumne River, California, U.S.A. Intl. J. River Basin Management. 2 (1), 21-37.

Wilcock, P.R., McArdell, B.W., 1997. Partial transport of a sand/gravel sediment. Water Resour. Res. 33 (1), 235-245. doi: 10.1029/96WR02672.

Wood, P.J., Armitage, P.D., 1997. Biological effects of fine sediment in the lotic environment. Environ. Manage. 21 (2), 203-217. doi: 10.1007/s002679900019.