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<http://dx.doi.org/10.1016/j.ecoleng.2017.06.057>

PUBLISHER

© Elsevier

VERSION

AM (Accepted Manuscript)

PUBLISHER STATEMENT

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Basic, Tea, J. Robert Britton, Stephen P. Rice, and Andrew G. Pledger. 2019. "Impacts of Gravel Jetting on the Composition of Fish Spawning Substrates: Implications for River Restoration and Fisheries Management". figshare. <https://hdl.handle.net/2134/25970>.

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

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Running title: Gravel jetting impacts on spawning gravels

Keywords: Gravel jetting; *Barbus barbus*; Spawning gravels; Habitat management.

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23 **Abstract**

24 Fine sediments can impact river biota, with egg and larval stages of lithophilic fish
25 particularly sensitive to deposition of sand- to clay-sized particles ('fines') in spawning
26 gravels. Mitigation and restoration methods include jetting to cleanse gravels of fines.
27 Despite wide application, impacts of jetting on gravel composition and quality have
28 rarely been quantified. Here, gravel jetting impacts on sediment composition in the
29 River Great Ouse (UK), were tested during an *in-situ* experiment completed at riffle
30 ($55.6 \pm 13.4 \text{ m}^2$) and patch (0.3 m^2) scales to determine its magnitude and persistence on
31 surface and subsurface substrate conditions. Before-after (riffle) and control-impact
32 (patch) designs were used, with bedload sediment traps installed downstream of
33 experimental patches to investigate the sediments mobilised during jetting. At the riffle
34 scale, surface grain size was significantly altered; fines were removed resulting in
35 coarser and better-sorted sediments. Similar patterns were detected at the patch scale,
36 although sediment sorting was not significantly altered. Despite reduced fine sediment
37 content of subsurface gravels at the riffle scale, the overall grain size composition was
38 not significantly altered. At the patch scale, no subsurface improvements were detected.
39 Temporally, at the riffle scale, no changes in surface or subsurface sediments lasted
40 more than 12 months; patch scale changes generally persisted for less than 3 months.
41 Thus, whilst gravel jetting could improve spawning gravel quality for surface spawning
42 fishes, including European barbel *Barbus barbus*, its effects are short-lived. Because
43 subsurface sediments are not affected by gravel jetting, the benefits are limited for redd-
44 building fishes, such as salmonids. Consequently, reducing fine sediment delivery to
45 rivers, such as by changes in agricultural practices, is more sustainable for managing
46 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 et 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, 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, 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-economic 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 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 (spread of the grain size distribution), 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 km², 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, the fisheries regulatory authority of England, 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.

167

168 Figure 1. Location of the study reach in the UK, highlighting sampled riffles in the River Great Ouse between Newport Pagnell and
 169 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,
 170 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;
 171 sites 3, 5 and 6; patch scale) experiments (Ordnance survey 2005; Ordnance survey 2015).

The 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). The experiment was completed at two spatial scales; riffle (55.55 ± 13.35 m²²) and patch (0.25 m²: i.e. small areas within a riffle), to quantify how jetted area influences the magnitude and temporal persistence of restoration effects. The Environment Agency typically restores smaller patches of riffles during jetting. Therefore, patches always retained the same size of 0.25 m², whereas the size ranges of riffles utilised in the experiment varied from 26.88 m² to 98.04 m².

In 2014, five of these 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, because collecting a core sample
before jetting at a smaller scale would influence bed stability during patch-scale jetting,
hence outcomes of the procedure.

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222 Figure 2. Schematic diagrams presenting the experimental procedure for a) riffle-scale and b) patch-scale experiments, performed in
 223 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, $D5$, $D50$, $D95$ 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 $\approx 0.005 \text{ m}^3$; 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.

$D5$, $D50$, $D95$ 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).

$$\% \text{ organic matter} = \left(\frac{m_{pre} - m_{post}}{m_{pre}} \right) * 100 \quad (1)$$

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).

D_5 , D_{50} , D_{95} 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 by multiplying the average transported mass with corresponding riffle area, 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 $D5$ (LMM; $P < 0.01$), $D95$ (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 $D5$, $D50$ and $D95$ 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 quasilielihood; 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, $P > 0.05$

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395 Figure 3 Surface percentiles and statistical parameters significantly affected by
 396 treatment, pre-jetting (1), 24 hours post-jetting (2) and 12 months post-jetting (3) at the
 397 riffle scale. Thin horizontal lines represent 10, 25, 85 and 90 percentiles. Thick black
 398 horizontal lines, circles and asterisks represent medians, outliers and significant
 399 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 quasilielihood; 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; $P > 0.05$)

439 b)

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

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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 significantly affected the subsurface $D5$ (GLMM; $P < 0.05$), sand content (GLMM; $P < 0.05$) and silt content (GLMM; $P < 0.01$) (Table 3a). In contrast, $D50$ (LMM; $P > 0.05$), $D95$ (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 quasilielihood; 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; $P < 0.01^{**}$)

503 **b)**

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

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521 Table 4 Outputs from linear and mixed linear models testing for differences in
 522 subsurface sediment parameters between control and jetted patches 1 hour post-
 523 jetting. Mean differences are from estimated least-square means (difference
 524 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); $\chi^2 = 2.20$; $P > 0.05$)

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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 ($n = 9$; $\pm$ SE).

Metric	Value	
<i>D</i> 5 (mm)	0.29 ± 0.02	
<i>D</i> 50 (mm)	1.68 ± 0.47	
<i>D</i> 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. Jetting caused a reduction in the fines content of subsurface sediments at the riffle scale, and

most other grain size parameters were unaffected. 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) identified fewer significant alterations in surface percentiles (D_{50} , D_{84}) as a function of gravel restoration via modified suction dredging in North America, with a decrease in surface particle sizes following restoration. However, 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 a reduction in fines content at the riffle scale, but no change in D_{50} or 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 the 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 if riffle-scale jetting had been employed. 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 possible 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). It is then possible that scour depths would be increased (Montgomery et 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 downstream sediment displacement of predominantly sand-sized material, which could deposit in clean gravels downstream, with negative implications for habitats there (Pander et al. 2015). Although quantification of suspended sediment fluxes were beyond the scope of the study observations of suspended sediment plumes during jetting suggested the release of suspendable particles and their downstream displacement under baseflow conditions.

Mobilisation of these sediments 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 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). Eggs and larvae spend less time within gravels, especially as the warmer temperatures help minimise the time between egg deposition and emergence. Thus, the impacts of substrate fines might be limited. Even though the reductions in fine sediment achieved by jetting are short-lived, the technique might therefore be beneficial for 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 local 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 fish communities. 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 utilised post-jetting to enhance flows over restored areas, limiting fines ingress and potentially maintaining post-jetting conditions for longer periods. This is speculative but could be tested in future studies. 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 have been 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. At the largest scale, 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), because they address the cause of sedimentation in rivers, rather than treat the local ‘symptoms’. To be effective,

determination of fine sediment sources within catchments and their overall contributions to sediment fluxes are required (Collins and Walling 2007a, 2007b; Naura et al. 2016). However, these actions are often costly, time-consuming and not feasible without substantial policy changes. Therefore, it is particularly important 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 conservation. Approximately 5-70 USD/m² is spent on substrate improvements (e.g. gravel addition and cleaning), while placement of in-stream structures costs between 119 and 190 USD/m² (Cramer 2012) or around 20 000 USD per project in the USA (Bernhardt et al. 2005). 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.

5. Acknowledgments

This work was supported by a studentship funded by the Environment Agency and Barbel Society, UK.

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