Lowland stream restoration by sand addition: Impact, recovery, and beneficial effects on benthic invertebrates

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Funding information
Waterschap Vallei en Veluwe, Programma Lumbricus, and the Dutch ministry of Agriculture, Nature and Food Quality, Grant/Award Numbers: KB-24-001-007 and Project KB-24-001-007; CNPq Brazil, Grant/Award Number: 200879/2014-6, 2014

Abstract
Up to now, most lowland stream restoration projects were unsuccessful in terms of ecological recovery. Aiming to improve the success of stream restoration projects, a novel approach to restore sandy-bottom lowland streams degraded by channel incision was launched, consisting of the addition of sand to the stream channel in combination with the introduction of coarse woody debris. Yet it remained unknown whether this novel measure of sand addition is actually effective in terms of biodiversity improvements. The aim of the present study was therefore to evaluate if sand addition can improve hydromorphological stream complexity on the short term leading to an increase in macroinvertebrate biodiversity. To this end, particle transport, water depth, current velocity, dissolved oxygen dynamics, and sediment composition were measured. The response of the macroinvertebrate community composition was determined at different stages during the disturbance and short-term recovery process. Immediately downstream the sand addition site, transport and sedimentation of the sand were initially intense, until an equilibrium was reached and the physical conditions stabilized. The stream section matured fast as habitat formation took place within a short term. Macroinvertebrate diversity decreased initially but recovered rapidly following stabilization. Moreover, an increase in rheophilic taxa was observed in the newly formed habitats. Thus, although sand addition initially disturbed the stream, a relatively fast physical and biological recovery occurred, leading to improved instream conditions for a diverse macroinvertebrate community, including rheophilic taxa. Therefore, we concluded that sand addition is a promising restoration measure for incised lowland streams.

KEYWORDS
channel incision, instream habitat restoration, macroinvertebrates, rheophilic species, sand addition, sedimentation
1 | INTRODUCTION

Channelization, embankment, and water table regulation by weirs have a profound effect on the natural hydromorphological processes in many streams around the world (Simon, 1989). As a consequence, natural streams became homogenized channels, with high discharge dynamics (floods and droughts) and low substrate loads (Bartley & Rutherfurd, 1999). Particularly in lowland areas, many streams were straightened (Verdonschot & Nijboer, 2002), and the subsequent channelization and water table regulation led to a decrease in sediment supply and an increase in particle transport (Bukaveckas, 2007), jointly causing streambed incision. This channel incision negatively affects streambed and bank heterogeneity (Lau, Lauer, & Weinman, 2006; Simon & Rinaldi, 2006) and isolates the aquatic from the terrestrial ecosystems (Bartley & Rutherfurd, 1999), resulting in both habitat and biodiversity losses (Downes, Lake, & Schreiber, 1995).

The importance of recovering the natural hydromorphological complexity and land–water connection of channelized streams is widely recognized, leading to the first restoration attempts focusing on small-scale interventions in stream channels and riparian zones (Lake, 2007). It was assumed that due to stream morphology restoration by physical habitat improvements, species would return and ecological functions would be re-established (Jähnig et al., 2010; Palmer et al., 2005; Pander & Geist, 2013). Yet, despite the diverse options for stream morphology restoring measures (Brookes & Shields, 1996), up to now, most restoration projects were not very successful in terms of ecological recovery (Palmer et al., 2005).

Aiming to improve the success of stream restoration projects, a novel approach to restore sandy-bottom lowland streams degraded by channel incision was launched by water and nature managers, which consists of the addition of sand to the stream channel in combination with the introduction of coarse woody debris. Although sand inputs are generally recognized as a stressor in high-gradient gravel-bed streams and rivers (e.g., Rosenfeld et al., 2011), in low-gradient streams, sand is the natural dominant substrate. Hence, instead of posing a threat, the addition of sand might actually improve the ecological quality of incised lowland streams. Sand addition may increase streambed height and heterogeneity through hydraulic changes and may restore the link between the stream and the surrounding terrestrial ecosystems by producing a wider and shallower streambed (Lisle, 2008). It is expected that by decreasing the channel dimensions over a relatively large spatial scale, inundation of the stream valley during spates would be stimulated, resulting in less streambed erosion and in turn an increase in instream hydromorphological habitat heterogeneity that sustains a higher biodiversity. By reconnecting the stream to its valley, it is anticipated that land–water gradients can recover, revitalizing both the stream and the riparian zone (Pilotto et al., 2018). Yet it is not known whether this novel measure of sand addition is actually effective in terms of biodiversity improvements. The aim of the present study was therefore to evaluate if sand addition can improve hydromorphological stream complexity leading to an increase in macroinvertebrate biodiversity.

Directly after the sand addition, the sand movement disturbs the stream ecosystem, after which physical and biological recoveries are expected to take place, improving habitat heterogeneity and macroinvertebrate diversity. Our hypothesis was that recovery after the initial disturbance takes place within a short time span, and therefore, our research efforts were concentrated on studying the initial instream recovery of habitats and macroinvertebrate biodiversity.

To study the short-term instream physical changes induced by sand addition and the effects on the receiving stream ecosystem, sediment traps were installed to measure particle transport. Additional effects on depth, current velocity, sediment composition, and effects on dissolved oxygen were regularly measured. Furthermore, macroinvertebrate community composition was determined at different phases of the sand addition and the short-term recovery processes.

2 | MATERIALS AND METHODS

2.1 | Study area

The sand addition experiment took place in the Leuvenumse stream (52°19′08″N, 5°42′24″E), the Netherlands. The Leuvenumse stream is part of the Hierdense stream catchment, which is characterized by sandy soils and a slope of 1.3 m/km (0.13%; de Klein & Koelmans, 2011). The stream is a typical low-gradient, slow-flowing, sand-bed lowland stream, with an average daily discharge of 0.23 m³/s (1994–2018), an approximate width of 4 m, and a maximum depth of 1 m. The stream channel is fully shaded by deciduous and coniferous forest. For further description of the studied stream, see Verdonschot, Oosten-Siedlecka, Braak, and Verdonschot (2015).

Historical changes in upstream land use, in which peat marshes were drained and turned into agricultural grassland and cropland, in combination with channelization and regulation of most of the stream, have resulted in a channel incision up to 1 m in the downstream forested stretch in which the present study was executed.

2.2 | Outline of the study

Sand was added at seven sites along a 3-km stretch (Figures 1 and S3). Upstream channelized incised stretches were used as controls, positioned upstream of the sand addition sites.

The sand originated from a nearby drift sand rehabilitation project (Hulshorstzerzand), in which the top soil layer was removed to initiate aeolian geomorphic processes. This sand is characterized by a low percentage of organic matter (average 0.4%) and a small grain size (average phi 2.4). Sand was added on four to seven occasions between 2014 and 2016, by scooping material into the stream channel by an excavator (Figure 1). On forehand, dead woody debris patches were added to the sand addition sites, as sand retention structures.

At each sand addition site, the stream stretch was divided longitudinally into nine plots (Figure 2): four plots upstream (Plots I, II, II, and IV), four plots downstream (Plots VI, VII, VIII, and IX), and one plot including the sand entry point (Plot V).
During the first 4 weeks after the sand addition, physical stream disturbance was assessed by measuring sediment transport, hydraulic conditions (current velocity and water depth), and proportional substrate cover. After these 4 weeks, when most of the sand had settled, the nutrient concentrations and percentage organic matter in the deposited sediment were characterized. Furthermore, oxygen probes were installed to evaluate potential effects of the changed instream conditions on dissolved oxygen saturations. Finally, the response of the macroinvertebrate community to the changing instream conditions was determined.

2.3 | Sediment transport, hydraulic conditions, and substrate cover

Because the installation of sediment traps disturbed the stream bottom, the most downstream sand addition site (S7) was chosen to perform these measurements, to avoid influencing the other sand addition sites (Figure 1).

The physical measurements took place in four plots upstream (I, II, III, and IV) and four plots downstream of the sand addition site (VI, VII, VIII, and IX). Plot V, the actual sand addition site, was not used for measurements, because the huge amount of sand deposited in the stream prevented a proper installation of samplers and measurements.

Each of the eight plots was divided into 33 grid cells of one square meter. In each plot, 14 grid cells were randomly selected: nine for streambed sediment traps (Gordon, McMahon, Finlayson, Gippel, & Nathan, 2004) and five for suspended sediment traps (Liess, Schulz, & Neumann, 1996) installation. To collect rolling and jumping particles, further indicated as bed-load transport, the streambed sediment traps were placed in such a way that the entrance was at the level of the stream bottom. To collect suspended particles, the entrance of the suspended sediment traps was positioned at a height of 15 cm above the stream bottom.

On July 2, 2015, about 50 m³ of sand was deposited in the stream at Site S7, and sediment transport measurements started by opening the preinstalled sediment traps. The exposure time of the sediment...
traps varied between 18 and 160 hr, in which the exact exposure time depended on the time necessary to collect sufficient particles in the traps to conduct further analyses but at the same time preventing that the traps would become overfilled with sediment. Measurements were repeated weekly, over a period of 4 weeks. Current velocity, depth, and substrate cover measurements took place weekly as well, just before collecting the sediment traps.

The amount of suspended and bed-load sediment was determined by weighing the amount of sediment collected, after drying at 70°C to a constant weight. The data were standardized to grams of particles collected during 24 hr. Particulate organic matter content of the transported sediment was measured by loss on ignition. After overnight drying at 105°C, a standardized 5-g subsample was taken, burned at 550°C for 16 hr, and weighed again at a precision scale (0.1 mg). Grain size was determined by first wet sieving approximately 20 g of sediment with a 0.063-mm sieve, followed by dry sieving with a set of sieves (1, 0.5, 0.25, and 0.125 mm) and weighing the retained material per sieve. Afterwards, the graphic mean was calculated according to Folk (1980).

Discharge was measured daily at a gauging station just downstream of the sand addition sites in 2014–2016. Current velocity was measured with an electromagnetic sensor (SENSA/ADS, model RC2;v6d) and depth with a ruler. Weekly, substrate composition per plot was estimated visually, and the substrate types as defined by Hering et al. (2003) were expressed on a percentage cover scale (0–100%).

2.4 | Sediment composition and oxygen regime after stabilization of the streambed

Quantification of the sand addition effects on dissolved oxygen regime and deposited sediment organic matter was performed at sand addition Site S2, upstream of Site S7, to avoid interference with the sediment transport measurements. The site was divided into plots as described in Figure 2, and measurements took place in Plots I, IV, V, VI, and IX.

In August 2015, 4 weeks after the third sand addition took place, dissolved oxygen concentrations were determined, and sediment composition measurements were performed. At this sampling occasion, three replicate sediment samples were taken from the five plots at Site S2, using an acrylic core. The samples were dried at 70°C, sieved over a 2-mm sieve, and ball-milled for 5 min at 400 RPM. For each sample, sediment composition was measured in duplicate. Particulate organic matter content of the sediment was measured by loss on ignition in the same way as described previously for the transported sediment. Carbon (C), nitrogen (N), and sulphur (S) concentrations were determined using an elemental analyser (Elementar Vario EL, Hanau, Germany). Total phosphorus (TP) was determined by first igniting 1 to 2 g of sediment at 500°C for 16 hr, after which the remaining sediment was extracted with 0.5M sulfuric acid, and finally, particulate inorganic phosphorus was determined by using the colorimetric molybdenum blue method (Murphy & Riley, 1962).

Dissolved oxygen concentration and water temperature were recorded at a 15-min interval during 3 days using Hach LDO (Luminescent Dissolved Oxygen) dissolved oxygen probes (Hach Company, Loveland, CO, USA), placed just above the streambed in Plots I, IV, V, VI, and IX of Site S2.

2.5 | Macroinvertebrate community composition

Macroinvertebrates were sampled at five sand addition sites: S1, S2, S3, S4, and S5, in October 2014. The five sites were considered replicates. Four types of plots were selected at each of the five replicate sand addition sites: (a) plots recently covered by sand, which was slowly moving in downstream direction, representing the initial disturbed situation; (b) plots just upstream of the sand addition point, where flow obstruction resulting from the sand addition caused siltation; (c) stabilized plots in the process of habitat formation, representing the recovery phase of the stream ecosystem; (d) upstream of the five sand addition sites plots were selected as controls.

From each plot per site, three Surber samples (625 cm²; mesh size: 0.5 mm) were sorted alive in the field (time to scan a sample was standardized to 5 min), identified to family level and pooled. Abundances were estimated using abundance classes (1, 1 individual; 2, 2–5 individuals; 3, 6–25 individuals; 4, 26–100 individuals; and 5, >100 individuals). Additionally, species richness (taxa number), Shannon-Wiener diversity index, and the Ephemeroptera, Plecoptera, and Trichoptera richness were calculated. The rheophilic taxa richness was derived using the flow preference classification from the autecological database for freshwater organisms, Version 7.0 (Schmidt-Kloiber & Hering, 2015). The size of the autumn species pool for this specific catchment was obtained from Westveer, van der Geest, Emiel van Loon, and Verdonschot (2018). Based on this information, the proportion of the number of rheophilic taxa present in the plots was calculated.

2.6 | Statistics

Log-transformed data of depth, current velocity, oxygen regime, organic matter, macroinvertebrate abundances, and indexes were tested separately using one-way analysis of variance, followed by a Tukey post hoc test (R-package stats). In those cases where the conditions of data normality (Shapiro–Wilk test) and homogeneity of variances (Levene’s test) were violated, differences between means were calculated using a nonparametric Kruskal–Wallis test, followed by Mann–Whitney U tests to make pairwise comparisons (Bonferroni corrected) to compare the different plots (R-package multcompView).

To evaluate macroinvertebrate community structure among plots, a multivariate ordination procedure, nonmetric multidimensional scaling, was performed on log-transformed taxon-abundance data (R-package Vegan) followed by an analysis of similarities (R-package Vegan) to test differences between sites.
3 | RESULTS

3.1 | Sediment transport

Higher suspended and bed-load sediment transport was observed in the plots downstream of the sand addition site compared with the upstream plots (Figure 3a,b and Tables S1 and S2). During the studied period, there was a tendency of decreasing bed-load sediment transport towards Week 4 in Plots VI, VII, and VIII, whereas in Plot IX, bed-load sediment transport increased towards Week 4 (Figure 3b).

In agreement with the lower transport of bed-load sediment upstream, the ratio between bed-load and suspended sediment transport was always lower in the plots upstream to the sand pile (I, 1.5 ± 0.8; II, 1.7 ± 0.8; III, 0.9 ± 0.5; and IV, 1.5 ± 0.8) in comparison with the downstream plots (VI, 34.7 ± 32.8; VII, 13.55 ± 9.1; VIII, 10.8 ± 10.9; and IX, 3.6 ± 3.1; mean and standard deviation were calculated per plot among weeks), where the bed-load transport was at least three times higher than the suspended transport. In the downstream plots (VI, VII, VIII, and IX), the contribution of bed-load particles decreased, whereas suspended particles transportation increased gradually towards Plot IX.

3.2 | Composition of the transported sediment

Both the suspended sediment and the sediment transported as bed-load in the plots upstream of the sand addition site (Plots I, II, and IV) contained a significantly \( P < .05 \) higher organic matter percentage than the sediment transported in the plots positioned downstream of the sand addition site (Plots VI, VII, VIII, and IX; Table 1). In the upstream plots, grain size of the transported material decreased (phi increased) gradually in the direction of the sand addition site for both suspended and bed-load sediment. The suspended particle grain size was significantly smaller than the bed-load grain size, except in Plots VIII and IX, where the suspended and bed-load grain sizes and organic matter content were similar.

3.3 | Hydraulic conditions: Discharge, current velocity, and water depth

The median discharge recorded during the study period (2014–2016) was 0.13 m\(^3\)/s, ranging from 0.02 to 0.82 m\(^3\)/s (Figure S1). In Plots III and IV of Site S7, current velocity was always significantly

![Figure 3](image.png)

**TABLE 1** Mean percentage organic matter (OM) and grain size (phi) of suspended (n = 5; ±1 SD) and bed-load (n = 9; ±1 SD) sediment collected over 4 weeks after the sand addition

| Plot | I | II | III | IV | V | VI | VII | VIII | IX |
|------|---|----|-----|----|---|----|------|-------|----|
| Suspended | | | | | | | | | |
| OM % | 28.6 (9.7)\(a\) | 42 (9.8)\(a\) | — | 44.3 (6.6)\(a\) | — | 1.3 (0.6)\(b\) | 1.6 (0.7)\(b\) | 1.8 (1.3)\(b\) | 9.5 (13.8)\(b\) |
| Phi | 3.7 (0.7)\(ab\) | 3.8 (0.5)\(ab\) | — | 4.2 (0.3)\(ab\) | — | 3.1 (0.4)\(ab\) | 3.2 (0.5)\(ab\) | 2.6 (0.4)\(b\) | 2.8 (0.2)\(a\) |
| Grain size classification | Very fine sand | Very fine sand | — | Coarse silt | — | Very fine sand | Very fine sand | Fine sand | Fine sand |
| Bed load | | | | | | | | | |
| OM % | 13.1 (8.5)\(a\) | 23.9 (17)\(a\) | — | 25 (17.3)\(a\) | — | 1.7 (1.1)\(b\) | 1.2 (1.5)\(b\) | 1.5 (2.3)\(b\) | 8.7 (13.1)\(ab\) |
| Phi | 2.2 (0.3)\(a\) | 2.9 (0.7)\(a\) | — | 3.5 (0.2)\(a\) | — | 2.5 (0.5)\(b\) | 2.5 (0.4)\(a\) | 2.5 (0.2)\(a\) | 2.8 (0.3)\(ab\) |
| Grain size classification | Fine sand | Fine sand | — | Very fine sand | — | Fine sand | Fine sand | Fine sand | Fine sand |

Note. Letters indicate significant differences between the means \( P < .05 \).
(p < .05) lower (Figure 4a and Table S4 in) and depth was always significantly (p < .05) higher (Figure 4b and Table S5) than in Plot I and all downstream plots, except for Plot IX in Weeks 1 and 2. Depth decreased significantly (p < .05) in the downstream sections (Plots VI, VIII, and IX) after Week 1 (Figure 4b and Table S5). In Plot IX, the current velocity became significantly (p < .05) higher in Weeks 3 and 4, and depth decreased towards Week 4 (Table S5).

3.4 Substrate cover, sediment composition, and oxygen regime

The proportional substrate cover patterns differed among the plots (Figure 5). Plot I (the upstream control site) deviated from all other plots, having a heterogeneous substrate cover during all 4 weeks (Figure 5). Substrate cover of Plots II–IV (upstream of the sand addition site) was constant as well but strongly dominated by fine particulate organic matter (FPOM). Plots VI–VIII, downstream of the sand addition site, were sand-dominated during all 4 weeks, whereas in Plot IX, the transition from an organic stream bottom to a sand-dominated situation was observed with sand entering the plot from upstream. Simultaneously, habitat formation took place in Plot VI, where the proportional cover of other substrates than sand increased in Week 4.

After stabilization of the streambed, percentage particulate organic matter, nitrogen, sulphur, carbon and phosphorus concentration and C/N ratio were all significantly (p < .05) lower in Plots V and VI compared with Plot I (Table S3). Dissolved oxygen saturation values were comparable in of these all plots and were never below 67% saturation (Figure S2).

3.5 Macroinvertebrate community composition

The nonmetric multidimensional scaling ordination of the macroinvertebrates sampled at the five replicate sites showed that the

FIGURE 4  (a) Current velocity (m/s) and (b) depth (cm) per plot (I–IV upstream and VI–IX downstream) at sand addition Site S7 during the first 4 weeks after sand was supplied to the stream channel. The dots represent the sampling points (15 per plot) [Colour figure can be viewed at wileyonlinelibrary.com]
macroinvertebrate community composition of the control and siltation plots was comparable. The plots recently covered by moving sand and those that recovered from the sand addition differed from the control and siltation plots but also from each other (Figure 6; analysis of similarities: $r = .54$, $p = .001$).

The differences in macroinvertebrate community composition were further expressed by Shannon–Wiener diversity and rheophilic taxa richness. Diversity and total richness were significantly ($p < .05$) lower in the plots recently covered by sand, whereas rheophilic taxa richness was significantly ($p < .05$) higher in the recovering plots (Figure 7 and Table S6). Moreover, in the recovered plots, on average 25.3% of all rheophilic taxa occurring in the streams' catchment and 30% of the taxa recorded in the stream were collected. These numbers were significantly ($p < .05$) higher in comparison with the other plot types (Table S6).

4 | DISCUSSION

Aiming to improve the success of stream restoration projects, a novel approach to restore sandy-bottom lowland streams degraded by channel incision was launched, but it remained unknown whether this novel measure of sand addition is actually effective in terms of biodiversity improvements. The aim of the present study was therefore to...
evaluate if sand addition can improve hydromorphological stream complexity on the short term leading to an increase in macroinvertebrate biodiversity, as discussed below.

4.1 | Hydromorphological effects of sand addition

As a novel restoration measure, large amounts of sand were added to the presently studied lowland stream. Sand coverage of the streambed and sediment transport initiated immediate disturbance and short-term recovery processes within the stream ecosystem. This resulted in a characteristic sequence of instream spatiotemporal hydromorphological changes. As a result of the sand addition, the water flow was partially blocked at the upstream beginning of the sand slug, where the suddenly sloping bed acted as a physical obstruction. In agreement with the observations of Smakhtin (2001), this obstruction resulted in local flow cessation, leading to the accumulation of fine organic material on the streambed in Plots II, III, and IV.

The sand added to the stream channel formed a sand slug, which moved downstream in a wavelike motion, a dynamic sequence of transport and storage, in a similar way as previously reported by Bartley and Rutherfurd (1999) and Pryor, Lisle, Montoya, and Hilton (2011). In our study, waves of moving sediment particles resulted in major changes in substrate and hydrological conditions, in line with James (2010) and Sims and Rutherfurd (2017). This might explain the observed high variability in the amount of trapped sediment among and within traps. Timing, duration, and magnitude of the impact of the sand addition on the downstream plots were determined by sediment and streambed characteristics, as well as by hydraulic parameters, as also reported by James (2010). In accordance with other studies (e.g., Bankert & Nelson, 2018; Buendia, Gibbins, Vericat, & Batalla, 2014; Pryor et al., 2011), we observed that eventually all downstream plots (VI to IX) went through a phase of burial and dynamic sand movement, in which the entire streambed was covered by a layer of sand. The sediment pulses established a new sandy-bottom condition, in line with Madej, Sutherland, Lisle, and Pryor (2009). This caused a homogenization of the local channel topography, whereas the new bottom also contained a lower organic matter percentage and lower nitrogen, carbon, and phosphorus concentrations, which is not surprising given the origin of the material, which consisted of drift sand relatively poor in organic matter and nutrients.
In Plot V, where the sand was added to the stream channel, the phase of streambed instability was followed by a phase of stabilization. In the plots downstream of the sand addition site, particles settled and a sediment sorting gradient developed. Fine grains were washed out or transported as bed load and accumulated downstream, whereas the coarser material remained in position.

At the same time, instream and terrestrial derived fine and coarse particulate organic matter, and dead woody debris were deposited on the streambed, increasing substrate heterogeneity further. These changes initiated the recovery of the stream ecosystem. It is expected that the introduced coarse woody debris patches will retain the sand and prevent further downstream migration of the sand sludge, promoting faster bed modification. Together with a gradual accumulation of coarse organic material and dead woody debris from the adjacent terrestrial environment, the fine particulate organic matter from the upstream plot (IV) and the new hydraulic conditions resulted in a habitat recovery gradient starting at Plot V. This habitat formation processes is in line with the observations made by Phillips (2009), Cummins and Klug (1979), and Jordan, Correll, and Weller (1997).

The upstream and downstream effects of the sand addition on the hydraulic conditions led to the prediction of impacts on ecosystem processes such as decomposition, sediment oxygen demand, and therefore, differences in dissolved oxygen regimes (Jones et al., 2012). Nevertheless, 4 weeks after the sand addition, dissolved oxygen regime showed no variation among plots, all showing relatively high dissolved oxygen concentrations. This may be explained by the continuous inflow of oxygen-rich water from upstream and the low organic matter content, decreasing the influence of bottom respiration (Verdonschot et al., 2015).

### 4.2 Effects on macroinvertebrate community composition

Sand addition led to an initial decrease in macroinvertebrate richness. This was expected given the detrimental effects of sedimentation previously observed in other studies (e.g., Larsen, Pace, & Ormerod, 2011; Murphy et al., 2015). Nonetheless, the adverse effects of the sand addition were followed by a rapid recovery in terms of richness, diversity, and representation of Ephemeroptera, Plecoptera, and Trichoptera taxa and an increase in the number of rheophilic taxa. This fast colonization is in line with observations of Westveer et al. (2018), who studied the colonization of reconnected former channels in the same stream in autumn. In the recovered plots, the increased habitat heterogeneity appeared to have provided suitable habitat and flow conditions for the arriving colonists (Astudillo, Novelo-Gutiérrez, Vázquez, García-Franco, & Ramirez, 2016; Eros & Campbell Grant, 2015; Matthai, Weller, Kelly, & Townsend, 2006; Muehlbauer, Collins, Doyle, & Tockner, 2014; Rolls et al., 2018), which might have opened a “window of opportunities” (sensu Balke, Herman, & Bouma, 2014) for the rheophilic species present in the catchment.

This increased occurrence of rheophilic taxa showed the importance of longitudinal connectivity in recovery processes (Lake, Bond, & Reich, 2007). Pilotto et al. (2018) pointed out that the positive responses of aquatic organisms to restoration projects might be related to a combination of local and regional-scale approaches. By tackling local hydromorphological improvements in a stream stretch and at the same time connecting restored sites to sites with high-quality macroinvertebrate source populations, streams may benefit most from restoration efforts.

Although our study only recorded the short-term effects of sand addition, eventually, all downstream impacted plots were expected to recover in a similar way as we observed in the plot closest to the initial sand addition. Additionally, we observed that taxa present in the unimpacted parts of the catchment colonized the stabilized stretches, indicating that within this catchment, dispersal limitation does not hamper recovery, as often observed in restoration projects (Sarremejane, Mykrä, Bonada, Aroviita, & Muotka, 2017; Sundermann & Stoll, 2011; Westveer et al., 2018). Such a fast biotic recovery suggests a high resilience of lowland stream ecosystems, an important condition to make restoration projects successful (Palmer et al., 2005).

### 5 RECOMMENDATIONS FOR SAND ADDITION RESTORATION PROJECTS

As a practical recommendation, the sand addition technique should be used only under specific conditions: in low gradient streams; gradually applied over time; spatially distributed along the stream interspersed with treatment-free stretches for maintaining instream organic matter and invertebrate source population in the upstream catchment; in stream stretches constrained by dead woody debris patches to limit further sand sludge dispersion; and in a suitable landscape matrix, allowing input of terrestrial coarse organic matter, essential for the increase in habitat patchiness. Furthermore, long-term and larger scale monitoring is suggested to validate the expected aquatic–terrestrial changes from sand addition, such as riparian zone reconnection, stream valley rewetting, and improvements on ecosystem structures and processes.

### 6 CONCLUSIONS

The evident hydromorphological differences among downstream and upstream plots showed that the stream channel had undergone major changes after the sand addition. In the downstream plots, raising the streambed quickly led to new hydrological conditions characterized by a sandy bottom in a shallow stream with a higher current velocity. These characteristics are commonly described as negative side effects of sand waves in studies of catchment erosion, but in the present case, they were counteracting the negative effects of channel incision by elevating the stream bed and improving flow conditions.

In conclusion, this study confirmed the hypothesis that sand addition initially disturbed the stream ecosystem, but this was followed by a fast recovery leading to increased substrate heterogeneity and improved flow conditions. Lowland macroinvertebrate assemblages benefited from the habitat changes induced by the sand addition,
among others, reflected by an increasing proportion of rheophilic taxa within the macroinvertebrate community. Already on a short term, the negative effects of the sand addition started to become outweighed by the positive effects, indicating that sand addition could be a promising restoration measure for incised low gradient streams.

ACKNOWLEDGEMENTS

We would like to thank Natuurmonumenten and Waterschap Vallei and Veluwe for providing the opportunity to study the sand additions in the Leuvenumse stream, Maarten Veldhuis for providing the picture of the sand addition, Thijis de Boer for helping with GIS, and João Lotufo, Dorine Dekkers, and Mariska Beekman for their help in the field. We thank laboratory technicians Chiara Cerli, Joke Westerveld, and Leo Hoitinga. P. C. R. O. received funding from CNPq Brazil (Grant Number 200879/2014-6, 2014), and R. C. M. V. was funded by Waterschap Vallei en Veluwe, Programma Lumbriicus, and the Dutch ministry of Agriculture, Nature and Food Quality (Project KB-24-001-007).

CONFLICT OF INTEREST

The authors declare no conflict of interests.

DATA AVAILABILITY STATEMENT

Data are available from the Zenodo data repository and openly accessible via http://doi.org/10.5281/zenodo.2631774

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