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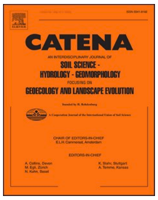

Suitability and sustainability of spawning gravel placement in degraded river reaches, Belgium

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ABSTRACT

Restoring in-stream spawning habitats in degraded rivers has received increasing attention as a tool for mitigating local wild fish population declines, notably in response to the European Water Framework Directive (WFD). However, spawning gravel placements are far too often designed without accurate knowledge of the morphodynamic river processes, resulting in a limited efficacy and longevity of the artificial spawning ground. To address the combined effects of bedload transport and fine sediment clogging processes on the sustainability of artificial spawning gravel habitats, we examined the effects of such rehabilitation actions on six degraded river reaches in Wallonia, Belgium. The monitoring scheme was based on the evolution of the thickness and clogging of the spawning gravel (using wooden stakes driven into the gravel layer to measure the depth of the anoxia) and on the PIT-tagged tracking of gravel dispersion over a period of 3.6–8.5 yrs. On the one hand, the results highlighted that several artificial spawning grounds were quickly clogged because of improper sizing of the spawning material. Gravel that was too coarse to be mobilized by the river and that had a narrow grain size range favoured fine sediment accumulation within the interstices of the gravel layer. On the other hand, one spawning gravel placement was rapidly scoured (after 2.2 yrs) because of an undersizing of the gravel with respect to flow competence. In the end, one gravel placement presented adequate gravel sizing, allowing periodic gravel transport over short distances (the mean annual travel distance was ~3 m). The longevity of a gravel placement and the ability of the displaced gravel to form new spawning grounds downstream were strongly dependent on the distance that the placed gravel was likely to travel, which in turn depended on several hydromorphological parameters, such as unit stream power, channel morphology and bed texture. The key parameters highlighted in this study need to be acknowledged when designing spawning gravel placement projects.

1. Introduction

Many rivers have been profoundly altered by human activities (e.g., channelization, land use change, and damming), resulting in morphological changes in river channels (Gregory, 2006; Brown et al., 2018) and consequences on physical and ecological processes (Petts, 1984; Brookes, 1988). Such disturbances cause different types of degradation, including in-stream habitat loss associated with global declines in freshwater biodiversity (Palmer et al., 2007; Geist, 2011). Since the nineties, efforts to restore altered streams have subsequently increased (Sear, 1994; Brierley and Fryirs, 2005; Wohl et al., 2005, 2015), and in-stream habitat restoration was among the most frequently used types of restoration measures (Bernhardt et al., 2005; Morandi et al., 2014). In-stream gravel augmentation, that is, artificially adding bed material to the channel, has received increasing attention as a tool for mitigating the effects of sediment deficits below dams (Gaeuman, 2012; Liedermann et al., 2013; Rollet et al., 2014; Heckmann et al., 2017) and for rehabilitating degraded spawning habitats of lithophilic fish species (Iversen et al., 1993; Kondolf et al., 1996). In that respect, the addition of spawning gravel has become a popular tool, first in dammed rivers of North America (Kondolf et al., 1996; Wheaton et al., 2004; Merz et al., 2006; Zeug et al., 2014; Gaeuman et al., 2017) and thereafter in Japan (Ock et al., 2013) and Europe (Iversen et al., 1993, Barlaup et al., 2008; Pedersen et al., 2009; Pulg et al., 2013), notably in response to the European Water Framework Directive (WFD), which requires that the ecological functioning and quality of rivers achieve at least a "good

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ecological status” (European Commission, 2000).

In regulated rivers, the restoration of spawning substrate by gravel placement is commonly seen as one of the most important mitigation measures to stem local wild fish population declines (Barlaup et al., 2008; Pasternack, 2008). However, far too often, spawning gravel placements are designed on an empirical basis. While the biological requirements of lithophilic spawning fishes are generally taken into account, few considerations are given to river processes (i.e., gravel entertainment by floods and fine sediment clogging), and the longevity of spawning grounds can be strongly affected. The downstream displacement of gravels during floods can induce scour that threatens eggs laid in the bed and exposes deeper levels to the infiltration of fine sediment (Lisle, 1989). Moreover, the resulting decrease in the thickness of the spawning ground may affect its suitability and reduce its sustainability, considering the burial depths of the lithophilic fish species (Merz et al., 2006; Barlaup et al., 2008; Pedersen et al., 2009; Hauer et al., 2011). On the other hand, channel stability is not an appropriate goal for spawning habitat restoration because a lack of scour can favour the accumulation of fine sediment in a gravel habitat, which reduces the gravel permeability, interstitial velocity and oxygen supply to buried eggs, resulting in increased embryonic mortality (Wood and Armitage, 1997; Acornley and Sear, 1999; Greig et al., 2005; 2007). Moreover, fine sediment clogging can also threaten the ability of fish to spawn, although some salmonid species have the capacity to clean gravel by redd cutting (Kondolf et al., 1993).

Although gravel addition projects are common, assessments of their efficiency and sustainability are limited (Kondolf and Micheli, 1995; Wheaton et al., 2004; Morandi et al., 2014; Staentzel et al., 2020). Most assessments are based on the short-term benefits of gravel augmentation schemes and rely on biotic indicators, such as the occurrence of redds observed on introduced gravels, the quantification of fry emergence density, and the fish population structure (Barlaup et al., 2008; Pedersen et al., 2009; Pulg et al., 2013; Zeug et al., 2014). Relatively few studies have been performed to evaluate the persistence of spawning grounds over time, focusing on abiotic parameters, in particular, on the interactions between sediment transport processes and the sustainability of rehabilitated spawning grounds. Some assessments aim to evaluate the quality of the spawning substratum by measuring the percentage of fine sediment within the spawning gravel substrate (i.e., the ratio of matrix sand, silt and clay clasts to the framework gravel sizes) (Merz et al., 2004; Heywood and Walling, 2007). For instance, Pulg et al. (2013) monitored the effectiveness of gravel addition conducted between 2004 and 2008 in a shalk stream in southern Germany, focusing on sediment conditions (e.g., sediment grain size distribution and interstitial oxygen concentration). They concluded that rehabilitation gravels would reach unsuitable conditions for reproduction within 6 yrs. A similar study conducted in Norfolk, UK, has suggested a longevity of 8 yrs (Mitchell, 2015). The few other studies conducted focus on the effects of bedload transport on the sustainability of spawning gravel placements. In this way, Merz et al. (2006) and Wheaton et al. (2010) estimated fluvial sediment budgets based on repeated topographic surveys. Hauer et al. (2020) evaluated gravel dispersion at spawning gravel placements in Norway through various methods, including quantifying the spatial extent and dynamics of the spawning sites and grain size distributions at the spawning sites, from which they determined the degree of erosion of the spawning sites and predicted a maximum life span of 15 yrs. Finally, a few studies have used tracers to assess the erosion of spawning grounds, first with tracer rocks (Kondolf et al., 1991; Merz et al., 2006; Sellheim et al., 2016) and then with low-frequency passive integrated transponders (PIT tags) (Arnaud et al., 2017). Of these few studies, none address the combined effects of the two processes of bedload transport and clogging, which are commonly studied individually. In addition, there is still a lack of knowledge about which discharge or unit stream power values are necessary to winnow the framework gravel of artificially created spawning grounds. Moreover, the discharge-related travel distance of the displaced spawning material and its ability to form new spawning grounds downstream have received little attention so far.

These issues are underpinned by two research questions: (i) To what extent does the combination of sedimentary processes affect the quality and sustainability of artificial spawning grounds? (ii) Can the displaced gravel form new spawning grounds downstream? To answer these questions, we evaluated the efficiency of spawning gravel placements conducted in six rehabilitated river reaches in Wallonia, Belgium, in the period 2010–2015 based on monitoring results of the thickness and clogging of the spawning grounds and the dispersion of the spawning gravels over periods of 3.6–8.5 yrs. The use of the same grain size fraction for all gravel addition operations and the geomorphological diversity of the study sites (i.e., in terms of unit stream power, channel morphology and bed texture) provided beneficial results for future gravel addition projects.

2. Study sites

2.1. From river engineering to river restoration

The six study sites are located in the Eau Blanche River (259 km^2) and Bocq River (233 km^2) catchments in Wallonia, Belgium, which are both part of the Meuse River basin (Fig. 1). The hydrographic systems of these two catchments are characterized by an oceanic rainfall hydrological regime, even though their hydrological regimes differ slightly due to geology. The Eau Blanche River catchment is dominated by Upper Devonian shale, whose impermeable nature results in a more contrasted hydrological regime than that in the Bocq River catchment, where stream flow is mainly dominated by base flow discharged from the Upper Devonian sandstone and Carboniferous limestone aquifers (Petit and Pauquet, 1997). Land use in the Eau Blanche River catchment is dominated by forested land (63%) and grassland (19%), whereas cropland (49%) and forested land (34%) prevail in the Bocq River catchment. Nevertheless, the concentration of suspended sediment is low in both catchments (between 120 and 200 mg/l at the bankfull stage (Q_b); Van Campenhout et al., 2013).

Study sites EB1, EB2 and EB3 are located in the downstream part of the Eau Blanche River catchment in the Fagne Region, in which the shale bedrock in the valley has formed a large depression occupied by grassland. Here, the Eau Blanche River has a low slope (~1‰) and a low energy (the unit stream power at the bank full stage is between 12 and 14 W/m^2). The bed material at site EB1 is mainly composed of coarse sand and shale gravel that usually exhibit a marked flatness, while the bed material at sites EB2 and EB3 are coarser particles of shale and limestone (Table 1). The 14.5-km course of the Eau Blanche River in the Fagne Region was channelized since the 1950s for flood mitigation and drainage improvement in such a way that its course was greatly straightened (sinuosity reduced from 1.6 to 1.1; Peeters et al., 2013a), and its banks were stabilized with riprap to create a trapezoidal channel cross section. As a result, the lateral sediment supply was severely impeded, so the river course became a sediment supply-limited system. Moreover, the relatively featureless bed displays a very low diversity of benthic habitats and very few habitats suitable for lithophilic spawning fishes.

The Eau Blanche River was subject to a large-scale restoration project between 2009 and 2014 (European LIFE + project Walphy). Various rehabilitation techniques have been tested over 6.8 km in total (Peeters et al., 2013a, 2015; Castelain et al., 2018). Site EB1 concerns the reconnection of a 500-m meandering channel, while sites EB2 and EB3 are part of a restoration scheme based on the creation of a sinuous low-flow channel within the over-widened stream bed. These three restoration designs include the rehabilitation of specific habitats and use spawning gravel placements for two target species, namely, the barbel *Barbus barbus* and the resident brown trout *Salmo trutta fario*.

Study sites Bo1, Bo2 and Bo3 are located in the Bocq River catchment, which is mainly in the Condroz Region. The fluvial pattern of the

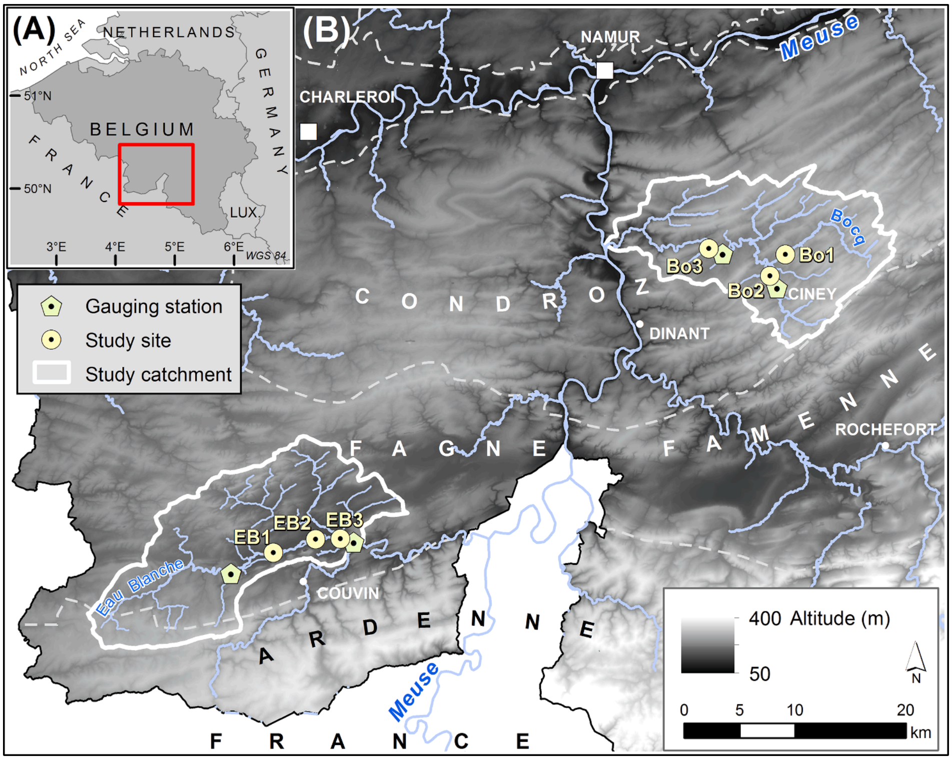

Fig. 1. Location of the study sites within Belgium (A) and at the regional scale (B).

Bocq River and its tributaries is characterized by a slightly sinuous single-thread channel, in which bed material is usually composed of sandstone and limestone pebbles. However, some stretches of the Bocq River were locally straightened for several reasons, such as road construction (site Bo1 on the Bocq in Emptinal), drainage improvement (site Bo2 on the Leignon in Ciney, its tributary) and water supply protection (site Bo3 on the Bocq in Spontin). Furthermore, the middle course of the Bocq River, where sites Bo1 and Bo2 are located, is characterized by a stream bed with almost no pebbles. It is instead composed of compacted silt material, probably resulting from ancient anthropogenic activities (e.g. Middle Ages deforestation, agricultural practices or operation of mill weirs; Peeters et al., 2013b). Therefore, this 13-km river course is characterized by sediment supply-limited conditions. In this context, sites Bo1 and Bo2 have a low slope ($\sim$2–3‰) and a low energy (the unit stream power at the bank full stage is between 18 and 35 W/m^2). Site Bo3 is a 600-m long reach that was completely channelized (i.e., stream bed and banks made of concrete and masonry) in the 1960s to avoid any risk of contamination of the nearby drinking water well and surrounding area. The low roughness of the area results in hydraulic conditions that make the reach impassable for fish (i.e., high flow velocity, even in low water conditions). Site Bo3 has a much greater energy (200 W/m^2 at the bank full stage) than the other Bocq River sites because of a steeper slope and a higher bankfull discharge value.

Because of their low diversity of benthic habitats and their lack of spawning substrates for lithophilic target fishes (e.g., the European grayling *Thymallus thymallus* and the resident brown trout *Salmo trutta fario*), sites Bo1, Bo2 and Bo3 were rehabilitated through the above-mentioned European Walphy project. For study sites Bo1 and Bo2, the restoration scheme was based on the creation of a new channel meandering within the existing channel, with the installation of hydraulic structures made of wood and the placement of spawning gravel (Peeters et al., 2013a; Castelain et al., 2018). The rehabilitation scheme at site Bo3 was focused on modifying the roughness and hydraulic conditions of the concrete reach to make it passable for the target fishes. Rock weirs were placed at regular intervals to create a succession of 23 steps, raising the water level by 35 cm on average. Additional habitats were installed between the steps, such as rock berms, scattered boulders and spawning gravel (Peeters et al., 2013a).

2.2. Gravel placement procedure

The gravel placement strategy relies on the creation of spawning riffles within the river channel, except for site Bo3, where gravel was placed between successive rock weirs (Table 1). The riffle configurations were designed to promote the exchange of water between the stream and gravel interstices. The gravel placements were performed from September to October to provide brown trout with unclogged gravel that would be directly usable for spawning (brown trout reproduce between October and January; Table 2). Site Bo3 was the only exception, as the gravel placements were constrained by the work implementation schedule. Gravel was dumped into the channel, ideally during low-flow periods, and then rearranged so that the spawning ground had a certain thickness, water level and water velocity compatible with the preferences of the above-mentioned lithophilic fish species (Table 2). The material placed at all the sites consists of well-rounded washed river pebbles ranging from 17 to 47 mm in diameter, with a median (D_{50}) and percentile D_{90} equal to 28 and 36 mm, respectively (these values were calculated by sampling and measuring 400 particles according to the Wolman method, 1954). This low grain size range was reflected by a sorting index (D_{84}/D_{16}) of 1.5. The size of the materials was based primarily on the needs of the lithophilic spawning target species. The substrate diameter was also adapted to prevent predation by leaches and bullhead *Cottus gobio* of the embryos within the intragravel voids (diameter $\leq$ 37 mm, according to Olsson and Persson, 1986). In addition, the project design was based on the assumption that the use of well-sorted gravel will provide a large volume of interstices and thus favour the circulation of oxygenated water.

The initial gravel placements, made between 2010 and 2012, consisted of several small patches ($\sim$10 m^2) arranged along the rehabilitated reaches, with a thickness between 16 and 26 cm. Only the artificial reach of site Bo3 had locally larger patches. The length of the rehabilitated reaches corresponds to 4–35 times the channel width, except for

Table 1
Characteristics of the spawning study sites: The initial thickness of the gravel layer was inferred from the amount of gravel dumped and the area of the spawning ground.

Site ID		EB1	EB2	EB3		Bo1		Bo2	Bo3	
Site name		Eau Blanche (Boussu-en-Fagne)	Eau Blanche (Mariembourg)	Eau Blanche (Nismes)		Bocq (Emptinal)		Leignon (Ciney)	Bocq (Spontin)	
Reach scale	Drainage area (A) (km^2)	125	143	249		50		32	163	
	Bankfull discharge (Q_b) (m^3/s)	17.0	17.0	29.0		5.1[¶]		10.0	23.0	
	Return period of Q_b (yr)	1	1	0.43		2.99		2.99	5.5	
	Local slope (m/m)	0.0012	0.0013	0.0010		0.0022		0.0033	0.0062	
	Width at Q_b (w_b) (m)	14.2	18.4	20.5		6.2		9.2	7.0	
	Stream power at Q_b (W/m^2)	14	12	14		18		35	200	
	D_{50} of stream bed (mm)	2.8 [†]	20 [‡]	19 [‡]		Stream bed made of compacted silt		Stream bed made of compacted silt	Stream bed made of concrete	
	D_{90} of stream bed (mm)	6.2 [†]	29 [‡]	31 [‡]						
	Gravel placement ID and date	1 (Sept. 2015)	1 (Oct. 2010)	1 (Sept. 2011)	2 (Oct. 2015)	1 (Oct. 2011)	2 (Oct. 2015)	1 (Sept. 2010)	1 (April 2012)	2 (Feb. 2015)
	Length of the rehabilitated reach (m)	500 (~35 w_b)	180 (~10 w_b)	90 (~4 w_b)	90 (~4 w_b)	75 (~12 w_b)	75 (~12 w_b)	110 (~12 w_b)	600 (~86 w_b)	150 (~21 w_b)
	Total volume of added gravel in the reach (m^3)	28.8	10.0	8.4	13.8	6.9	8.8	6.0	87.5	21.9
	Number of patches	6	4	4	3	4	3	5	21	6
	Mean volume per patch (m^3)	4.8	2.5	2.1	4.6	1.7	2.9	1.2	4.2	3.6
	Mean spacing between patches (m)	83	45	23	30	19	25	22	29	25
Study site scale	Latitude / Longitude	50.07749 / 4.45523	50.09143 / 4.51445	50.08557 / 4.55548		50.31523 / 5.10027		50.30546 / 5.08536	50.31794 / 5.01691	
	Volume of added gravel (m^3)	10.8	2.6	2.2	5.3	1.6	3.6	1.9	6.7	3.5
	Area of the study spawning site (m^2)	40	10	9.7	18	10	45	9.5	33.7	8
	Initial tickness of the added gravel layer (cm)	27	26	23	40 [§]	16	24 [§]	20	20	45
	Channel bedform	Riffle	Riffle	Riffle-pool transition		Riffle		Riffle	Pool between artificial steps	

†: weighted average of grain-size distribution
‡: Wolman pebble count
§: tickness taking into account both gravel additions
¶: discharge (q) extrapolated from the discharge (Q) at the 13-km downstream gauging station using the relation (Bravard and Petit, 1997): $q = Q(a/A)^{0.8}$

Table 2
Spawning habitat preferences of the studied target species.

Target species	Egg burial depth (cm)	Near-bed water velocity (10 cm above bed; cm/s)	Water depth (cm)	Diameter of bed material (mm)	Channel bedform	Spawning period
Barbus barbus	2–30[a]	25–75[a]	20–30[a]	20–50[a]	Riffle[b]	May – June[b]
Thymallus thymallus	~5[c]	37–61[c]	10–80[b] [c]	2–64[c]	Riffle[b]	March – April[b] [c]
Salmo trutta trutta m. fario	0–25[d]	28–50[c]	17–45[c]	6–54[b]	Riffle[c]	October – January[d]

Sources: Baras, 1992, 1994[a]; Poncin, 1993[b]; Parkinson et al., 1999, 2001[c]; DeVries, 1997[d]

site Bo3, where the rehabilitated concrete section is 86 times the channel width. In the meandering channel reaches, gravel patches were placed every 0.5 meander wavelength. Based on the responses to the first gravel additions, new gravel placements were made in 2015 either over larger areas (~40 m^2) or to increase the thickness of the gravel layers. In the latter case, the objective was to allow larger spawners to breed at site Bo1, whereas replenishment was intended to mitigate gravel scour at sites EB3 and Bo3. At the reach scale, the volume of the added gravel ranged from 6 to 28.9 m^3 for the rehabilitated meandering channel reaches (sites EB1, EB2, EB3, Bo1 and Bo2) and was 87.5 m^3 for the concrete bed at site Bo3. For each study reach, a gravel placement was selected to analyse its efficiency and evaluate its longevity (Fig. 2).

3. Methodology

The methodology was based on (i) the survey of the hydromorphological parameters used to characterize the suitability of the rehabilitated spawning ground (site scale) and (ii) the evaluation of the bedload transport process to appraise its effects on the sustainability of the spawning grounds and the ability of the displaced gravel to form new spawning grounds downstream (reach scale).

3.1. Hydrological and hydromorphological monitoring

River discharge values (1-hour frequency records) were recorded at four gauging stations (Fig. 1). Sites EB1, EB3, Bo2 and Bo3 are close (<5 km) to their associated gauging stations. Site EB2, although located 10 km downstream from the nearest gauging station, is assumed to have similar flow values as the gauging station because of the absence of significant tributaries between the site and the station. In contrast, discharges at site Bo1 were extrapolated from the discharge values recorded at the 13-km downstream gauging station.

Fig. 2. Spawning study sites. Gravel was arranged along hydraulic structures made of wood at sites EB1, Bo1 and Bo2 and upstream of rock weirs at site Bo3. Sites EB2 and EB3 have no hydraulic structures. The PIT-tagged gravels are visible in red at site Bo2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

To characterize flood magnitude, we used *(i)* the ratio between the maximum discharge ($Q_{max.}$) and the bankfull discharge (Q_b), *(ii)* the recurrence interval (RI) calculated according to the Gumbel method based on the partial series (Van Campenhout et al., 2020), and *(iii)* the unit stream power of the maximum peak flow (W/m^2) calculated using the following equation:

$$\omega = (g.\rho.Q.S)/w \qquad (1)$$

where g is the acceleration due to gravity (m/s^2), ρ is the density of the water (kg/m^3), Q is the peak discharge (m^3/s), S is the slope (m/m) and w is the width of the water surface (m). The latter was obtained from the average of the widths measured at the bankull stage (w_b) at the total station along the study reach. The number of width measurements varies between 8 and 35 depending on the length of the study reach, which corresponds to a measurement spacing of 0.5–1 w_b. The slope was measured using MNT-LIDAR data for sites EB1, EB2 and Bo1 and from the survey of high-water marks for sites EB3, Bo2 and Bo3 (Peeters et al., 2013b).

Note that the river reach occupied by site Bo2 is bypassed by a head race of a former mill, which leads to uncertainty about the discharge passing through the site. In addition, the flow record at the nearby station is too short (<10 yrs) to calculate recurrences accurately. This is why the recurrences used correspond to the station close to the Bo3 site.

Water depth and water velocity were measured several months after gravel placement to verify their compatibility with the requirements of the target species. The depth was measured to the nearest centimetre with a levelling rod. The water velocity was measured with a direct electromagnetic current meter (Marsh-McBirney Flo-mate 2000) 10 cm above the bed, as recommended by Petit (1988). A minimum of six measurements were carried out for each site during low-flow conditions.

The initial thickness of the gravel layer was inferred from the amount of gravel dumped and the area of the spawning ground, whereas the subsequent thicknesses corresponded to the average of a minimum of 6 measurements made in the gravel layer. The measurements were carried out by driving a metal bar into the gravel layer until a significant difference in resistance was identified, reflecting the change in sediment composition.

3.2. Monitoring clogging of the spawning ground

To evaluate the clogging of the gravel layer, we used the wooden stakes method, which consists of driving 30-cm-long pine stakes into the gravel layer and leaving them for a period of 4 weeks (Boulton et al., 2002; Marmonier et al., 2004). Once recovered, the stakes show a dark coloration in their lower part, which indicates the hypoxic subsurface environment where the porosity is reduced and thus the oxygen used by biogeochemical processes (presumably because of manganese, sulfur or iron salt deposition; Descloux et al., 2010). The anoxia to hypoxia limit is marked by an abrupt change in colour (from light brown to dark grey or black) that could be measured from the gravel surface. The depth of anoxia reflects the extent of interstitial clogging of the gravel layer.

The spawning grounds were equipped with 4–8 stakes, depending on the surface area of the study sites. These stakes were surveyed and reimplanted at the same locations 3–6 times, preferentially during the spawning period but also during the egg incubation period, as embryos are relatively vulnerable to fines sedimentation (Lisle, 1989).

3.3. *Monitoring gravel dispersion*

Gravel dispersion was assessed by particle tracking using PIT tags. This tracing method has the advantage of identifying the particles individually. Such tracers are used in fluvial geomorphology to analyse bedload transport (Lamarre et al., 2005; Liébault et al., 2012; Houbrechts et al., 2015; Papangelakis and Hassan, 2016; Vázquez-Tarrío et al., 2019) but also to appraise the river rehabilitation actions (MacVicar et al., 2015; Arnaud et al., 2017; Chardon et al., 2018; Brousse et al., 2019) and evaluate the effects of low-head dams on bedload transport (Casserly et al. 2020; Peeters et al., 2020). The PIT tags used were 23 mm long and were inserted into a slot made using a grinder, which allowed us to equip gravel of almost the same length (a-axis) and diameter (axis b) up to 18 mm. Despite the small size of the gravel and the use of epoxy glue to seal them, the density and shape of the gravel were not significantly modified. For each site, 100 particles were collected randomly following the Wolman method (Wolman, 1954) so that the size of the tagged particles corresponds to the grain size of the added gravels. Afterwards, these marked particles were deployed onto the rehabilitated spawning grounds either in three lines or in three patches to prevent tracer signal collisions (i.e., tags in close proximity to each other are undetected; Cassel et al., 2017). Tracer positions were tracked after a period of high flow with an antenna able to detect tagged particles with a high degree of precision (within a 0.5 m radius). The location of each marked pebble found was determined using measuring tapes and subsequently reported on the topographic survey, which provides a position with an accuracy within the range of one metre. The distances travelled were then calculated by plotting the tracer positions in arcGIS. Note that the distance considered for the meandering reaches is that measured along the centre of the channel; this required projecting the measured position on the bank towards the centre of the channel.

Tracer analysis was performed to evaluate the degree of gravel dispersion and the ability of the displaced gravel to form new spawning grounds downstream. For each monitoring period, delimited by two successive tracer surveys (S_i and S_{i-1}), tracer travel distances were assessed through the mean travel distance of tracers common to the two surveys, taking into account the immobile tracers. Individual tracers were considered mobile when they covered a distance ≥ 1 m between two successive surveys due to sources of error related to the accuracy of the detection antenna and the positioning of the measuring tapes. The number of recovered tracers takes into account the inferred tracers, i.e., tracers that were absent from the given survey but were found in previous and subsequent surveys and remained immobile throughout (Arnaud et al., 2017). Displacement between two successive surveys was considered significant when the mean travel distance was ≥ 1 m and the percentage of mobile tracers was $\geq 10\%$ (Houbrechts et al., 2006).

Each monitoring period has a specific hydrological signature with regards to the number of floods, their magnitude and duration. To characterize this signature, we used not only the unit stream power of the maximum flow event of the period but also the sum of the unit excess power values of the period (ω–ω_c, in W/m^2). The unit excess power is defined as the difference between the unit stream power at the peak discharge (ω) and the unit stream power at the critical discharge (ω_c, i.e., the threshold of motion for a given grain size D_i). This calculation therefore requires knowing the critical discharge (Q_c), which can be determined empirically or theoretically. The empirical approach is based on the analysis of tracer surveys over long time series that include a wide range of peak flow magnitudes. Only Q_c at site Bo3 could be determined by this approach. The theoretical approach was used for the other sites. The determination of the theoretical Q_c was based on the relation between unit stream power and the transported grain size ($\omega = 0.142.D_i^{\ 1.28}$) established by Houbrechts et al. (2015) from a large dataset (i.e., 73 observations of bedload displacement in medium-size gravel-bed rivers). We used a D_i equal to the D_{50} of the added gravel (28 mm) so that all the displacements provided positive values of excess stream power. In this way, Q_c was calculated with ω_c (10.1 W/m^2) for each study site using Equation 1.

4. Results

4.1. *Suitability and sustainability of spawning gravel placements*

According to the values of water depth and water velocity measured several months after the gravel placements were made (Table 3), all the sites appear to be suitable to the preferences of the target fish species (see Table 2 for the spawning habitat preferences), with the exception of site EB3 and, to a lesser extent, site EB1. The first gravel addition conducted at site EB3 was characterized by low velocities, providing a habitat not very favourable for the reproduction of barbel *Barbus barbus*. Despite a second gravel addition, the habitat did not evolve favourably, with a decrease in depth and little change in velocity. For site EB1, only the depth was unsuitable, but as the measurements were made during very low water conditions (close to the Q95 low-flow index), it is likely that this parameter will improve under higher flow conditions.

The assessment of the sustainability of the rehabilitated spawning grounds was based on the analysis of the evolution of the clogging and thickness of the study spawning grounds and on the mobility of their gravel.

The monitoring data of gravel layer thickness (diamonds in Fig. 3) indicated that sites EB1, EB2 and Bo1 had a very high stability in gravel thickness over time, despite the occurrence of several flow events. This is also the case, but to a lesser extent, for site Bo2, which showed an initial decrease of 3.5 cm, followed by a period of considerable channel stability. Site EB3 is also marked by an initial decrease in thickness of 5 cm and a subsequent period of constant thickness, but it is then followed by a more pronounced decrease of 8 cm. This evolution is likely explained by the balance between the scour of the gravel and the sediment supply from three other spawning gravel placements located upstream along the meandering channel. Only site Bo3 reflected considerable channel instability for the two study gravel placements. The first one showed a slight increase resulting from low-flow events ($T_{Qmax} = 0.33$ yrs), which probably supplied the study placement with gravel from the upstream placement (located 18 m upstream), and then a sharp decrease (from 24 cm to 0 cm) following a period marked by a 3.2-yr peak flow. The second placement also experienced a significant decrease in thickness after a period marked by a 1.1-yr peak flow.

Regarding the thickness of the clogged gravel layer (squares in Fig. 3), all the sites showed a significant increase after gravel placement, although the standard deviations are high for site EB2. Thereafter, this increase is followed by a plateau at sites EB1, EB2 and EB3, with the latest surveys indicating a remaining unclogged thickness of 6.5, 8.4 and 3.2 cm, respectively. Such clogged thicknesses reduce the suitability of gravel placements, especially for spawners who bury their eggs deep in the gravel. On the other hand, the 2nd gravel addition carried out at site EB3 resulted in an unclogged thickness of 23.5 cm 1 yr after gravel placement, suggesting that the spawning ground there was still sufficient. At sites Bo1 and, to a lesser extent, Bo2, the thickness of the clogged gravel layer showed a higher variability over time, with systematically lower clogged thicknesses during the October-January period than for the rest of the year. This can be related to the brown trout spawning activity (i.e., their ability to unclog gravel to bury their eggs) observed each year during the monitoring period at sites Bo1 and, to a lesser extent, Bo2. The latest surveys, carried out in March-April, showed a remaining unclogged thickness of 12 and 6.6 cm for Bo1 and Bo2, respectively, indicating that spawning grounds can reclogged

Table 3
Near-bed water velocity and water depth of the rehabilitated spawning grounds (mean with standard deviation).

Site ID	Gravel placement ID (date)	Near-bed water velocity (10 cm above bed; cm/s)	Water depth (cm)	Number of measures	$Q_{measurement}$ / Q_b	Date of measurement and time since gravel addition (month)
EB1	1 (Sept. 2015)	37 ± 4	12 ± 3	6	0.01	29/06/2016 (9)
EB2	1 (Oct. 2010)	45 ± 7	22 ± 7	6	0.02	3/07/2012 (21)
EB3	1 (Sept. 2011)	18 ± 11	31 ± 9	6	0.03	30/05/2012 (9)
EB3	2 (Oct. 2015)	19 ± 12	13 ± 9	6	0.04	6/10/2016 (12)
Bo1	1 (Oct. 2011)	60 ± 11	18 ± 1	6	0.11	27/05/2013 (19)
Bo1	2 (Oct. 2015)	55 ± 9	14 ± 1	6	0.08	15/09/2016 (11)
Bo2	1 (Sept. 2010)	37 ± 6	29 ± 2	7	N/A†	24/06/2011 (8)
Bo3	1 (April 2012)	60 ± 10	46 ± 6	6	0.03	27/06/2012 (7)
Bo3	2 (Feb. 2015)	52 ± 19	33 ± 3	6	0.04	4/11/2016 (21)

†: gap in the discharge values recorded during this period.

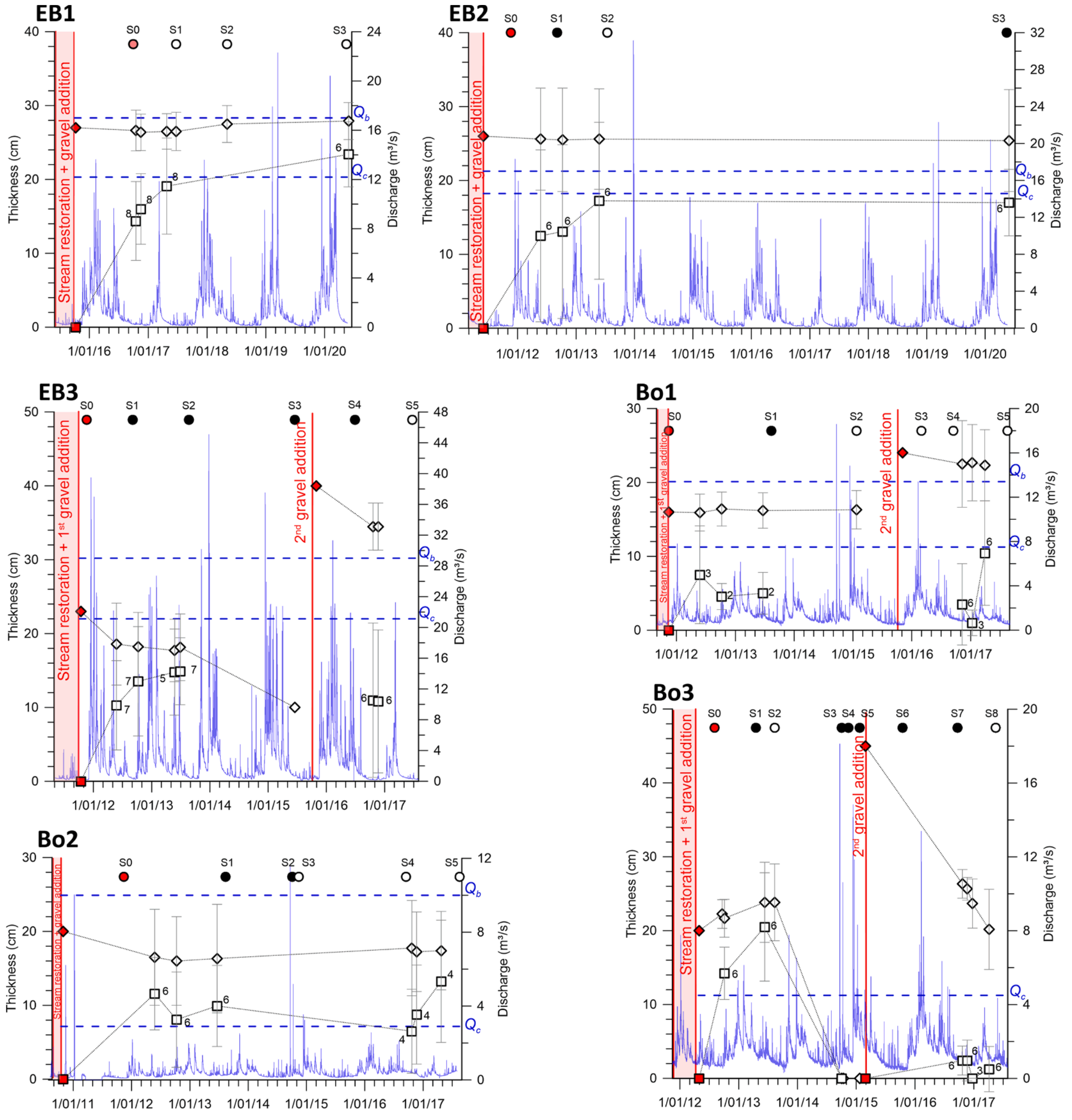

Fig. 3. Monitoring framework related to the hydrograph of the 6 study sites. Red diamonds show the theoretical thickness of the gravel layer (calculated from the area and the volume of the added gravel), and grey diamonds show the measured thickness of the gravel layer (mean with error bars representing the standard deviation 1σ). Red squares denote the theoretical thickness of the clogged gravel layer (assumed equal to 0 cm at the time of placement), and grey squares denote the measured thickness of the clogged gravel layer (mean with error bars representing the standard deviation 1σ and numbers referring to the number of measures). Circles show the PIT-tagged surveys (Si) with a colour indicating a tracer deployment (in red), a lack of mobilization (in white) and a significant mobilization (in black). Q_b represents the bankfull discharge, and Q_c shows the theoretical critical discharge of the added gravel for all sites, except for site Bo3, where Q_c was determined empirically. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

rather quickly (in 2.5 and 5 months, respectively). For site Bo3, the thickness of the clogged gravel layer was significant with the first gravel placement until the gravel was subsequently completely scoured. The second placement resulted in almost no clogging of the gravel layer, which might indicate a positive effect of the hydraulic structures or an unclogging effect of the brown trout spawning activity.

With regard to gravel mobility, PIT-tagged particle tracking led to the identification of three scenarios. First, sites EB1 and Bo1 showed a near-zero mobility of the marked gravels (Table 4). Despite the occurrence of a 3-yr peak flow, the surveys did not highlight any significant displacements, except for the first survey at site Bo1 (mean travel distance of 1.1 m). The marked gravel dispersed over a distance < 10 m in

Table 4

Synthesis of PIT-tagged particle tracking and characteristics of the related flow events. Italics indicate significant displacements defined by a mean travel distance ≥1 m and a percentage of mobile tracer ≥10%.

Site - Survey	Number of peak flow > Q_c during period	Hours > Q_c during period	Date of Q_{max}	Q_{max} (m^3/s)	Q_{max}/ Q_b	ω (w/ m^2)	RI (yr)	Tracking length (m)	n_r	n_{same}	$n_{mob.}$	% mob. = $n_{mob.}$ /n_{same}	Mean distance (m)	Max. Distance (m)
EB1 - S1	1	8	09-03-17	11.8	0.69	10	0.40	70	75	75	13	17	0.6	2.5
EB1 - S2	2	36	14-12-17	13.6	0.80	11	0.54	70	69	59	2	3	0.2	1.6
EB1 - S3	5	208	15-03-19	22.3	1.31	18	2.90	70	71	55	14	25	0.7	6
EB2 - S1	*2*	*33*	*16-12-11*	*18.3*	*1.08*	*13*	*1.3*	*50*	*82*	*82*	*42*	*51*	*1.2*	*3.5*
EB2 - S2	0	0	30-01-13	12.7	0.75	9	0.5	50	78	73	12	16	0.4	6.7
EB2 - S3	*7*	*177*	*25-12-13*	*31.1*	*1.83*	*22*	*8.90*	*80*	*88*	*70*	*32*	*46*	*1.6*	*13.6*
EB3 - S1	*5*	*154*	*17-12-11*	*39.5*	*1.36*	*19*	*1.2*	*100*	*79*	*79*	*65*	*82*	*10.2*	*43.9*
EB3 - S2	*6*	*139*	*30-01-13*	*26.7*	*0.92*	*13*	*0.35*	*195*	*82*	*71*	*40*	*56*	*6.4*	*81.5*
EB3 - S3	*11*	*263*	*25-12-13*	*45.1*	*1.55*	*22*	*2.3*	*250*	*89*	*78*	*32*	*41*	*8.3*	*82.1*
EB3 - S4	*4*	*89*	*10-02-16*	*31.3*	*1.08*	*15*	*0.53*	*250*	*88*	*81*	*17*	*21*	*4.3*	*81.5*
EB3 - S5	1	17	09-03-17	23.3	0.80	11	0.28	250	90	83	7	8	0.7	19.5
Bo1 - S1	*1*	*28*	*06-01-12*	*$3.0^{\dagger}$*	*0.59*	*10*	*0.41*	*100*	*77*	*77*	*35*	*45*	*1.1*	*4.1*
Bo1 - S2	6	94	21-09-14	$7.2^{\dagger}$	1.41	25	3.2	100	84	72	12	17	0.4	4
Bo1 - S3	3	50	09-02-16	$5.2^{\dagger}$	1.02	18	1.1	100	73	71	9	13	0.3	3.2
Bo1 - S4	0	0	16-06-16	$2.4^{\dagger}$	0.48	8	0.34	100	66	64	3	5	0.2	1.7
Bo1 - S5	0	0	28-05-17	$1.7^{\dagger}$	0.33	6	0.27	100	48	46	2	4	0.1	1.8
Bo2 - S1	*0*	*0*	*06-01-12*	*2.2*	*0.22*	*8*	*0.41*	*320*	*70*	*70*	*36*	*51*	*1.4*	*6.3*
Bo2 - S2	*1*	*20*	*21-09-14*	*11.6*	*1.16*	*41*	*3.2*	*320*	*60*	*56*	*25*	*45*	*1.5*	*27*
Bo2 - S3	1	7	09-10-14	5.2	0.52	18	0.67	320	60	56	0	0	0.2	0.9
Bo2 - S4	1	16	12-12-14	3.6	0.36	13	1.5	320	53	50	3	6	0.2	2.6
Bo2 - S5	0	0	09-03-17	1.3	0.13	5	0.26	320	47	42	0	0	0.05	0.6
Bo3 - S1	*4*	*90*	*01-02-13*	*6.1*	*0.27*	*53*	*0.33*	*95*	*77*	*77*	*40*	*52*	*5.2*	*23.9*
Bo3 - S2	0	0	30-05-13	3.4	0.15	29	0.25	95	68	48	4	8	0.4	2.1
Bo3 - S3	*3*	*76*	*21-09-14*	*18.6*	*0.81*	*161*	*3.2*	*320*	*78*	*56*	*53*	*95*	*28.6*	*61.5*
Bo3 - S4	*1*	*14*	*09-10-14*	*10.7*	*0.47*	*93*	*0.67*	*320*	*78*	*68*	*30*	*44*	*7.6*	*60.2*
Bo3 - S5	*4*	*143*	*14-12-14*	*14.8*	*0.64*	*129*	*1.5*	*410*	*75*	*62*	*38*	*61*	*31*	*101.5*
Bo3 - S6	*1*	*7*	*02-04-15*	*5.5*	*0.24*	*48*	*0.30*	*640*	*79*	*68*	*10*	*15*	*1.7*	*32.9*
Bo3 - S7	*11*	*248*	*09-02-16*	*13.4*	*0.58*	*116*	*1.1*	*640*	*70*	*60*	*19*	*32*	*10.7*	*106.8*
Bo3 - S8	0	0	09-03-17	4.0	0.17	34	0.26	640	68	62	4	6	0.6	11

n_r: number of recovered tracers

n_{same}: number of tracers that were found in both S_{i-1} and S_i

$n_{mob.}$: number of mobile tracers (travel distance > 1 m) that were found in both S_{i-1} and S_i

$\%_{mob.}$: percentage of mobile tracers from S_{i-1} and S_i

†: discharge (q) extrapolated from the discharge (Q) at the 13-km downstream gauging station using the relation (Bravard and Petit, 1997): $q = Q(a/A)^{0.8}$

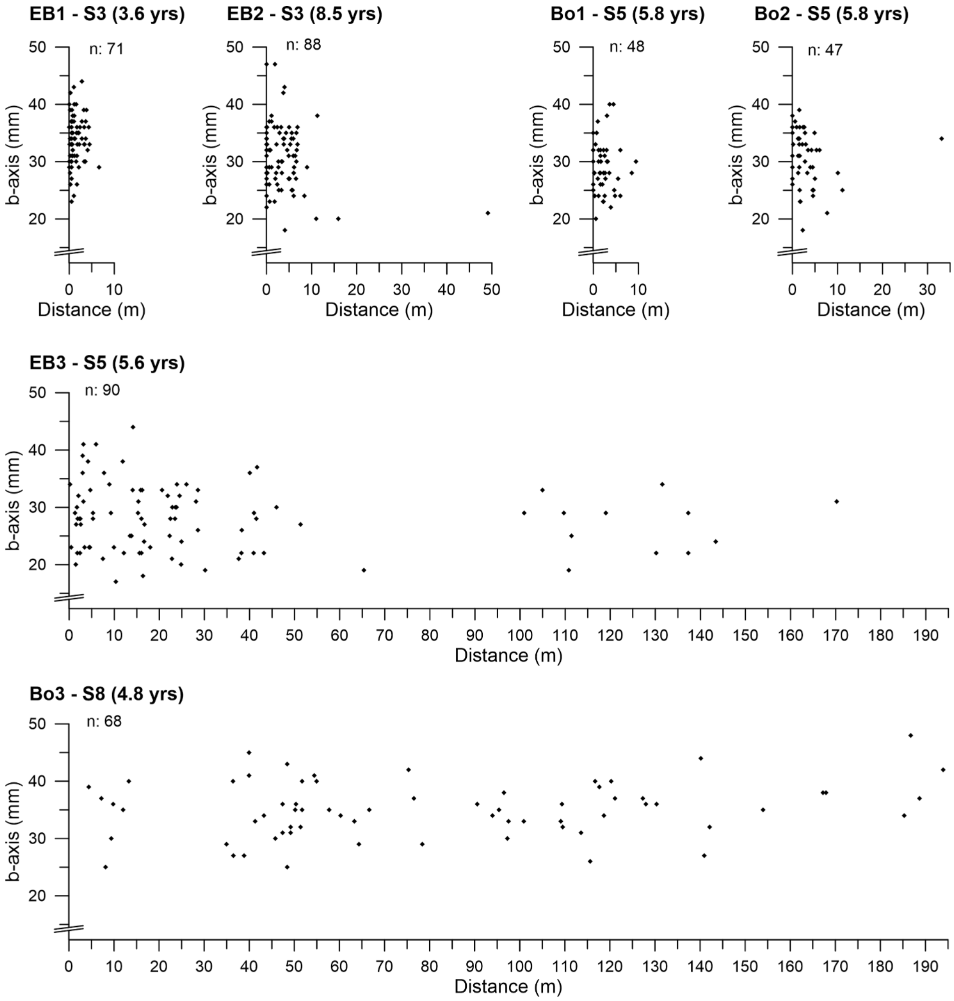

Fig. 4. Distance travelled by the PIT-tagged gravels between their deployment (S_0) and their latest survey (S_i) as a function of particle size. The time elapsed since tracer deployment is indicated in brackets.

3.6 and 5.8 yrs for sites EB1 and Bo1, respectively (mean annual displacement of 0.4 m/yr; Fig. 4). Site EB2 had a greater dispersal distance (furthest tracer at 50 m), but for a longer monitoring period (8.5 yrs), including an 8.9-yr peak flow, which also corresponded to a mean annual displacement of 0.4 m/yr. In addition, the plot between the distances travelled and the size of the PIT-tagged gravels (Fig. 4) shows an overall increase in distance travelled with a decrease in particle size at EB2. Second, the gravel mobility was slightly more pronounced at site Bo2, where significant displacement occurred only for the first flow event and then for the greatest flow event in the monitoring period (recurrence interval of 3.2 yrs). There, gravel was dispersed over a distance of 33 m after 5.8 yrs (mean annual displacement of 0.6 m/yr). Third, sites EB3 and Bo3 showed greater distances travelled and are analysed in more detail below.

4.2. *Gravel dispersion and ability of the dispersed gravel to form new spawning grounds downstream*

Whereas gravel at study sites EB1, EB2, Bo1 and Bo2 showed low to very low mobility, gravel dispersion was more pronounced for sites EB3 and Bo3, but to a variable extent that depended on the characteristics of the study reaches.

For the first spawning gravel placement monitored at site Bo3 (i.e., upstream from rock weir W3; Fig. 5b), the dispersion of gravel was rapid, resulting in a decrease in its thickness. Survey S3 showed that the 3.2-yr flow dispersed the gravel over a distance of 60 m downstream, resulting in complete erosion of the spawning ground after 2.2 yrs. Despite this, the displacement of gravel allowed the reconstitution of three new potential spawning grounds downstream. Two of these potential spawning grounds were reconstituted upstream of weirs W4 and W5 but with limited thickness (~10 cm). The third potential spawning ground was thicker (~20 cm) and established in the rock berm downstream of weir W4. The rest of the gravel from the study spawning ground was scattered in lateral rock berms and behind immobile boulders, as suggested by the position of the recovered tracers, but it did not present favourable conditions for spawning due to an insufficient thickness or surface area. Thereafter, the three reconstituted spawning grounds were again scoured and dispersed following two periods marked by 0.67-yr (S4) and 1.5-yr (S5) peak flows, resulting in scattering of the gravel over 140 m (S5), which no longer constituted spawning grounds downstream. Thus, the study gravel placement reached unsuitable conditions after 2.5 yrs, a period marked by 12 peak flows > Qc. Thereafter, a second gravel placement was made in February 2015 in six patches with thicknesses ranging from 25 to 60 cm. The subsequent 0.3-yr and 1.1-yr peak flows caused further erosion and dispersal of gravel from the spawning grounds and the reformation of new spawning grounds downstream, as indicated by surveys S6 and S7. Thus, 1.6 yrs after the second gravel placement, the six reconstituted spawning grounds had thicknesses varying between 10 and 25 cm and were still viable.

At site EB3, tracer seeding was carried out in 2011 on three of the four patches placed along the new meandering reach (Fig. 6A). PIT-

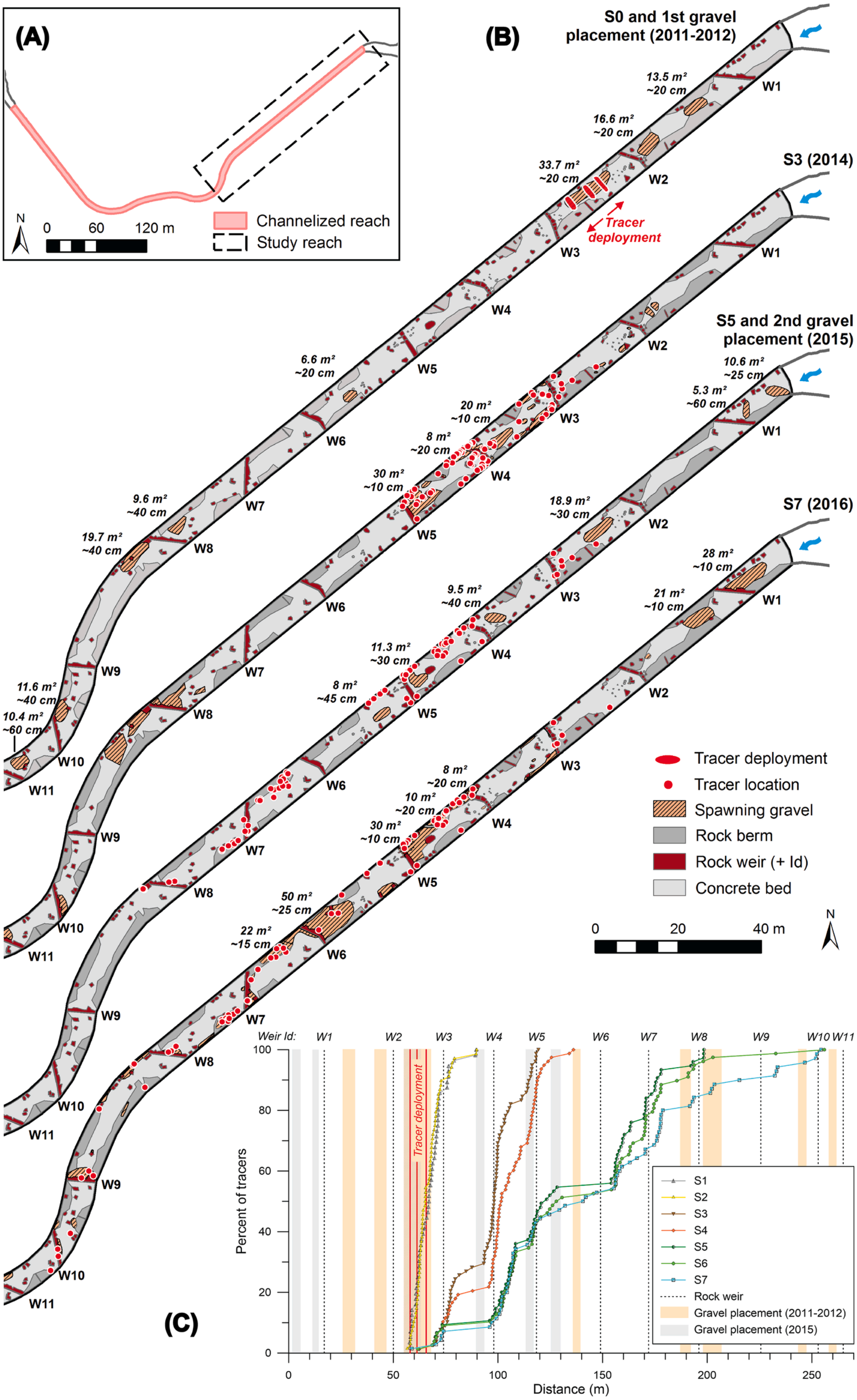

Fig. 5. Gravel dispersion at site Bo3. (A) Location of the tracer study reach within the channelized reach. (B) Tracer location along the study reach for S0 (and first gravel placement), S3, S5 (and second gravel placement) and S7. Distances are measured from the entrance of the channelized reach along the right bank. The PIT-tagged pebbles were deployed in three lines. (C) Cumulative distribution of the 7 tracer surveys (Si).

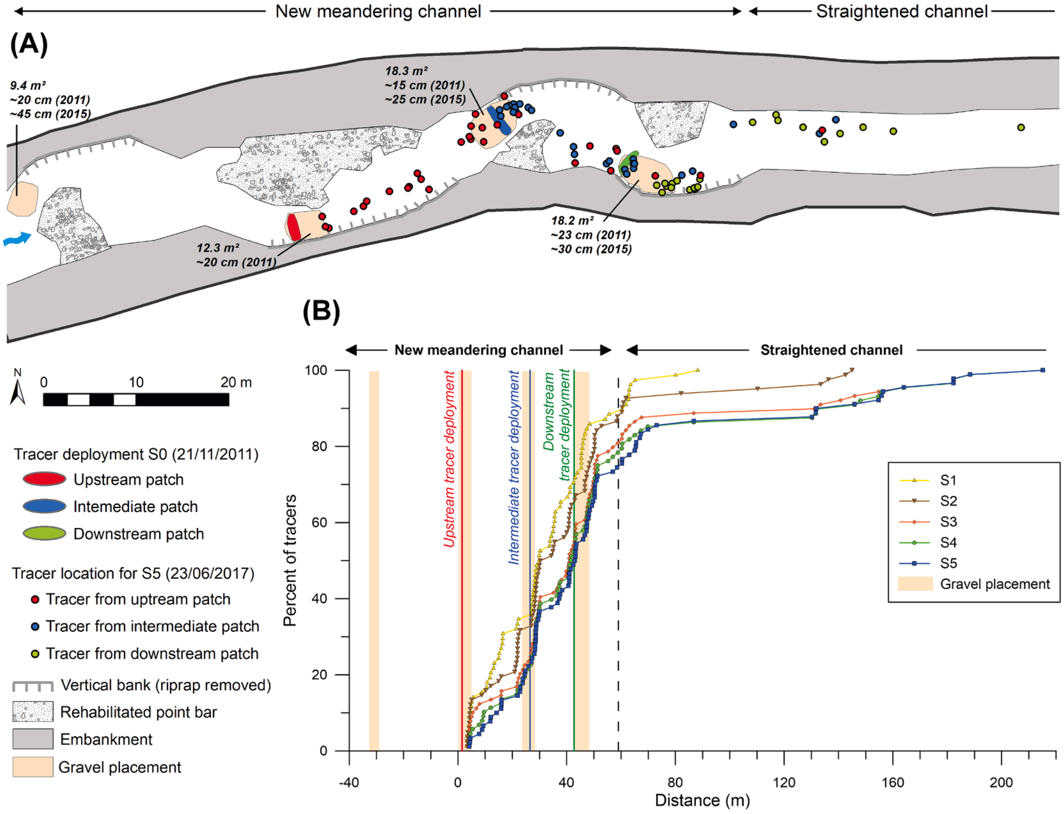

Fig. 6. Gravel dispersion at site EB3. (A) Gravel placements and tracer locations along the restored reach for S5. (B) Cumulative distribution of the 5 tracer surveys (Si). The PIT-tagged gravels were deployed on three patches of spawning gravel. Distances were measured from the most upstream patch of tracer deployment along the channel centreline.

tagged gravel tracking highlighted a slower dispersion at EB3 than that that at site Bo3 (Table 4). However, a proper analysis of gravel dispersion required the area to be divided into two separately treated reaches: the 90-m new meandering reach and the 100-m straightened reach located downstream and not covered by the rehabilitation scheme (Table 5). This highlighted a lower mobility in the meandering reach than in the straightened reach, with lower mean travel distances and percentages of mobile tracers, except for S5, for which mobilization was not significant (mean travel distance < 1 m). The sum of the mean travel distances in the meandering reach was 17.6 m over the monitoring period (5.6 yrs), which represents a mean velocity of approximately 3 m/yr. This indicates that the sinuosity created by the rehabilitation

Table 5
Synthesis of PIT-tagged particle tracking and characteristics of the related flow events at site EB3, with the meandering and straightened reaches treated separately.

Survey - reach	Number of peak flow > Qc during period	Hours > Qc during period	Date of Q_{max}	Q_{max} (m^3/s)	Q_{max}/Q_b	ω (W/m^2)	RI (yr)	n_{same}	$n_{mob.}$	% mob. = $n_{mob.}/n_{same}$	Mean distance (m)	Max. Distance (m)
S1 - meandering reach	5	154	17-12-11	39.5	1.36	19	1.2	70	59	84	9.1	43.9
S1 - straightened reach								9	9	100	9.5	30.2
S2 - meandering reach	6	139	30-01-13	26.7	0.92	13	0.35	62	33	53	3.1	16.7
S2 - straightened reach								9	7	78	28.5	81.5
S3 - meandering reach	11	263	25-12-13	45.1	1.55	22	2.3	64	21	33	3	32.1
S3 - straightened reach								14	11	79	31.6	82.1
S4 - meandering reach	4	89	10-02-16	31.3	1.08	15	0.53	63	12	19	1.7	24.5
S4 - straightened reach								18	5	28	13.2	73.8
S5 - meandering reach	1	17	09-03-17	23.3	0.80	11	0.28	63	6	10	0.7	19.5
S5 - straightened reach								20	1	5	0.5	7.5

n_{same}: number of tracers that were found in both S_{i-1} and S_i
$n_{mob.}$: number of mobile tracers (travel distance > 1 m) that were found in both S_{i-1} and S_i
$\%_{mob.}$: percentage of mobile tracers from S_{i-1} and S_i

measure favoured the maintenance of placed gravel in this reach, which therefore increased the life span of the initial spawning grounds and allowed the reconstitution of new spawning grounds downstream after floods. On the other hand, when the gravels entered the straightened sector, they were eventually scattered over long distances. Tracer tracking showed progressive gravel dispersion over time, with preferential areas of accumulation, as on the intermediate and downstream patches (Fig. 6B). This indicated that gravel supply from upstream allowed the downstream spawning ground to maintain a sufficiently thick layer for a certain time (18 cm after 1.8 yrs). Thereafter, the gravel dispersion continued until the remaining gravel was 8 cm thick, 3.75 yrs after gravel placement. Thus, the spawning ground was no longer suitable and required a new replenishment in 2015 to increase its thickness. Lastly, grain size analysis of mobilized tracers indicated that gravels with a b-axis > 35 mm travelled only short distances, whereas those with a b-axis < 35 mm were dispersed over longer distances (Fig. 4). This threshold is close to the limit of competence of the river reach, for which the D_{90} of natural surface substrate is 31 mm.

This analysis shows that the life span of the rehabilitated spawning grounds and the ability of their gravels to form new spawning grounds downstream are largely dependent on the hydromorphologic variables, mainly on the unit stream power of the flows, as shown by the plot of travel distance as a function of unit power (Fig. 7A) or unit excess stream power (Fig. 7B). Since some of the surveys were related to periods marked by multiple peak flows, this relation has a better fit when the sum of the unit excess stream power values are used (Fig. 7C).

To consolidate the relation using unit stream power (Fig. 7A), we supplemented the data from this study with 19 surveys from other studies using the same particle size range, namely, 10 surveys conducted on the Bocq River in two reference reaches located downstream from the sites of this study (Peeters et al., 2013b) and 9 surveys carried out on two other rivers in Wallonia with similar characteristics (Berwinne and Rulles Rivers; see Houbrechts et al., 2015). This relation is expressed in the form Mean distance = $0.0197.\omega_{max.}^{1.473}$ ($R^2 = 0.68$). This relation can be used to determine the mobility of spawning gravel and thus the life span of gravel placements. Considering that limited mobility is necessary to optimize the life span of the spawning ground (i.e., a mean annual displacement of 3 ± 2 m, as in site EB3 with a range of values assigned arbitrarily at 2 m), an annual peak flow with a unit stream power of between 14 and 43 W/m^2 is required. A flood with a higher unit stream power will disperse the gravel over longer distances, as in site Bo3, so the efficiency of placement may not be long-lasting. Similarly, to take into account multiple peak flows occurring over a year, the spawning gravel mobility can be determined using the relation from Fig. 7C: Mean distance = $0.1764. \sum(\omega_{max}\text{-}\omega_c)^{0.881}$ ($R^2 = 0.77$). In this way, the sum of the annual unit excess power values would be between 7 and 45 W/m^2, resulting in a mean annual displacement between 1 and 4 m.

Nevertheless, several points diverge from the above regression lines, suggesting that the unit stream power is not the only parameter involved in the analysis of the travel distance. First, channel morphology represents such a parameter, as highlighted by the above-mentioned tracer tracking at site EB3 (meandering *vs.* straightened reaches). Second, Fig. 7 shows differences in the tracer transport observations between the first displacements after tracer seeding and the second and subsequent tracer displacements. This is particularly the case for site EB3, but is also true for sites EB2 and Bo2. For Bo1, only the first survey was affected by a significant displacement. This underlines the control of particle arrangement and bed texture on the entrainment of individual tracer displacement. In addition, surveys S3 and S4 at site EB3 show a decrease in the average distance travelled over time in proportion to the unit power, which might suggest an increase in the degree of tracer stabilization due to the particle arrangement and bed texture. This may also be the case to a lesser extent for surveys S6 and S7 at site Bo3, where the lateral rock berms and scattered boulders promote the hiding effects on spawning gravel.

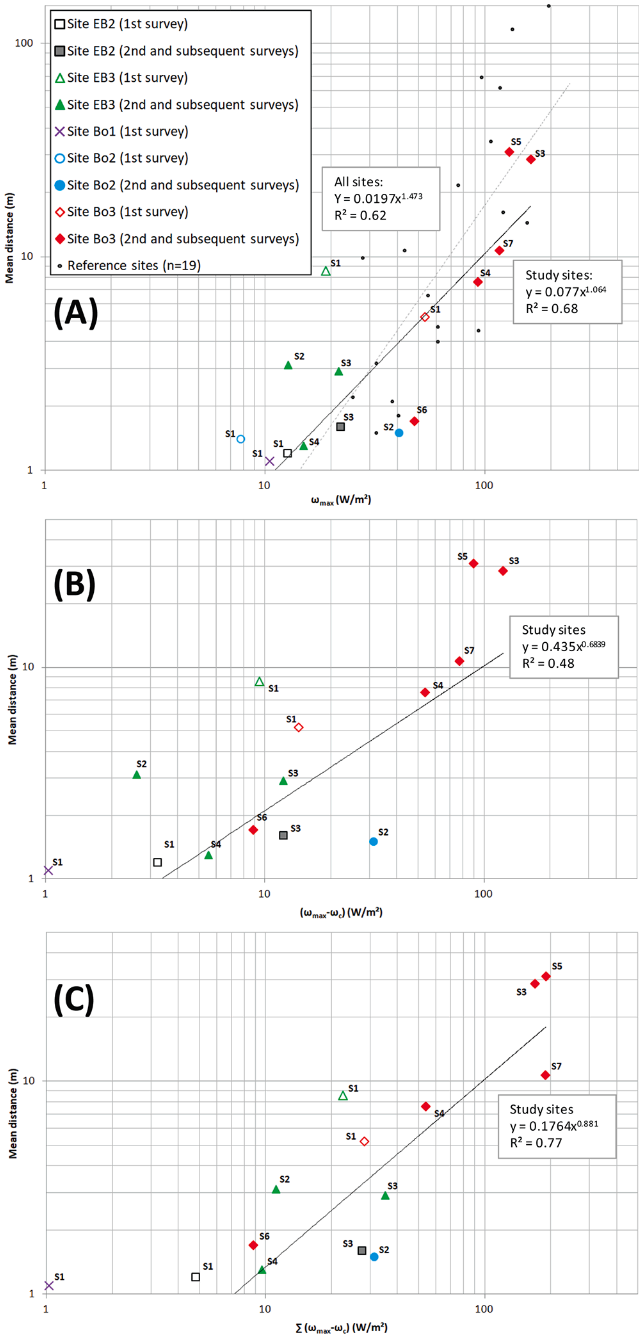

Fig. 7. Mean transport distance related to (A) the unit stream power of Q_{max} for the spawning study sites and reference sites from river reaches in Wallonia (Peeters et al., 2013b; Houbrechts et al., 2015), (B) the unit excess stream power of Q_{max} for the spawning study sites, and (C) the sum of the unit excess stream power values for the peak flows > Q_c for the spawning study sites. The regression lines do not include the first surveys after tracer seeding. Travel distances at site EB3 are those observed in the new meandering reach.

5. Discussion

5.1. Site-scale suitability and sustainability of spawning gravel placement

The success of spawning habitat enhancement by gravel placement depends on accurate knowledge of both the biological requirements of lithophilic spawners and morphodynamic river processes. The success of spawning gravel placement may not be long-lasting because of rapid gravel dispersion or gravel clogging. This is particularly the case in the absence of an upstream gravel supply or a very low upstream gravel supply that is unlikely to replenish the spawning ground. In these cases, the challenge is to ensure that the placed gravel periodically travels distances limited to a few metres during flood periods to unclog the gravel layer and thus maintain a sufficient life span of the spawning ground. To some extent, this was achieved for study site EB3, at which a mean annual displacement of 3 m is expected to maintain the success of long-lasting gravel placement. However, this was not the case for the other study sites, either because the mobility was too high (i.e., gravel dispersed quickly as at site Bo3) or too low (i.e., gravel clogged quickly as at site Bo2), or even near-zero (i.e., sites EB1, EB2 and Bo1).

In terms of morphodynamic constraints, PIT-tagged gravel tracking at study site Bo3 demonstrated that the spawning ground was completely scoured after 2.2 yrs due to the undersizing of the spawning materials relative to the river competence. Previous studies addressing this issue highlighted that the life spans of artificial spawning sites are between 1.5 and 15.5 yrs (Barlaup et al., 2008; Hauer et al., 2020), but these studies concerned rivers with lower concentrations of suspended sediment, which allows sizing based on a greater bed stability. Conversely, study sites EB1 and Bo1 showed near-zero mobility due to their low unit stream power values, indicating an oversizing of the gravel. Such a gravel stability will subsequently favour the infiltration of fine sediments into the gravel interstices until ultimately suffocating the gravel layer. This issue was previously addressed by Pulg et al. (2013) and Mitchell (2015), who identified life spans of 6 and 8 yrs, respectively. Among the gravel placements monitored in this study, only those carried out on the new meandering reach of site EB3 have a sizing appropriate for the river morphodynamics. Notably, 1.8 yrs after the placement of a 23-cm thick gravel substrate, the remaining gravel was 18 cm thick, and the spawning ground was still viable. However, 3.75 yrs after gravel placement, the remaining gravel was 8 cm thick. Thus, the spawning ground was no longer suitable and required a new replenishment to increase its thickness. In any case, a life span of 2 yrs for a gravel placement carried out in a reach with a perturbed bedload supply represents the minimum required life span according to Bunte (2004). Compared to the natural surface substrate composition at site EB3 ($D_{50} = 19$ mm; $D_{90} = 31$ mm), the introduced gravels were slightly coarser ($D_{50} = 28$ mm; $D_{90} = 36$ mm). This suggests that by introducing slightly coarser sediment than that of the natural bed, the distances travelled will be more limited, which will promote the longevity of the spawning ground.

Regarding the clogging of spawning gravel, most of the study sites were found to have significant clogged thicknesses, which sometimes increased over time. Only the second additions made at sites EB3 and Bo3 had an unclogged thickness greater than 20 cm. Because the studied rivers are not characterized by high suspended sediment concentrations, it is necessary to analyse the other parameters likely to govern the fine infiltration process through the gravel layer to explain this high degree of clogging. Among the site-scale parameters identified by Greig et al. (2007), hydromorphological conditions represent a key driver because they govern the complex interaction between the hydraulic and hyporheic exchange flux (Findlay, 1995; Stewardson et al., 2016) and the spawning preferences of the target species (Pasternack, 2008). Thus, the design of spawning ground must take into account the hydraulic changes in the river related to gravel placements at both meso- (geomorphic unit) and micro-scales (hydraulic pattern). In this study, the most common geomorphic unit designed through spawning gravel placements was the riffle unit because its bedform topography promotes surface-subsurface water exchanges (Kondolf, 2000). Only the gravel placement at site Bo3 differed from the riffle unit because there, the gravel was dumped in the pool between two artificial steps created by rock weirs. Because this configuration does not favour interstitial currents, artificial hydraulic structures made of boulders were placed to produce a range of hydraulic units and to promote surface-subsurface water exchanges, which may have been effective for the second gravel addition only, as the first gravel addition resulted in significant clogging. Hydraulic structures made of wood were also installed at sites EB1, Bo1 and Bo2 to create suitable water depths and flow velocities according to the spawning preferences of the target species, as previously acknowledged through several studies (see Wheaton et al., 2004).

Another parameter that governs the fine infiltration process through the gravel layer is the particle sizes of the gravel and the ensuing interstitial pore spaces (Greig et al., 2007). In this study, the spawning gravel design was based on the assumption that the use of well-sorted gravel (sorting index equal to 1.5) should provide a large volume of interstices and thus favour the circulation of oxygenated water. The significant thicknesses of clogged gravel suggested that this option was not effective. In contrast, according to Lisle (1989), well-sorted spawning gravel with great interstitial voids is particularly vulnerable to fine sediment infiltration because fine sediments that are smaller than the interstitial gaps settle at the bottom of the gravel layer and fill the pores among the gravel particles from the bottom up (Einstein, 1968). The use of well-sorted gravel in this study likely promoted bottom-up sediment accumulation. According to Lisle (1989), a wider range of gravel sizes should impede fine sediment infiltration. When the fine sediments that infiltrate the upper layer of gravel are too large to pass through, they could be trapped near the surface of the riverbed, thus reducing the interstitial void spaces of the subsurface layer. This leads to the trapping of successively smaller particles, resulting in the formation of a seal that prevents deeper penetration of fine sediment particles (Beschta and Jackson, 1979). Furthermore, several studies have demonstrated that a greater range of grain sizes will support a wider range of spawning fish (Kondolf and Wolman; 1993; Kondolf, 2000; Barlaup et al., 2008).

In any case, despite clogging, several of the rehabilitated spawning grounds were frequented by *Salmo trutta fario,* as evidenced by the many redds dug by spawners. Moreover, the large fluctuation in the clogged thickness over time at sites Bo1 and Bo2 showed that *Salmo trutta fario* could unclog the placed gravel during spawning. Such winnowing of fine sediment from gravel by salmonids, resulting in a reduction in the fine sediment within redds, has been widely recognized in natural conditions (Schälchli, 1992; Kondolf et al., 1993). However, our results also indicated that the artificial spawning grounds can reclog rather quickly (between 2.5 and 5 months, depending on the site).

5.2. Reach-scale sustainability of spawning gravel placement

The amount of gravel used for spawning gravel placement balanced several considerations, including the biological and hydromorphological functionality of the spawning ground and the cost of gravel placement. Thus, the amount of gravel per patch represented a compromise between too much gravel, which could alter the hydromorphological preferences of the target species in terms of water depth and velocity, and too little gravel, which would not provide a sufficient thickness for spawning. Nevertheless, the quantities were found to be slightly insufficient in some cases. The first attempts, made between 2010 and 2012, consisted of small volumes (~2 m^3) of gravel placed in small patches (~10 m^2), providing a thickness of approximately 20 cm, which sometimes proved to be insufficient due to the decrease in the thickness of the gravel layer following the rearrangement of the gravel after the first flood. The 2015 placements had larger volumes of gravel (between 2.9 and 10.8 m^3) and thus greater thicknesses and/or larger areas (~40 m^2). This latter option represented a good way to increase the volume of gravel added without modifying the thickness and therefore the morphodynamic parameters too much. In this way, the greater the volume, the longer the gravel placement will last.

To estimate what these volumes represent in relation to the mean annual bedload yield in natural conditions, the latter was calculated on the basis of a bedload supply (Q_s) between 0.05 and 2 $t.km^{-2}.yr^{-1}$ as a function of the unit stream power at the bankfull stage (ω_b) from the relation $Q_s = 0.0266 * \omega_b - 0.4616$ ($n = 23$; $R^2 = 0.69$; Houbrechts et al., 2006). Note that for sites EB1, EB2, EB3 and Bo1, a bedload supply of 0.05 $t.km^{-2}.yr^{-1}$ was set due to the specific context of these river reaches (low-energy river with a fine bedload) in comparison with the main part of the sites that support the above-mentioned relation (higher energy with coarser bedload). In this way, using a bulk density of 1.6 t/m^3, it appears that the added gravel volumes represent approximately half of the mean annual bedload yield at sites Bo2 and Bo3 and 1–2 times this yield at sites EB2 and EB3. In contrast, these gravel volumes were 4–7 times higher than the mean annual bedload yield at sites EB1 and Bo1. Previous studies addressing this issue have indicated that the volume of added gravel should correspond to the mean annual bedload transport capacity (Bunte, 2004; Arnaud et al., 2017), or even two times this yield (Brousse et al., 2019), but these studies had different contexts and focused on different issues (e.g., large rivers impacted by dams).

Site selection at the reach-scale for gravel placement was successful. The creation of successive spawning riffles along a meandering reach was found to be suitable for spawning. The most long-lasting configuration was to install spawning gravel at each riffle, i.e., every 0.5 meander wavelength, as in study site EB3, where the scour of the downstream gravel placements was compensated by the supply from the upstream scoured gravel placements. The same configuration was adopted at sites EB1, Bo1 and Bo2, but in the absence of gravel mobility, clogging occurred, and this approach was ultimately ineffective. For site Bo3, multiple placements were also made so that the dispersed gravel could reform and create new spawning grounds downstream, thereby extending the longevity of the most downstream spawning ground.

5.3. Ability of the displaced gravel to form new spawning grounds downstream

Our results highlighted that the ability of the displaced gravel to form new spawning grounds downstream is a function of the distance that the placed gravel is likely to travel, which in turn depends on several hydromorphological parameters.

First, travel length was strongly dependent on the frequency and intensity at which Q_c was exceeded and reflects the river energy, as shown by our results using the unit stream power. This corroborated the strong control that flow strength exerts on travel length, which was previously outlined by several studies (Hassan et al., 1992; Houbrechts et al., 2012, 2015; Vázquez-Tarrío and Batalla, 2019). Considering the grain size of the artificial spawning gravel in this study ($17 \leq D \leq 47$ mm), we observed the threshold of motion for unit stream power values between 10 and 15 W/m^2 depending on the site. Dépret et al. (2017) observed similar values (between 8 and 23 W/m^2) in the Cher River, France, where the D_{50} of the bed surface ranges from 22 to 38 mm. Such power values generally displace the gravel over a few metres, or even more, depending on the other hydromorphological parameters discussed below. Then, the higher the unit power is, the greater the travel length increases, as illustrated by the relationship obtained from the tracer surveys of this study. The relation (Mean distance $= 0.0197.\omega_{max.}^{1.473}$; $R^2 = 0.62$) obtained in this study is useful for apprehending spawning gravel mobility and thus the life span of gravel placements. In this way, the unit stream power of the annual peak flow can be determined on the basis of the stream bed geometric parameters (slope and width of the water surface) and hydrological data. The other way to predict the mobility of spawning gravel is to use the relation that takes into account multiple floods occurring over a year, namely, the sum of excess unit power values of peak flows $> Q_c$, which provided a stronger relation (Mean distance $= 0.1764.\sum(\omega_{max}\text{-}\omega_c)^{0.881}$; $R^2 = 0.77$). Although its determination requires more calculations than required for unit stream power, this metric was previously found to be relevant in several bedload transport studies, especially when the study periods include several peak flows (Houbrechts et al., 2015; Arnaud et al., 2017; Chardon et al., 2018).

Second, channel morphology has a strong influence on gravel dispersion, as demonstrated by the comparison of the travel length between the meandering and straightened reaches at site EB3. The shorter travel distances observed in the meandering reach favoured a longer life span of the spawning grounds. In their assessment of salmonid spawning gravel placements in lowland Danish streams, Pedersen et al. (2009) also highlighted a lower gravel mobility in rehabilitated meandering channels compared to that in straightened reaches. In natural gravel-bed rivers, this influence on particle dispersion has long been recognized (e.g., Petit et al., 2005) and was summarized by Pyrce and Ashmore (2003) and then by Vázquez-Tarrío et al. (2019).

Third, our results indicated that particle arrangement and bed texture exert control on gravel entrainment, marked by fostered mobility for the first displacement after gravel placement and a progressive increase in mobility over time with the degree of gravel stabilization. This is consistent with the data on natural gravel-bed rivers from the literature, summarized by Vázquez-Tarrío et al. (2019), which suggests that the distances travelled are greater for unconstrained-stone conditions (i.e., first displacement after tracer seeding) than for constrained-stone conditions (i.e., second and subsequent displacements). Houbrechts et al. (2015) also highlighted that gravel mobility decreases over time. Moreover, the relative grain size distribution (i.e., the ratio between the D_{50} of the artificial gravel and the D_{50} of the bed) may also have an influence on gravel dispersion. Although several studies indicated that a narrow grain-size range can increase the critical threshold for sediment mobilization (see Bravard and Petit, 1997), Gilet et al. (2020) showed that it can also affect bedload transport by limiting the travel distance. In the cases treated in this study, considering the small particle size distribution (sorting index equal to 1.5), the grain size ratio can be considered equal to 1 at the time of gravel placement, but once the gravel has left the gravel placement site, its relative grain size ratio will change and depend on the local particle size distribution of the stream. Although this ratio will vary slightly for sites EB1, EB2 and EB3, characterized by a similar gravel-bed composition, this ratio will increase sharply for sites Bo1 and Bo2, characterized by a streambed made of compacted silt, which should then result in a lower critical threshold for sediment motion and long-distance displacements, as was the case for the 3.2-yr flood monitored at site Bo2. For study site Bo3, spawning gravel is trapped in rock berms and behind scattered immobile boulders (hiding effect), as shown previously by Lamarre and Roy (2008) for natural step-pool systems.

6. Conclusion

While the rehabilitation of spawning habitats by gravel placement is recognized as a good measure to stem local wild fish population declines, its success relies on accurate knowledge of both the biological requirements of the lithophilic fish species and the river morphodynamics processes. If the physical or ecological context is not properly considered through a process-based approach that takes into account morphodynamic and ecological river processes, restoration measures can have a limited efficacy. To some extent, this was the case for several aspects of the spawning gravel rehabilitation measures followed in this study, as several artificial spawning grounds quickly became clogged and one was rapidly eroded. These elements of failure highlighted through the examples in this study have enabled us to identify the key parameters that drive the success of such rehabilitation projects. They have also led to recommendations for spawning gravel design.

Our findings showed that fine sediment infiltration resulted in the clogging of several spawning gravel placements, mainly due to improper sizing. On the one hand, the gravel was oversized in relation to the river competence, resulting in a high degree of stability, which favoured clogging over time and inhibited unclogging during flow events. On the other hand, the use of a narrow grain size range created large interstitial voids that likely favoured bottom-up sediment accumulation within the interstices of the gravel.

Regarding gravel dispersion, PIT-tagged gravel tracking has underlined the importance of the unit stream power as a key parameter influencing the distance that artificial gravel is likely to travel, which in turn controls the longevity of the spawning gravel placement and the ability of the displaced gravel to form new spawning grounds downstream. Considering the grain size of the spawning gravel placed in this study ($17 \leq D \leq 47$ mm), the threshold of gravel motion was between 10 and 15 W/m^2 depending on the site, and the related travel lengths were a few metres. Thus, the life span of the spawning ground was driven by the frequency and intensity at which the critical discharge was exceeded. However, we showed that additional hydromorphological parameters can exert strong control on particle travel distance, in particular, channel morphology and bed texture. Our results showed that an average annual displacement of 3 m in a meandering reach was a good option to sustain long-lasting artificial spawning gravel habitats.

This study highlighted the complexity of designing gravel placements due to the multiplicity of parameters to consider and their variability in time and space. The river manager must take into account the preferences of the target species (e.g., water velocity, water depth, proximity of fish shelters, diameter of bed material, thickness and area of the gravel placement) on the one hand, and the geomorphological processes likely to affect the spawning habitat (i.e., gravel entertainment by floods and fine sediment clogging) on the other hand. The key parameters highlighted in this study provided the river manager with operational elements useful for the design of future gravel placements. Taking these key parameters into consideration will ensure the suitability and sustainability of such rehabilitation projects.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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