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What Discharge Is Required to Remove Silt and Sand Downstream from a Dam? An Adaptive Approach on the Selves River, France

Rémi Loire [1,2,*], Loïc Grosprêtre [3], Jean-René Malavoi [1], Olivier Ortiz [4] and Hervé Piégay [2]

1 EDF, Hydro Engineering Center, Savoie Technolac, 73 370 Le Bourget du Lac CEDEX, France; jean-rene.malavoi@edf.fr
2 University of Lyon, CNRS UMR5600, Site of ENS, 15 Parvis R. Descartes, 69 007 Lyon, France; herve.piegay@ens-lyon.fr
3 Dynamique Hydro, 16 rue Masarik, 69 009 Lyon, France; lgrospretre@dynamiquehydro.fr
4 EDF, Center Unit Production, 14 av. du Garric, 15 000 Aurillac, France; olivier.ortiz@edf.fr
* Correspondence: remi.loire@edf.fr; Tel.: +33-479-606-030

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Abstract: An increasing number of scientific studies are tackling the management of discharges downstream of dams for environmental objectives. Such management is generally complex, and experiments are required for proper implementation. This article present the main lessons from a silt sand removal experiment on a bypassed reach of a dam on the Selves River (164 km^2), France. Three four-hour operational tests at maximum discharge (10, 15, and 20 m^3/s) were carried out in September 2016 to determine the discharge required for transporting as much silt and sand as possible without remobilizing coarser sediments. In September 2017, an additional flow release was performed over 34 h at 15 m^3/s. Suspended sediment concentration and water level were recorded throughout the releases. Monitoring at the reach scale was supplemented by morphological measurements. The results demonstrate that a discharge of approximately 10 m^3/s enables significant transport of suspended sediments (SS), whereas a discharge of 15 m^3/s enables significant sand transport. The results provide operational information on silt and sand transport applicable to other small rivers. This study represents an important contribution to the relatively sparse existing body of literature regarding the effects of water releases and sediment state. Our study also demonstrates that it is possible to successfully undertake water releases in small rivers with an adaptive management approach.

Keywords: flushing flow; channel maintenance flow; water release; sediment transport; river restoration; dam

1. Introduction

For centuries, many rivers have been regulated to limit flooding and enable a variety of uses, including hydroelectricity, leisure, irrigation, and drinking water supply. In the northern third of the planet, 77% of rivers now have a dam or river diversion in place [1]. Environmental impacts of dams have been described by many authors [2–5]. These impacts include effects of water-storage dams on the full range of the flow regime. In absence of floods, (high) sediment supply from tributaries downstream of dams can lead to aggradation of the bypassed reach (reach immediately downstream of the dam receiving only minimum flows) [2]. In particular, sedimentation of fine sediments may significantly disrupt biological functions by bed clogging or sand deposits [2].

In the light of potential ecological alterations of dams on river systems, researchers have recommended restoring a more natural flow regime [6–8]. The natural river regime is variable and this variability is key to maintaining indigenous species and biodiversity in general. The hydrological regime of regulated rivers can, therefore, be managed through the five components that characterize the variability of natural flow regime: flow magnitude, frequency, and duration, as well as variations in water levels at daily or seasonal scales [8].

High flow releases (or "flushing flows") are a tool for discharge management that aims to act on the morphology of the channel downstream of dams to meet environmental objectives [8]. The scientific literature largely agrees on the need to perform such releases [8–13] in the interest of imitating the effects of natural floods as much as possible [14–17]. By revitalizing fluvial processes along the river, high flow releases can potentially improve physical habitats more efficiently than hydromorphological restoration work [18], but their widespread use is relatively recent [10]. Experiments have been conducted in a number of countries in recent years [19], and some have been presented in dedicated scientific publications in Spain [20], Switzerland [21], and the USA [22,23]. These flushing flows have varied and sometimes multiple objectives, including reducing clogging in spawning areas [24–26], improving general habitat conditions [17], controlling algae proliferation in the river channel [20,27,28], and riparian forest maintenance [17,29].

According to the scientific literature, displacing sediments delivered by tributaries is rarely the primary objective of flushing flows, with the exception of the Colorado River [22,30]. Although the study of sand transport is often an integral part of research on improving clogging conditions in spawning areas, releases most often target silts and not sand. Therefore, sand is generally not monitored in this type of operation, and there are only a few studies describing the influence of flushing flows on the sand fraction, such as those conducted on the Colorado River [31,32] and the Bill Williams River [23].

In most cases, flushing flows aim to imitate a period of natural high flows [8], and the selection of key parameters, such as magnitude and duration, raise a number of issues. In particular, these parameters need to be determined to account for the energy loss of releases as they travel downstream (i.e., the attenuation of peak depth magnitude), thereby resulting in reduced effectiveness along a river continuum (reduced transport capacity) [33]. The choice of the flow discharge depends on the velocities and bed shear stresses required to induce the desired morphological process [27,29]. The required duration of a release is difficult to determine a priori as it depends on a number of parameters, such as the project reach length, slope, and morphology (particularly mesohabitat units) [34]. The duration of the release also depends on the particle size targeted by the operation. Some authors have shown that the peak of the silt pulse travels slightly more slowly [35], at the same speed [24] or slightly more quickly [36] than the peak water pulse. The duration, therefore, needs to be calculated so that the release can simultaneously impact the entire reach with a discharge that falls relatively slowly. Sand travels more slowly than silt [12]; furthermore, the duration required to export sand corresponds to the length of transit desired and is more difficult to calculate than for the duration to export silt [37,38]. In the end, the intensity and the duration of a flow release is a compromise between the required sediment transport for an effective flushing operation and the water volume available according to the reservoir dam capacity and allocations for other water uses associated with the dam or the river [39]. These elements highlight the fact that a priori determination of flushing flow characteristics is complex and support recommendations for using adaptive management [10,40–42] and closely-monitored experiments [24,36,43].

This study aims to summarize findings and recommendations from an adaptive management plan of flushing flows on the Selves River. The plan concerns a large reservoir dam whose bypass reach is subject to significant sand and silt deposits, which are suspected of impairing reproductive habitat conditions for trout. Four experimental flushing flows were carried out in 2016 and 2017 to evaluate the required intensity and duration of flow releases. A set of hydraulic, geomorphological, and biological parameters were monitored to observe the effects of the flushing flows on sediment grain size distribution and physical habitats in the bypassed reach. The results illustrate the effects of different discharges under very similar time and weather conditions in 2016. The results also provide operational information on silt and sand transport using an original approach potentially applicable to small rivers. Furthermore, this study represents an important contribution to the relatively sparse existing body of literature regarding the effects of water releases on streambed sediment conditions [44].

2. Site Description

The Selves River is a tributary of the Truyère River (Garonne Basin, France) that flows from east to west for a distance of 44.5 km through the Massif Central mountain range (Figure 1). Its source is at 1300 m altitude, and it drains a catchment area of 189 km^2. It crosses the Aubrac plateau up to the Maury dam, then flows into gorges over the last 10 km. The river catchment area primarily consists of little fractured and highly impermeable volcanic rock. It delivers large quantities of sand, which are found in the bed of the Selves and its tributaries. The region has a montane climate with an average annual precipitation of up to 1200 mm in lower-lying areas and up to 1800 mm in the higher-altitude catchment area. The catchment area is mainly occupied by meadows and woodlands.

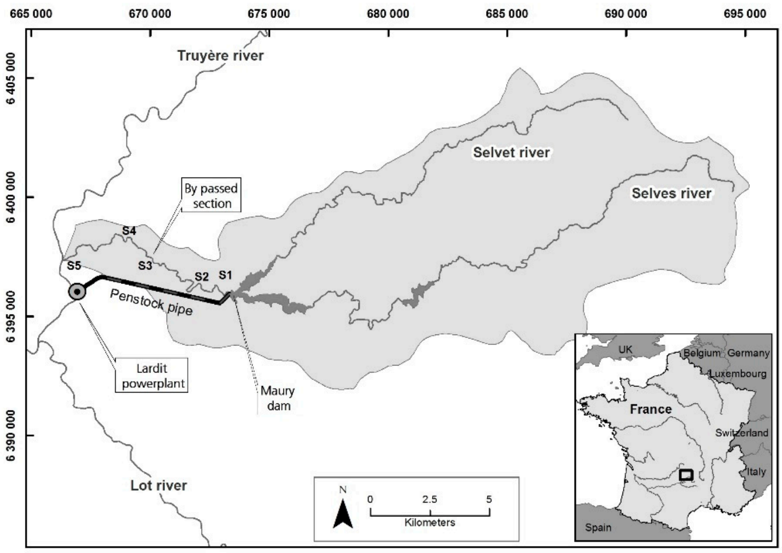


Figure 1. Location of the Selves River, its catchment area and the bypassed reach downstream of the Maury dam.

The Maury dam was commissioned in 1947 by Electricity of France (EDF) to produce electricity and is also used for tourism purposes (swimming, fishing, etc.). It is 65 m high and has a catchment area of 164 km^2 to create a reservoir of 166 ha with a normal storage capacity of 35 hm^3. The reservoir water is diverted to the Lardit powerplant located downstream of the Selves catchment area, bypassing the last 11.3 km of the Selves River.

The natural characteristic instantaneous discharges at the Maury dam are 4.8 m^3/s for the average flow, 61 m^3/s for 2-year return flow, and 110 m^3/s for 10-year return flow. The Maury dam has greatly modified the hydrology of the downstream river course as it was designed to store a large volume of water. Since 1947, a number of major floods have been observed upstream of the dam (1965: 120 m^3/s, 1981: 94 m^3/s, 2003: 110 m^3/s), but only one led to downstream overflows as the rain event had not been anticipated (1994: 74 m^3/s). The flows observed for over 70 years in the bypassed reach are, thus, almost exclusively at the minimum flow (240 L/s), in addition to the small inflows from small tributaries in the gorges. The many tributaries of the bypassed reach measure just a few hundred meters in length and have a catchment area representing 13% of that of the Selves downstream the Maury dam.

The transport capacity downstream of the dam has consequently been considerably reduced as has the sediment supply because the reservoir traps all of the incoming sediments. In the bypass reach, the current sediment supply comes from the aforementioned tributaries, mainly arriving during storms and is dominated by sand. It is not transported further once in the bypassed reach because the minimum flow has a low transport capacity, resulting in fairly widespread sand deposits (Figure 2). Some of these deposits also contain silt due to soil erosion, decaying organic materials (mainly leaves), and dam maintenance operations (bottom gate opening and drainage).

(**a**) (**b**) (**c**)

Figure 2. Sand deposits on a glide (**a**) and a gorge sector (**b**). Clogging of a lentic channel (**c**). In (**a**,**b**), the initial gravel substrate is no longer visible whereas in (**c**) silt deposits spread across the entire river bed.

The bypassed reach is located in a series of gorges of varying widths and depths with an average slope of 0.027 m/m. Rocky outcrops control the bed and its lateral mobility. The bed material grain size distribution is bimodal, with a coarse fraction of boulders and cobbles (>64 mm) and a fine fraction composed of silts, sand, and very fine gravel (<4 mm). In the slower portions of the river, widespread sand deposits can be observed on the bed near the main tributary mouths.

Although the aquatic invertebrate population is of high quality on the Selves River [45], sand aggradation and bed clogging have led to a reduction in fish populations compared to the natural capacity [46]. Electrofishing historically has demonstrated that there are larger trout populations at uninfluenced stations upstream of the dam than in the bypassed reach. A reduction in the frequency of small floods facilitates clogging of coarse alluvial substrates by fine sediments [24], which can significantly disrupt biological function, and reduce fish populations [47–49]. Clogging and sand deposits reduce the number and size of spawning areas as well as the amount of refuge and nursery habitat, which is especially problematic on the Selves [46]. Salmonid fish species (brown trout, *Salmo trutta fario*) inhabiting the Selves River require an unclogged substrate for reproduction. Managers from the local fish agency and EDF have observed silt and sand aggradation for many years. A joint decision was, therefore, taken to implement sand-removal releases downstream of the dam to improve conditions for the local trout population.

3. Materials and Methods

3.1. Designing Experimental Flow Releases

Two main morphological objectives were defined to improve biological functions:

- Remove a maximum of silt, sand, and organic material (leaves and small woody debris) from the bypassed reach channel,
- Avoid coarse sediment transport to prevent substrate disruption that would impact aquatic fauna (as there are no natural inputs of coarse sediments).

This approach requires determining the most effective flow magnitude and duration for unclogging and removing silt and sand deposits from the river, without affecting coarser sediments. Furthermore, the releases needed to be long enough to avoid fine sediment redeposition.

Following the recommendations of [34,37,50], a range of potential discharges to be tested were determined empirically from flow statistics and calculation of at-a-station sediment transport thresholds (flow velocity comparisons with Hjulström diagram, [51]). Hydraulic modelling was not used as there are too many uncertainties regarding sand transport in rivers with large boulders and steep slopes.

An adaptive approach [7,18] was, therefore, used to determine the most effective flow magnitude, with three different discharges being tested in 2016 (10, 15, and 20 m^3/s) before implementing a more ambitious approach. The peak flow duration, between 4 and 5 h, was chosen based on our operational experience (transfer time observed when opening the bottom gate) (Figure 3). A gradual increase in discharge, from minimum baseflow up to 10 m^3/s, was implemented to limit fish drift, followed by a one-hour stable flow at this discharge, which corresponds to the alert wave required for the safety of third parties. The hydraulic transit time for these releases was estimated at approximately 2 h 30 min. However, we chose to maintain the target discharges for, at least, 4 h to ensure that the operation was successful, to enable comparison between the releases, and to identify the impact of each release on the sand transport distance. The releases were generated by the bottom gate to retain a temperature similar to the minimum flow.

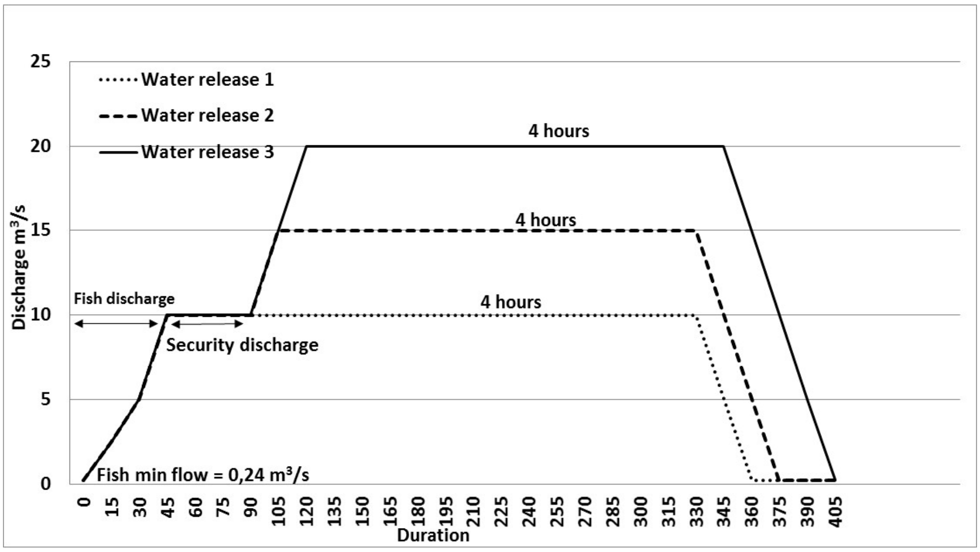


Figure 3. Hydrographs of successive flow releases carried out on the Selves on 6, 13, and 20 September 2016.

Following these initial experiments, a fourth flow release was carried out from 19 to 20 September 2017, with a maximum discharge of 15 m^3/s. The ascending and descending phases of the hydrograph were managed in the same way as previous releases, but the duration at maximum discharge was extended to 34 h to test the effects of duration.

The releases were carried out on 6, 13, and 20 September 2016, to avoid conflicting with other uses or temporal constraints: (i) In the summer, the reservoir needs to be kept at a high level to satisfy tourism requirements, and safety risks are at their highest because of extensive fishing in the bypass reach; (ii) heavy rain is likely in autumn and could disrupt the experiment; (iii) salmonid spawning, incubation and growth phases take place from November to June. Various authors [22,40,52,53] have outlined the biological risks of this kind of operation on spawning, incubation or survival rate of juveniles.

3.2. Continuous Monitoring of the Experiment

Suspended sediment concentration (SSC) and water level were monitored at two stations. The first is located at the foot of the dam and the second is located 800 m upstream of the confluence with the Truyère River (Station 5 of the geomorphological monitoring). SSC was monitored at 30-s time steps using a GGUN FL30/Albillia turbidimeter (Albillia, Neuchâtel, Switzerland) and a Tetraedre TRMC 5 autonomous data logger (Tetraedre, Auvernier, Switzerland). Twenty-four water samples were collected at Stations 1 and 5 to correlate SSC and turbidity and then total suspended sediment load transported during each release (SSL) by flux calculation (TSS concentration from turbidity measurement × water discharge). Water levels were measured using a probe and recorded every minute. Flow measurements were taken at Station 5 to verify the flow released by the dam with an ADCP RiverPro Teledyne RDI (Teledyne Marine, Stowe Drive Poway, CA, USA).

3.3. Geomorphological Monitoring

Geomorphological monitoring at reach scale, i.e., from the Maury dam to the confluence with the Truyère River, was based on 116 equidistant 100-m transects. Each transect is a cross-section within the wetted perimeter. Data collection was performed on these transects at 4 periods: (i) during the summer preceding all releases (T_{0_16}); (ii) in the autumn following the first three releases (T_{3_16}); (iii) one week before the fourth release (T_{0_17}); (iv) one week after the fourth release (T_{1_17}). Measurements of the following parameters were conducted every meter within each transect: water depth at the minimum flow, dominant sediment coverage within a 50 cm radius from the point of measurement using Wentworth's particle size classification [54], mesohabitats and thickness of fine sediments (silt, sand, and fine gravel).

Similar geomorphological monitoring was undertaken at 5 stations (250 m average length), corresponding to dominant sandy bed-surface sub-reaches, and located at increasing distance downstream of the dam: 950 m (S1), 1800 m (S2), 4200 m (S3), 5200 m (S4), and 10,400 m (S5). They generally had much greater sand patches than other sub-reaches because of a lower bed slope or tributary proximity, with the exception of Station 5, which was selected for its location (downstream of the bypassed reach) and easier access. Each station was described by approximately thirty transects, and the distance between two transects corresponded to its average active channel width. The parameters measured on each transect were the same as for the reach scale monitoring. In addition, cobble and pebble sediment patches were painted on the riverbed at each of the stations (from 2 to 8 patches depending on the campaign). This station scale monitoring was carried out only in 2016 to be able to assess the effect of each of the trial discharges (10, 15, and 20 m^3/s; Table 1): before the first release (T_{0_16}), after the first release (T_{1_16}), after the second release (T_{2_16}), and after the third release (T_{3_16}).

Table 1. Morphological monitoring schedule (X: measurement performed).

Year	Water Release	Discharge m^3/s	Max Discharge Duration (h)	Monitoring Steps	Reach Scale Monitoring	Station Scale Monitoring
2016	-	-	-	T_{0_16}	X	X
2016	1	10	5	-		
2016	-	-	-	T_{1_16}		X
2016	2	15	4	-		
2016	-	-	-	T_{2_16}		X
2016	3	20	4	-		
2016	-	-	-	T_{3_16}	X	X
2017	-	-	-	T_{0_17}	X	
2017	4	15	34	-		
2017	-	-	-	T_{1_17}	X	

Station 1 is immediately downstream of the upper tributary. This station was strategic as there was no sand supply during the releases upstream of this tributary: the upstream reach contained no sand, and the tributaries were at low flows.

To monitor sand transport distance, 400 kg of fluorescent tracers (with sorted sand, 2–4 mm diameter) were injected into the river bed (Figure 4) before the releases at Stations 3 (3 trials in 2016 and the 2017 trial), 2 (2017 trial only), and 5 (2017 trial only). Different colored tracers were used for each release. After each release, bulk samples (17 to 31) of approximately 5 kg of sediments were collected in sandy areas downstream from the injection points, continuing downstream until the colored sand had disappeared from the samples. Discoloration was considered to be a negligible effect (colored tracers were found 2 years after injection). Tracer concentration of the samples was determined by image analysis (automatic counting of colored sand) to report their longitudinal dispersion and define the median distance of transport. This tracing technique is frequently used in coastal environments [55,56], but few studies have used it in rivers [57,58]. The total sand transport volume was evaluated by multiplying the active layer measured with scours chains [59] on the riverbed at each of the stations with the median distance of transport: (width) × (scour depth) × (median distance).

Figure 4. Photograph of the fluorescent orange sand tracers injected in the Selves River (Station 3) before the first release on September.

4. Results

4.1. Continuous Monitoring of Water Levels, Water Velocities, and SSC

The various discharges tested generated substantially different hydraulic conditions (Figure 5). The hydrograph for each water release was well propagated downstream. The water velocities and depths measured by ADCP at the most downstream station for the release show that the peak discharge measured there was equal to the discharge generated by the upstream dam. However, the gradual increase to minimize the impact on aquatic fauna and provide a safety alert was not effective at the downstream station in either 2016 or 2017: the maximum discharge was reached in only 50 min.

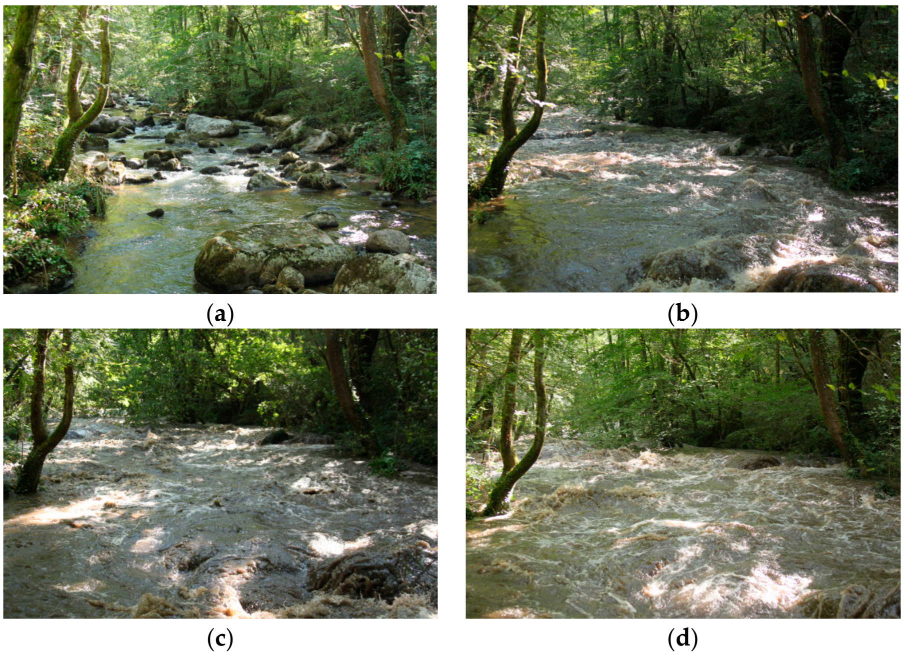
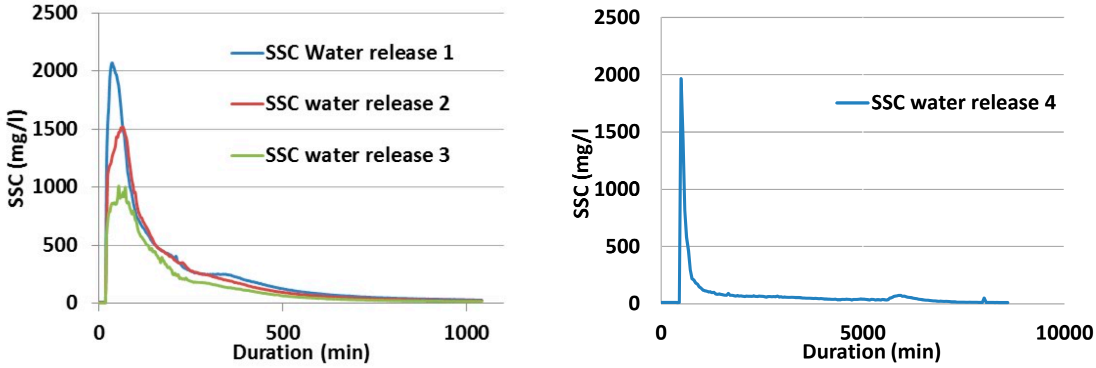


Figure 5. View from downstream of Station 4 (see Figure 1 for location) at (**a**) Minimum flow (**b**) 10 m^3/s, (**c**) 15 m^3/s, (**d**) 20 m^3/s.

SSC at the most upstream station, i.e., immediately downstream of the dam, was always below 0.1 g/L for 2016 releases and reached a maximum of 0.9 g/L in 2017. At the downstream station (near the confluence of the Truyère River), SSC reached 2.1 g/L, 1.6 g/L, 1.0 g/L, and 2.0 g/L during the four successive releases, respectively (Figure 6). The differences between the 2 stations indicate that each release evacuated fine sediment.



(**a**) (**b**)

Figure 6. Suspended sediment concentration (SSC) observed at the downstream station (Station 5, Figure 1) for each flow release in (**a**) 2016 and (**b**) 2017.

The total suspended sediment load (SSL) transported at the downstream station by the first three releases, of equal duration but increasing intensity, are 140, 190, and 176 tonnes (±5%, [60]) respectively. The 2017 water release was much longer and removed an intermediate volume of 180 tonnes. In 2017, the SSL was slightly lower than that of the second release in 2016, despite having the same discharge and a much longer duration, although the reach was already well-declogged in 2017 before the release.

For the three water releases in 2016 with a 4-h peak discharge, the SSC levels were substantially reduced just 2.5 h after flooding, by a factor of 4, 3, and 2 after the three water releases, respectively. The cumulative SSL curves (Figure 7) also demonstrate that 50% of the sediment was transported in less than 2 h and around 90% in 5 h. The duration of the 2016 releases was, therefore, sufficient to export most of the fine sediment that could be transported in suspension.

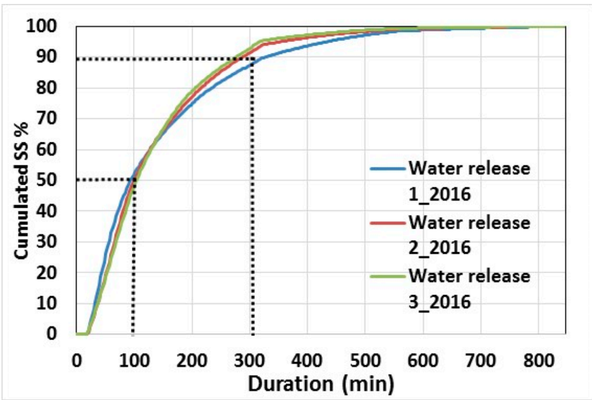


Figure 7. Cumulative percentage of suspended sediment load (SSL) of 2016 releases at the downstream station (Station 5).

4.2. Morphological Monitoring across the Bypassed Reach

Before the releases, large accumulations of silt and sand were observed at the confluences of tributaries and in sub-reaches where the slope was low (up to 50 cm, Figure 8). Between T_{0_16} and T_{3_16}, the majority of large fine sediment deposits observed before the releases (Figure 9a) disappeared, which resulted in a decrease of average fine sediment thickness and an increase of average water depth.

After these three releases, no significant resedimentation was observed on the bypassed reach except at Cross-section 32. Between T_{3_16} and T_{0_17}, a period of almost one year without flow releases, some new sedimentation patches were observed around the main tributaries, particularly downstream of Station 1 and Station 4 (Figure 9b). Between T_{0_17} and T_{1_17} (Figure 9c), sediments transported from Station 1 to Station 2 were moved and deposited again. Around Station 1, water depths increased. Downstream of Station 2, sedimentation patches alternated with scoured patches. Overall changes were less marked than between T_{0_16} and T_{3_16}, showing some redistribution of fine sediments along the bypassed reach. Comparing T_{0_16} and T_{1_17}, shows that the large sand deposits near the tributary confluences before the releases (T_{0_16}) were generally removed and that water depths usually dropped consequently in the same sub-reaches (Figure 9d).

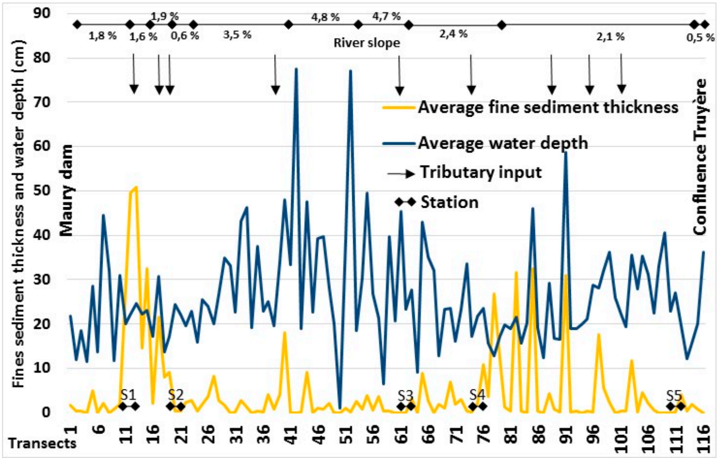
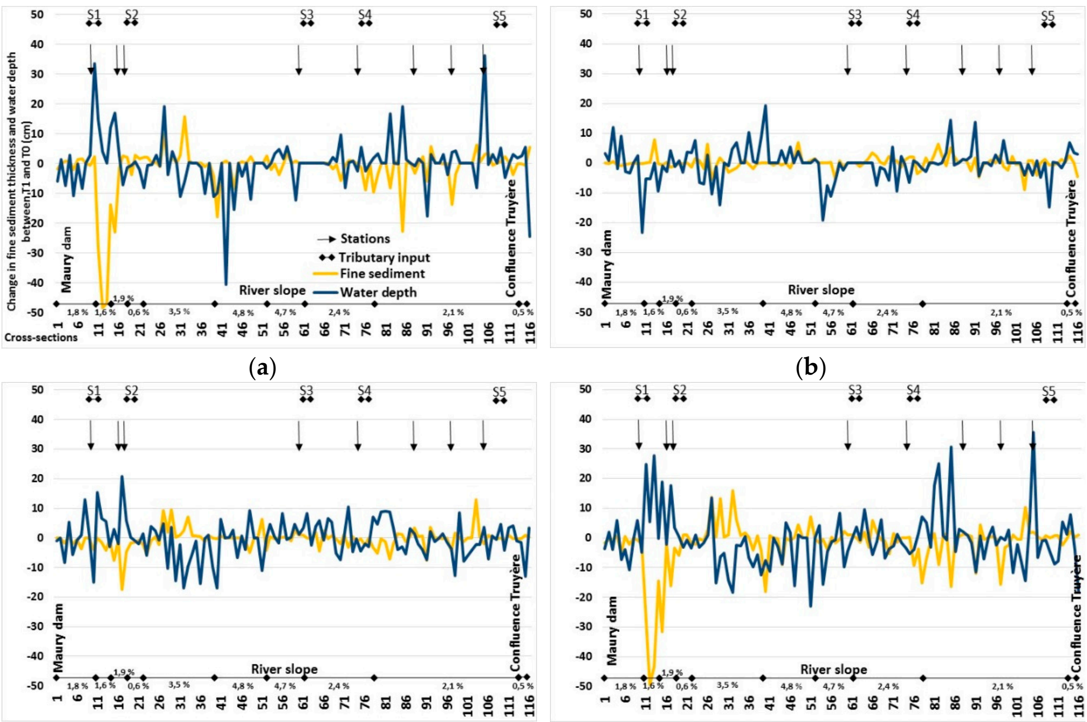


Figure 8. Longitudinal distribution of average water depth and fine sediment thickness at T_{0_16} in the bypassed reach and position of main geomorphic units with their respective slopes.



(**c**) (**d**)

Figure 9. Change in average water depth and fine sediment thickness on each of the cross-sections in the bypassed reach. (**a**) T_{0_16}–T_{3_16}, (**b**) T_{3_16}–T_{0_17}, (**c**) T_{0_17}–T_{1_17} and (**d**) T_{0_16}–T_{1_17}.

Average fine sediment thickness clearly dropped following the first releases (−1.8 cm between T_{0_16}–T_{3_16}) and the last release (−0.4 cm between T_{0_17}–T_{1_17}) (Table 2). The transient period between releases slightly increased the average sand deposit. The average water depth increased between T_{0_16} and T_{3_16} (+0.7 cm). It then dropped during the year between releases, presumably in relation to tributary inflows (−0.5 cm between T_{3_16}–T_{0_17}). It continued to drop between T_{0_17} and T_{1_17} (−0.8 cm).

Table 2. Average water depth and fine sediment thickness in the bypassed reach for each of the surveys.

Parameters	T_{0_16}	T_{3_16}	T_{0_17}	T_{1_17}
Average water depth (cm)	26.0	26.7	26.2	25.4
Average fine sediment thickness (cm)	4.8	3.0	3.1	2.7

The change in cumulated fine sediment thickness between successive releases clearly showed a drop in the sedimentary stock of fine materials in the river (Figure 10). The first 3 releases performed between T_{0_16} and T_{3_16} had a significant effect. The cumulated average fine sediment thickness reduced by a little more than 29% following the three releases. However, only a small difference is observed between T_{3_16} and T_{0_17}. A slight trend for sand to aggrade is again observed at the first tributary confluence for Station 1 and after the river gorges. The final release also contributed to a drop in sedimentary stock, but to a lesser extent. Downstream of Station 1, progressive erosion is clearly evident between T_{0_16} and T_{3_16} and between T_{3_16} and T_{1_17}. It is the clearest erosion effect observed on the reach. The downstream V-shape narrow valley reach (between Station 2 and Station 3 or even 4) generally seems to be in sediment balance, since sediment inflows and outflows do not seem to have any repercussions on the changes to fine sediment thicknesses between releases. This is, therefore, a sediment transfer reach. Erosion processes then pick up again downstream of the narrow valley, and the balance stabilizes after the valley widened (downstream from Station 4).

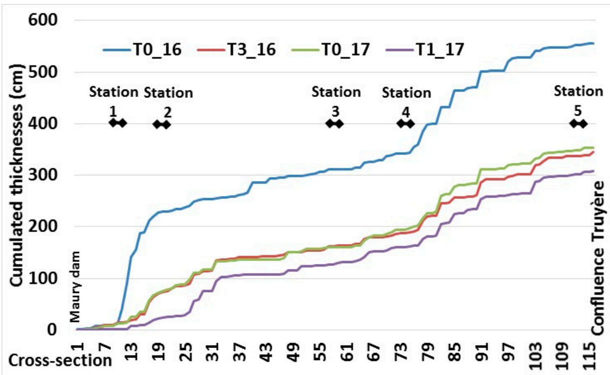


Figure 10. Cumulative fine sediment thickness in the bypass reach.

Changes in fine sediment thickness are significantly tied to the various mesohabitats units [61]. In particular, changes were particularly clear for glides (Figure 11), where median sediment thickness dropped considerably after each flow release (reduction by a factor of 2 or more). Faster flowing mesohabitats units (riffles, cascades, and rapids) showed no change.

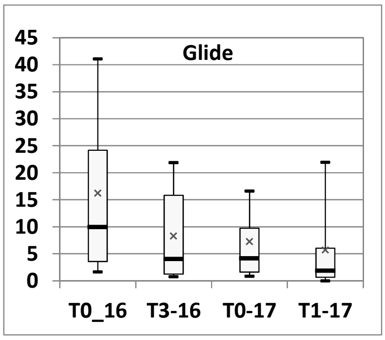


Figure 11. Distribution of average fine sediment thickness on glide at T_{0_16}, T_{3_16}, T_{0_17}, and T_{1_17} (cross = average, bars = median, 25th and 75th percentiles and min and max).

Bed-sediment composition became progressively coarser during the experiments, as determined by measured grain-size distributions (Figure 12). The proportion of silt was reduced by a factor of 2.5 after the three short releases of 2016 (from 10% to 4% between T_{0_16} to T_{3_16}) and became null (1%) after the long release of 2017 (T_{0_17} to T_{1_17}). The intermediate period between the third and fourth releases led to slight silt deposits (+2%, T_{3_16} to T_{0_17}). The proportion of sand in the sediment distribution decreased very slightly after each release, although a portion of the sand was exported to the edges (observed but not calculated). As a result of the overall decrease of fine sediments, coarse particles, such as boulders, rocks, and flagstones, and primarily coarse cobbles were more common after the releases.

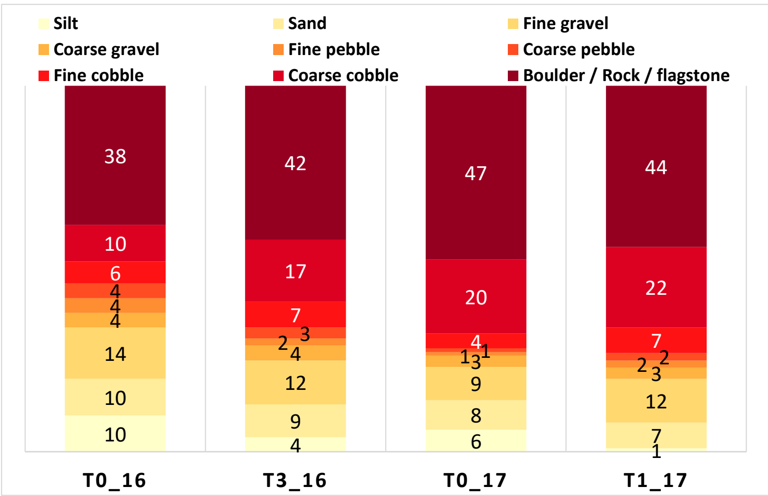


Figure 12. Distribution (%) of particle sizes observed for the four monitoring campaigns (T_{0_16} to T_{1_17}) in the bypassed channel.

4.3. Station-Based Morphological Monitoring

At Station 1 (where the incoming sediment supply is low), fine sediment thickness dropped by approximately 60% following the first flow release and around 90% after the second one (Figure 13a). This translates into a sharp increase in water depth, which almost doubled after the second release (Figure 13b). The third release was less effective because the remaining fine sediments were trapped behind boulders.

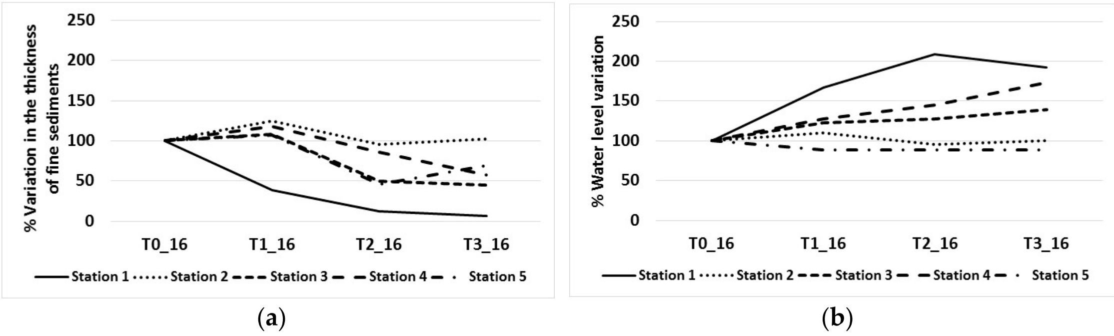


Figure 13. (**a**) Evolution of average fine sediment thickness and (**b**) average water level before and after each 2016 release at the 5 stations (100 base level at T_{0_16}).

At the other stations, fewer changes were observed because of the incoming fine sediment supply from upstream sub-reaches. At Station 2, fine sediment thickness and water depth remained relatively constant during all of the 2016 experiments because of a strong sand supply coming from Station 1. At Station 5, water depth did not change significantly despite a decrease of fine sediment thickness after two releases. In fact, fine sediment thickness was already very low in this station before the experiments so that its evolution in terms of absolute value was limited. At Station 3 and 4, the first release led to insignificant changes, but average water depth increased progressively as fine sediment thickness decreased after the second release.

4.4. Bedload Monitoring

4.4.1. Pebble and Cobble Entrainment

According to the painted particles survey, the largest particles mobilized by all releases in 2016 were small cobbles (64–128 mm), but they were few in number and transported only over short distances (less than 5 m). Most of the painted particles transported were medium gravels (8–16 mm) during the 1st release, coarse gravels (16–32 mm) during the 2nd release and very coarse gravels (32–64 mm) during the 3rd release. The discharge values of the first two releases (10 and 15 m^3/s) resulted in limited entrainment of medium-sized particles (required for fish spawning and to preserve the diversity of aquatic habitats). In contrast, the discharge value of the 3rd release (20 m^3/s) resulted in much greater mobilization of coarser sediments, which is contrary to the initial objectives agreed upon.

4.4.2. Sand Export

At Station 3, the transport distances of fluorescent tracers (2–4 mm) increased linearly with discharge with a proportionality ratio greater than 1 (Table 3). Compared to the first release, the median transport distance was increased by a factor of 2.4 for the second release and by a factor of 3.6 for the third release. For a constant volume of water, the transport efficiency of a release should be improved if one maximizes its peak flow rather than its duration. However, the previous results showed that 20 m^3/s release can be detrimental to coarse sediments necessary for fish spawning patches.

The fourth release was dimensioned in light of this last observation, keeping a flow rate of 15 m^3/s but increasing its duration. At Station 3, the median transport distance was only slightly more than twice that obtained for the second release despite a duration five times greater.

For the water releases in 2016, the total sand distance transport increased with the discharge from 30 m to 111 m. In fact, based on a similar active layer depth as measured by scour chains, the volume transported is proportional to the particle transport distance: The increase in discharge from 10 to 15 m^3/s transported a volume 2.8 times greater; when the discharge doubles, i.e., for the 20 m^3/s release, the transported volumes increase by a factor of 3.9.

Ultimately, the estimated transported volumes ranged from approximately 100 m^3 for the 2016 releases, to several hundred m^3 for the 2017 releases.

Table 3. Transport distances of the fluorescent tracers.

Parameters	Flow Release 1 2016 Station 3	Flow Release 2 2016 Station 3	Flow Release 3 2016 Station 3	Flow Release 4 2017 Station 3	Flow Release 4 2017 Station 2	Flow Release 4 2017 Station 5
Discharge (m^3/s)	10	15	20	15	15	15
Duration (h)	5	4	4	34	34	34
Median transport distance (m)	30	71	111	164	879	223
Total sand transport (m^3)	24	68	93	162	550	368

5. Discussion and Recommendations

5.1. Design of the Flow Release and Impacts on SSC

The attenuation of peak depth magnitude sometimes observed in the flow diffusion downstream of dams [33,35] did not occur on the Selves at maximum flow, even during the short 2016 releases: The nominal flow rate was the same from the Maury dam to the output of the bypassed reach. However, attenuation of peak magnitude was observed for the lowest discharges, corresponding to the alert wave (for safety and fish protection). In the absence of flow measurements in the middle part of the bypassed reach, it is impossible to define where the energy loss occurred in 2016. Thanks to the installation of a water level monitoring station in 2017 at S2, it seems that this loss occurred between Stations 2 and 3. We attribute a large portion of this loss to the pronounced step-pool morphology of the bed channel between Stations 2 and 3 where the slope of the valley bottom is higher. Longitudinal variations in channel morphology must, therefore, be taken into account to ensure that the alert wave (for fish protection and safety) are effective along the entire reach.

SSC was closely monitored to meet regulatory requirements and to evaluate the success of the releases with respect to the export of fine sediments. The SSC peaks coincided with the flood waves and their peak values decreased for each successive release, despite their increasing intensity. Similar decreases in SSC have already been observed in other rivers following successive releases which have the same peak discharge value [36,62,63].

The increase in volumes between the first and second releases can be attributed to higher specific stream powers and water levels: Besides the obvious influence of flow intensity on transport rate, the higher water level of the second release has remobilized more overbank fine materials. The lower SSL of the third release, despite an even greater discharge, shows that the environments were already well-leached after the second one. The example of the Selves in 2016 illustrates that the volume of fine sediment transported may increase if the flow discharge of a following release is higher than the first, even when it is undertaken relatively soon (i.e., 1 week) after the previous one. It is difficult to compare the 2017 release with the previous releases because it took place in a reach that was already well-declogged, demonstrating flow release success is highly contingent on initial conditions. However, the volume of sediment transported in 2017 shows that the environment tends to gradually reclog, requiring frequent flow releases. Thus, even if the SSC level achieved can be an indicator of release success in itself, the volumes transported should also be calculated in such cases to evaluate and compare the effects of successive releases.

The percentage of silt in the channel bed was reduced from 10% to 4% after the first release. This first result shows that regular flow releases of 10 m^3/s during 5 h is efficient to entrain silt in the bypassed reach of the Selves River. This flow is approximately twice the pre-dam average annual flow. Tests could also be performed at slightly lower discharges to observe their efficacy.

5.2. Meso-Habitat Improvement

Unlike for silt, the four flow releases were not long enough to export all of the sand from the bypassed reach, however, they did result in a significant decrease in the amount of sand stored in the bed channel. This decrease can be explained by a partial export to the Truyère River and by sand accumulation along the river edges (Figure 14), as also observed on the Colorado River [31]. The latter phenomenon, which has also been documented for larger rivers [23,29,32], ultimately results in improved channel mesohabitat conditions without requiring complete sand transport over the entire bypassed reach, which would require a much longer release. Lateral sand export allows for achieving habitat objectives while also minimizing gravel transport and economizing water volumes used during the releases. However, the lateral accumulation of sand could result in raising and progressively disconnects the adjacent floodplain.

(**a**) (**b**)

Figure 14. (**a**) Creation of new sand bars and (**b**) sand deposition on the river banks.

The 10 m^3/s discharge is likely to promote sedimentation on reaches sensitive to sand aggradation. The critical shear stress is undoubtedly not reached for this discharge in such areas. The 15 m^3/s release seems the most effective as it generates a clear reduction in the percentage of silt and sand for all stations, with no exceptions, and without significant coarse sediment transport. The last 20 m^3/s release had contrasting effects on sand deposits at the station scale. As the discharge was theoretically more effective than for the second release, this observation is only due to the irregularity of inflowing sediments. Diverging results between stations have already been reported by other investigators during water releases, despite those stations having a similar gradient [23]. This diverse behavior shows the importance of monitoring sediment transfer at the reach scale to learn from experiments and choosing the most effective discharge. In addition, the release resulted in greater mobility of coarse sediments. However, as there is no natural replacement of this sediment due to upstream trapping by the dam, mobilizing the coarse sediment could work contrary to the objectives, in that these sediments are one of the major components of desired fish habitat [37,39].

The average thickness of silt and sand was reduced by a factor of 1.8 in the bypassed reach channel after the four releases, which is largely due to the export of silt. The reduction in fine sediments below the dam had positive effects on substrates, and more generally on physical habitats, by increasing the water depth at low flow. This last effect, which is not obvious at the bypassed reach scale, is clearly positive for the monitoring stations most sensitive to fine sediment deposits. Other authors have previously reported an increase in water depth following water releases [12], creating new habitats for fish, however, for the Selves River, this is a localized effect (only very clogged stations were affected) and does not apply to the whole reach.

5.3. Sand Export

The fluorescent tracing of sediment particles was motivated by the need to evaluate the release duration necessary to evacuate sand from the bypassed reach. According to the results from the 2016 experiment on a single station, the transport distance is linearly related to discharge magnitude with a proportionality ratio greater than one (see Table 3). The 2017 experimental results from three stations demonstrate that transport distances differ strongly from one site to another, even when these sites did not initially appear to have substantial morphological differences. At Station 3, this result could be explained by heterogeneous hydraulic conditions within the reach, probably less favorable for transport in its downstream part. In the same way, the results obtained downstream from the two other stations are significantly different because of specific hydraulic conditions including bed slope, bankfull width, and hydraulic roughness. These results confirm the need to equip several sites because responses are site-specific [18]. Three hypotheses explain these differences among sites. The first hypothesis is that there is an attenuation of the peak depth magnitude further downstream [33,35]. However, this hypothesis is highly unlikely since the range of water depths at the most downstream station were the same as those further upstream. The second hypothesis is related to site-specific morphological and hydraulic conditions. Previous investigators have shown that the results obtained from water releases cannot necessarily be applied from one site to another [18]. Local flow conditions are likely to be key in determining morphodynamic responses [64], which create different responses for each site. The main difference between the sites is that downstream of Station 1, the released water is already completely saturated with sand, thereby reducing its capacity for erosion. Finally, the last hypothesis corresponds to a measurement bias with the fluorescent tracers. For example, at Station 2, some of the tracer material settled on the river banks and was not taken into account in the analyses, which leads to overestimation of the distances travelled. Given all of these uncertainties, for a 15 m^3/s release, we adopted a median transport velocity of around 15 m/hour in areas conducive to sand transport and slightly less in more lentic reaches. Based on these assumptions, it would take at least 30 days and up to 45 days to fully export sand from the entire bypassed reach at a constant discharge of 15 m^3/s.

For all of the 2016 water releases, which are quite similar in terms of duration, the transported volume increased with increasing discharge. An increase in discharge from 10 to 15 m^3/s resulted in a transported volume around 2.8 times higher. Likewise, an increase in discharge from 15 to 20 m^3/s transported a volume around 3.9 times greater. These results are similar to those made by Collier et al. [22], where the volumes of sand transported also increased significantly with discharge. However, the rate of increase given by Collier et al. [22] specifically an 8-fold increase in transported volume when discharge was doubled, was not observed in our case. This difference can be attributed to the difference in size and morphology of the rivers studied.

Finally, these results show that even relatively low peak discharges can influence the physical habitat of the flow channel in rivers with a high sand load [23]. In our case, a flow equal to three times the pre-dam mean annual flow is effective.

5.4. Perspectives

Our study demonstrates that it is possible to successfully undertake water releases in small rivers with an adaptive management approach. Specifically, we have shown that hydraulic modelling is not always necessary for this type of operation and that simple geomorphological monitoring is able to provide the necessary information to evaluate the effectiveness.

Although the movement of materials larger than those targeted is inevitable, it should be limited as far as possible in the absence of coarse sediment supply downstream from the dam. It is, therefore, strongly recommended to continue to use an iterative approach to determine this critical discharge in terms of magnitude, duration, and frequency, starting with low discharges for a short duration.

For the Selves River, two discharge levels are now recommended: 10 m^3/s for silts and 15 m^3/s for sands. To export most silt out of the bypassed reach, the release time required is only 5 h. For sands, the duration is not yet defined because it should be adapted to the quantity of tributary inputs. These contributions are not yet known but could be quantified at stations to be established immediately downstream of the tributaries, using the same measurement protocol presented in this study.

Initial results show that silt aggradation can be observed between two releases one year apart. This annual silt deposit is not necessarily problematic for the environment, but a target threshold should be defined beyond which a water release should be carried out. We suggest continuing the full geomorphological monitoring of the reach and to carry out new water releases when the silts reach more than 7% of the overall grain size distribution corresponding to a "good" situation for the stakeholder and also equivalent to conditions observed at T_{0_2017}. This value should be reassessed with the forthcoming biological monitoring results. For sand, monitoring events (storms) likely to transfer sediments into the Selves River from tributaries would provide useful information to quantify the effects of major storms on the volume of sediment stored into the Selves. It would then be possible to conduct a release to ensure a well-balanced sediment budget.

To evaluate the biological effects of these releases (and ultimately their ecological efficacy), biological monitoring (fish, spawning areas, macroinvertebrates) should be continued for at least five more years to ensure that the conditions defined by these thresholds are adequate. There is also a need to compare monitoring results (both sediment and biological responses) with reference conditions on a nearby river to objectively evaluate release success.

It is difficult to use data from other publications without at least some basic information and meta-analysis of such experiments are needed to improve release design and determine a priori potential channel responses. Therefore, to make these types of studies comparable, we strongly recommend that experimenters systematically state at least the following information in their publications: catchment area, historical data on flood and average discharges, average bed slope and particle size distribution of the channel and of the sediment load.

6. Conclusions

Conducting iterative water releases on the Selves River paid off with a reduction of surficial clogging, effective sand export, and water depth increases while avoiding mobility of coarser sediments, all while requiring only limited human and financial resources. Although the discharges were chosen empirically, they ultimately were in the necessary range for the management objectives and allowed us to identify the optimum discharge for future operations. We now know that a discharge slightly below or equal to 10 m^3/s enables significant transport of SSCs but not of the sand, whereas a discharge of 15 m^3/s provides much greater movement of sand sediments. Higher discharges are not cost-effective because of the risk of entrainment of coarse particles and because the gain in distance traveled relative to the increased discharge is smaller.

The measurements performed at station scale and at the overall bypassed reach scale provided complementary information. For example, we saw that water levels increased significantly in clogged areas but did not vary at the reach scale. The station-scale monitoring allowed us to precisely describe the effects of each release and, thus, to validate each step according to an adaptive management process.

The status of the watercourse and the state of its streambed sediment has been improved by transporting silt and sand out of the bypassed reach, through over bank deposition, and by increasing the water depth in sandy sectors, thereby meeting stakeholder expectations. Managers and users are now convinced of the value of this kind of operation because of visual habitat improvement with no evidence of potential ecological damage during the experiment. Water releases are, therefore, a management option that is now locally accepted.

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