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Morpho-sedimentary dynamics associated to dam removal. The Pierre Glissotte dam (central France).

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1 **Keywords:** River restoration; Bedload continuity; Morpho-sedimentary adjustments; Hydromorphological
2 trajectory; Yonne River.

3 4 5 **1. Introduction**

6
7 Dam removal has greatly increased since the 1990s, particularly in the USA where 1,700 removals were
8 recorded in February 2020 in the American Rivers database (www.americanrivers.org). Different goals or
9 needs motivate this type of operation: safety and economic issues when there is a risk of dam failure or when
10 the dam is approaching its engineered life expectancy and incurring increasing maintenance costs; landscape
11 and eco-geomorphic problems when the purpose of the removal is river restoration (Bellmore et al., 2017;
12 Major et al., 2017). In the latter case, the objective of establishing “natural components and regenerative
13 processes” (Hart et al., 2002) relies to a great extent on restoring fish passages and sediment continuity. The
14 reactivation of hydro-sedimentary dynamics is often expected to re-shape the river at different spatial scales,
15 modifying channel morphology, the fluvial landscape and fauna and flora habitats. Several dozen operations
16 have been studied and published in connection with one or more hydromorphological aspects (e.g. Egan and
17 Pizutto, 2000; Stanley and Doyle, 2003; Major et al., 2012; Randle et al., 2015; Ibisate et al., 2016;
18 Magilligan et al., 2016; Gilet et al., 2018). Based on numerous case studies, a series of reviews have already
19 gathered and compared findings in the literature on the geomorphic effects of dam removal (Skalak and
20 Pizutto, 2005; Sawaske and Freyberg, 2012; Grant and Lewis, 2015; Bellmore *et al.*, 2017; Foley et al.,
21 2017a, b; Major et al., 2017).

22 Although some common trends in river adjustments have emerged from these studies, the reviews also
23 emphasize the many interacting factors that influence the river response at local scale and may prevent the
24 accurate prediction of the impacts of dam removal: the time that has elapsed since the dam was first built; the
25 distance from the dam of a given reach; the size of the dam; the volume of sediment and the composition of
26 the reservoir fill; the location of the dam in the river network; the hydromorphological context (the geology
27 and morphology, flow and sediment regime, morphological features, etc.), the anthropogenic context and
28 history of the river (Foley et al., 2017a; Major et al., 2017; Poepl et al., 2017). Despite possible similarities,
29 it is hard to predict differences in the way the many hydro-physical conditions will interact with each other
30 from one site to another (Bellmore et al., 2019). Uncertainty in how the river will respond also arises when
31 unexpected discoveries are made during the removal operation such as anthropogenic structures (Wilcox *et*

32 *al.*, 2014; Magilligan et al., 2016) or different substrate materials (Harris and Evans, 2014; Gartner et al.,
33 2015) that control incision or lateral erosion. Ultimately, exactly where and when adjustments will occur in a
34 given river reach cannot be foreseen. Indeed, changes in the dynamics and rates of the river response in
35 space and over time make predicting the river trajectory complex (Major et al., 2017).

36 All these sources of uncertainty - differences in the chain of interactions and feedback between sites,
37 unexpected discoveries, spatial and temporal variations in the response of a river at the same site, but also
38 changes in the hydromorphological conditions in the period between when the dam was constructed and its
39 removal - make it difficult to predict exactly how the river will respond, and to guarantee beforehand that it
40 will return to its pre-dam hydromorphological and ecological state (Foley et al., 2017a; Bellmore et al.,
41 2019). However, rivers' responses to dam removal help to inform the discussion around restoration and
42 rehabilitation paradigms (Dufour and Piégay, 2009). Only a few studies have sought to interpret the post-
43 removal conditions (forms and processes) in the hydromorphological trajectory: do they correspond to a pre-
44 dam equilibrium? Do the conditions implemented under the dam's influence still prevail? Has a completely
45 new hydromorphological equilibrium emerged? The meaning of restoring sediment dynamics should also be
46 questioned: when fill sediments are significantly eroded and the reestablishment of sediment continuity is
47 successful, does it lead to the restoration of the hydromorphological functioning of the river? How much
48 time does the restoration or the achievement of a new functioning require? This last question and the
49 frequently changing patterns in river adjustment to dam removal contribute to the need for long term studies
50 to fully grasp the effects of dam removal at different time scales (Foley et al., 2017a). Until now, even when
51 the long-term response was being assessed (Evans, 2007; Skalak et al., 2011; Peck and Kasper, 2013), most
52 of the studies were short-term (1-2 years) (Bellmore et al., 2017).

53 Our paper reports on a four-year study of river readjustment after the removal of the 90-year-old and 7.3 m
54 high Pierre Glissotte dam, located on the Yonne river. 1This gravel bed stream running through a medium-
55 mountain range (Morvan massif) was deeply modified from the 16th century on by log driving, mills and
56 damming. At the start of the 2010s, the reservoir was almost completely filled, mainly with fine sediments,
57 stopping bedload particles at the entrance of the impoundment. The removal of the dam took place in two
58 steps, one in July-August 2015 and the other in October 2017. The hydromorphological monitoring carried
59 out during and after the sequenced removal of the Pierre Glissotte dam was accompanied by a study of
60 current bedload transport dynamics of the Yonne River at two neighboring sites not directly affected by the

61 dam removal. The four-year monitoring project thus offered a good opportunity to: (i) examine the modes
62 and response processes of a river whose bedload dynamics have been characterized at other sites around the
63 structure; (ii) measure the hydromorphological adjustments, the patterns of change in morphodynamics
64 (rates, timing, duration) and in driving mechanisms, and the spatial and temporal variations of these
65 processes in the impoundment and in the downstream reach over a period of four years; (iii) examine the
66 implications of restoring sediment continuity for the general hydromorphological functioning of the river
67 around the former dam.

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69 **2. The upper Yonne river and the Pierre Glissotte hydroelectric complex**

70
71 The Morvan massif is a Hercynian medium-elevation mountain range located in the southeastern part of the
72 Seine catchment in central France, where the maximum altitude is 902 m (Fig. 1). The substratum is mainly
73 granitic and gneissic rocks, and the climate is temperate oceanic with pluviometry influenced by the
74 orography. Mean annual precipitation in the region is 900 mm. Combined with the impermeability of the
75 substratum, this has led to the formation of a channel network with high drainage density. The landcover of
76 the hillslopes in the upper Yonne catchment, where the Pierre Glissotte complex is located, is mainly
77 meadows and forests (Fig. 2).

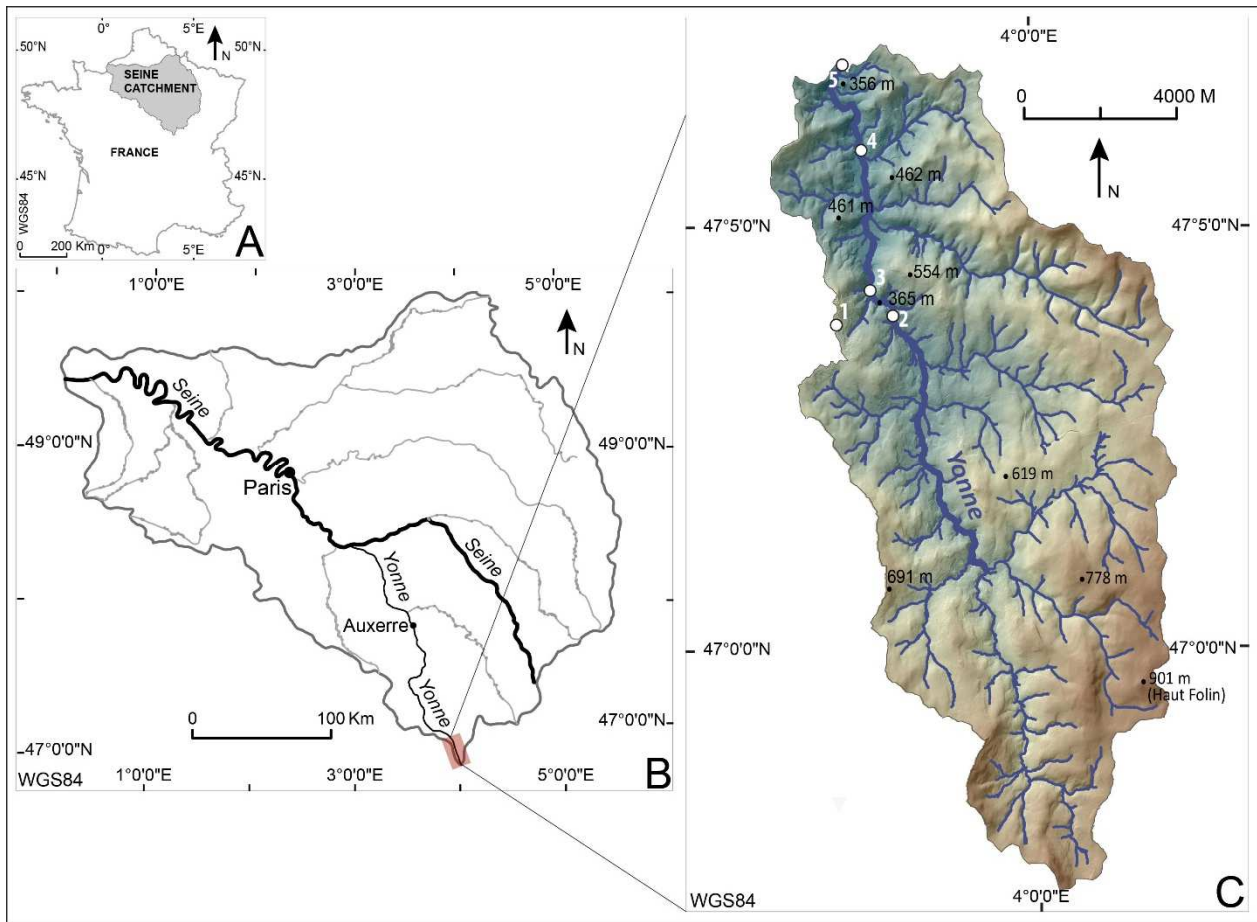
78 The engineering history of the upper Yonne river is old. Between the middle of the 16th century and the early
79 20th century, the river and its headwater tributaries were used for log driving. The significant
80 geomorphological effects of log driving on the upper Yonne river were studied and characterized by Poux et
81 al. (2011) and Jacob-Rousseau and Gob (2020). To give an example, management of the river for the log
82 driving industry resulted in the bed degradation of the head water streams and in the aggradation of the upper
83 Yonne river in its middle reach. The sediment stored in the Yonne river has not yet been removed.

84
85 The hydromorphological trajectory around the Pierre Glissotte dam period is far from linear. The Pierre
86 Glissotte dam (supplementary material, Fig. S1A) was built between 1923 and 1927, after log driving was
87 abandoned. Originally the 7.3 m high dam was built to provide electricity for nearby rubber factories.
88 Hydroelectric production stopped, and the dam was then opened for 30 years (1955-1985) because the first
89 hydroelectrical plant burned down. The dam started to function again in 1985, but in 2002 a storm stopped

90 the sluice gate functioning. As a result, in 2015, the Pierre Glissotte reservoir was almost completely filled
91 with sediment (42 600 m³, Gilet et al., 2018) and the dam acted as an obstacle to biological (there was no
92 efficient fishway) and sediment continuity. The reservoir fill was mainly fine sediment composed of sand and
93 silt. For the upper half of the reservoir fill, we were able to estimate that layers of sand ($D_{50} = 153 \mu\text{m}$)
94 represented 40% of the deposit. The other materials corresponded to a mixture of silt ($14 \leq D_{50} \leq 21 \mu\text{m}$) and
95 organic matter, the proportion of which increased near the dam (Gilet et al., 2018). Most of the pebbles and
96 cobbles, the bedload of the Yonne river, were deposited in the tail of the reservoir (the tail coarse deposit
97 formed between 1985 and 2015 has been estimated at 2,300 m³). At the Pierre Glissotte dam, the mean
98 discharge of the Yonne river is 2.1 m³/s.

99 Another dam, the “Moulin Blondelot dam” is located 1,200 m upstream from the Pierre Glissotte dam (Fig.
100 2, and supplementary material, Fig. S1B), where the mean discharge of the Yonne River is 1.9 m³/s. This
101 3.49 m high dam creates only a small impoundment (700 m³) and a mobile gate is automatically opened
102 gradually during a flood event. A maximum discharge of 2.3 m³/s is diverted from this dam to the Moulin
103 Blondelot hydroelectric plant, located 820 m downstream. The tail race of the plant conducts the diverted
104 discharge back to the Yonne river at the entrance of the Pierre Glissotte reservoir (Fig. 2). The maximum
105 diversion capacity of the bypass canal, 2.3 m³/s, mainly affects the small floods flowing into the bypassed
106 reach. In addition, the bedload sediments flow easily through the Moulin Blondelot dam. These conditions
107 and the steep bed slope of the Yonne river in the bypassed reach ($1.5 \% < s < 3.5 \%$) contribute to the active
108 bedload transport in the section of the river leading to the Pierre Glissotte reservoir (Gilet et al., 2018; Gilet
109 et al., 2020). Allowing sediment continuity through the Pierre Glissotte dam was consequently all the more
110 necessary.

111



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Fig. 1 Upper Yonne catchment and location of the Pierre Glissotte dam. Map C: 1. Château-Chinon city; 2. Moulin Blondelot dam; 3. Pierre Glissotte dam; 4. Corancy hydrometric station; 5. Tail of the Pannecièr reservoir.

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3. The removal project

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The removal project was implemented by the private owner of the Pierre Glissotte complex (the Pierre Glissotte Hydroelectric Company) and the Seine Normandie Water Agency. Discussions began following the owner's need to modernize the Pierre Glissotte power plant to comply with the Water and Aquatic Environments Act (2006), i.e. restoring biological and sediment continuity. The managers of the water agency seized the opportunity to propose a project that would allow the uppermost part of the Yonne catchment (78 km²) to be reconnected with another 32.5 km² of its catchment, between the Pierre Glissotte dam and the Pannecièr reservoir located 5.5 km downstream (Fig. 2). The project proposed by the owner and the water agency was based on three main elements: (i) the removal of the Pierre Glissotte dam in two steps separated by a two-year period; (ii) the replacement of the fish pass at the Moulin Blondelot dam; (iii) the abandonment of the Moulin Blondelot hydroelectric power plant and the modernization of the Pierre

130 Glissotte hydroelectric power plant (Fig. 2). The latter would be provided with a new longer penstock
131 extending the diversion canal that reached the Moulin Blondelot hydroelectric plant (Fig. 2). The new
132 penstock started to function and bypass the reservoir reach in March 2016, with a maximum diversion
133 capacity corresponding to that of the upstream diversion canal ($2.3 \text{ m}^3/\text{s}$).

134 The emptying and water level drawdown of the Pierre Glissotte reservoir started on July 20, 2015. The
135 emptying was operated using the butterfly valve and the old penstock that usually provided the Pierre
136 Glissotte power plant with water. During the emptying, this penstock (soon to be replaced) was disconnected
137 from the power plant and water was released in the river just downstream of the dam. The top three meters of
138 the dam were removed between August 11 and August 17. The second stage of the removal took place
139 between October 13 and October 17, 2017. The remaining 4 meters of the dam were removed but only from
140 the right third of the valley width, so as to protect the renovated power plant located downstream of the dam,
141 near the left hillslope. The river was thus partly channelized at the dam site and just upstream as large
142 boulders were also placed on the left bank along 50 m to protect the water pipe (new penstock) that supplies
143 the new turbines (supplementary material, Fig. S2).

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145 **4. Methods**

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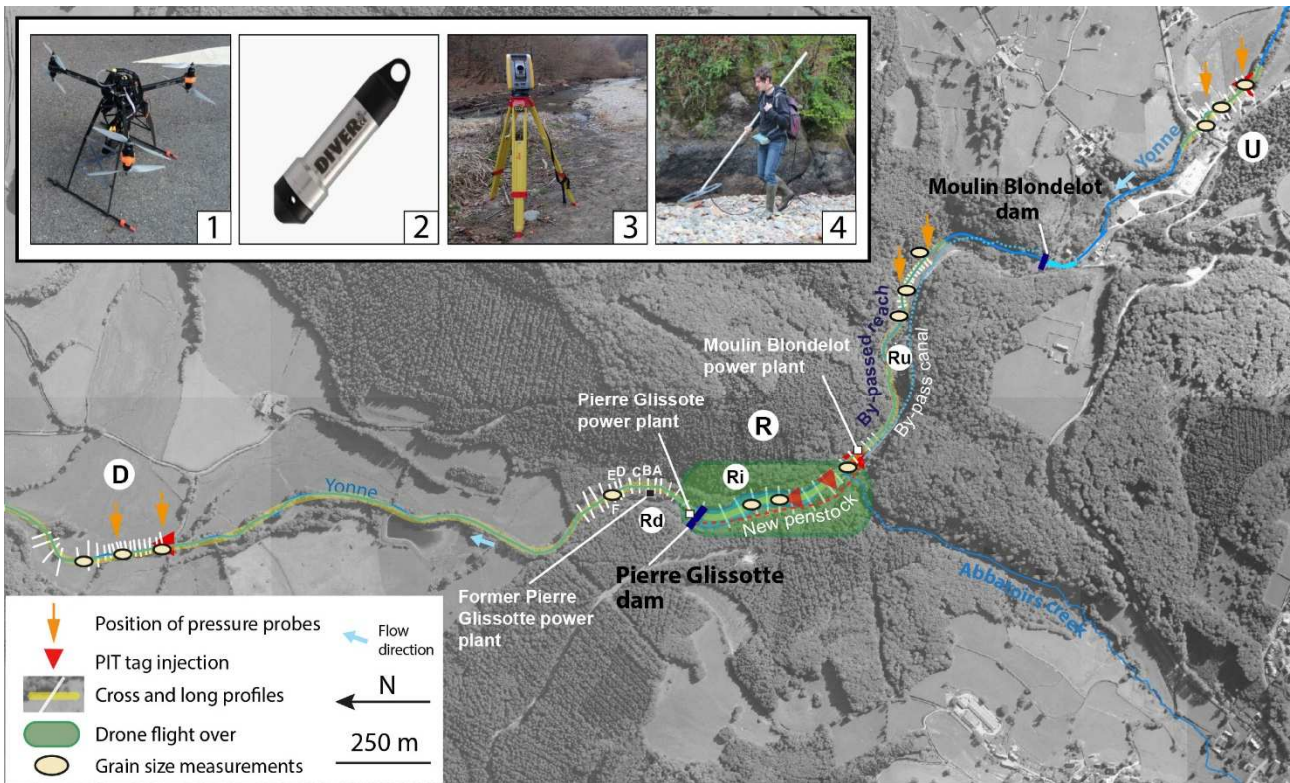
147 Several tools and methods were used over the four-year monitoring period to assess the hydromorphological
148 effects of the removal of the Pierre Glissotte dam. The flow regime was monitored with pressure probes.
149 Bedload dynamics were investigated by individual tracing of coarse particles. Other methods were used to
150 detect and quantify changes in the river's geometry and planforms: topographic surveys (total station), aerial
151 photographs (drone) combined with SFM photogrammetry. Measurements of grain-size distribution
152 (Wolman) in the riverbed completed the morpho-sedimentary characterization of the river's response. A
153 complete overview of the workflow and methodology developed on the Yonne river is presented in Figure 2
154 and Tables 1 and 2. As shown in Table 2, the different methods were rarely implemented together and at all
155 study sites during the same fieldwork campaign. Methodological strategy (e.g. one prime site / control sites)
156 and practical necessities (logistics, practicability) are the reasons for this. The prime study site itself, Pierre
157 Glissotte (R), is divided into three sub-reaches that were equipped and monitored differently: the former
158 impoundment (Ri) and its immediate upstream (Ru) and downstream (Rd) reaches.

159 **4.1 Hydro-sedimentary monitoring**

160
161 To understand the consequences of the removal of the Pierre Glissotte dam on bedload transport, the
162 movement of particles was monitored individually using radio frequency identification (RFID) technology.
163 Tracking sediment mobility using RFID has become widespread in the last decade (Liébault et al., 2012;
164 Bradley and Tucker, 2012; Chapuis et al., 2014; Houbrechts et al., 2015, Dépret et al., 2017). We used
165 passive integrated transponders (PIT tag, Passive Integrated Transponder) from Texas Instruments and two
166 detection systems: one configured by the company *CIPAM* and the other by *Technologie Aquartis senc*. The
167 transponders we used are glass bulb type PIT tags, operating at low frequency (134.2 kHz), 23 mm or 32 mm
168 long and 3-4 mm thick. At each monitoring site, PIT tags were inserted into particles randomly taken from
169 the bed according to the pebble count method developed by Wolman (1954). The objective was to have
170 tagged particles (tracers) representative of the alluvium present in the bed. At the Pierre Glissotte study site
171 (R), the reservoir fill was occupied by fine particles. Tracers were therefore collected in the immediate
172 upstream reach, where the D_{50} of the riverbed equates 108 mm (Gilet et al., 2018, supplementary material,
173 Fig. S3). On average, tracers remained smaller than the particles in the riverbed (Table 1, and supplementary
174 material, Fig. S3) because of technical constraints (tracers not equipped on site).

175
176 In addition to the site of the former Pierre Glissotte dam reservoir (R), bedload transport was also monitored
177 at two control sites, upstream (U) and downstream (D), that were not influenced by the dismantling of the
178 structure (Fig. 2). These sites were also selected to represent the diversity of existing hydrological situations
179 in the study area (Table 1). Both were positioned outside the hydrological influence of the dams, upstream
180 and downstream of the study area (U is located 0.6 km upstream of the Moulin Blondelot dam and D is
181 located 1.3 km downstream of the Pierre Glissotte dam). The study of river reaches not affected by the
182 dismantling operation was expected to help inform our understanding of the specific functioning of a typical
183 transient site after the removal of a dam.

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186 **Fig. 2 Location of the study sites and overview of the methods and technologies.** 1. Hexacopter
 187 drone; 2. Diver pressure probe (water level); 3. Total station Trimble S6; 4. PIT tag detection
 188 antenna. In Rd sub-reach, A, B, C, D, E, F correspond to the cross-sections of Figure 8.
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191 **Table 1. Location and characteristics of the study sites.**

Site	Location with respect to the PG dam	Hydrological Regime	Slope (m/m)	Bankfull width (m)	Specific stream power for Q_{bf}^a (W/m^2)	D_{50} river bed (mm)	D_{50} tracers (mm)
U	Upstream	Not influenced	0.0073	9.5	45.2	74	59
D	Downstream	Not influenced	0.0085	11.7	67.7	83.5	63.5
Ri- Pierre Glissotte	Impoundment	Moderately Influenced ^b	Evolving	Evolving	Evolving	Evolving	52 (1 st injection) 69 (2 nd injection)
Ru-Pierre Glissotte	Immediately upstream the reservoir	Influenced ^c	0.015	10.5	77.1	104	No tracers
Rd-Pierre Glissotte	Immediately downstream the reservoir	Moderately influenced ^d	0.013	11.5	64.3	73.5	52 (1 st injection) 69 (2 nd injection)

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193 ^a Q_{bf} : Bankfull discharge

194 ^b No influence on the Pierre Glissotte site was observed between July 2015 and March 2016 (the time needed to extend the diversion canal from the former Moulin Blondelot power plant to the Pierre Glissotte plant). After, the reservoir reach was bypassed up to 2.3 m³/s (a minimum discharge of 300 l/s must be left in the by-passed reach).

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 196
 197
 198 ^c The reach is bypassed up to 2.3 m³/s, with a minimum discharge required of 300 l/s (derivation of the discharge starts at the Moulin Blondelot dam).
 199

200 ^dThe first 95 m of the reach are by passed up to 2.3 m³/s for the functioning of the Pierre Glissotte plant
201 (except for the July 2015-March 2016 interval, without discharge diversion).
202
203

204 Sites U and D were each equipped with 75 tracers: the first 50 were injected in October 2014 and the
205 remaining 25 in October 2015. Site R in the former Pierre Glissotte reservoir (Ri) was equipped with 200
206 tracers in July 2015, just before the start of the reservoir emptying. At this time, the riverbed was composed
207 of sandy and silty sediments of the reservoir filling (Gilet et al., 2018). The second series of 172 tracers were
208 injected in July 2017, a few months before the second step of the removal (October 2017). At that time, a
209 gravel riverbed had formed again ($41 \leq D_{50} \leq 61$). At each site and at each injection, the tracers were placed
210 along several cross sections to avoid future detection “conflicts” (i.e. difficulties for the RFID reader to
211 identify tracers that are very close). 10 “RFID cross sections” were used on U and D, 24 on Ri study site. A
212 minimum distance of 2 m was left between each cross section and a distance of at least 1.20 m was left
213 between each tracer along the same cross section. Subsequently, a flexible tape measure was unrolled along
214 the bank to measure the distances travelled by the marked particles.

215
216 The distance travelled by the tracers was recorded five times at U and D, and 11 times at R between their
217 injection and July 2019 (Table 2). RFID surveys were more numerous at Pierre Glissotte (R) as the system
218 was transient. Moreover, conditions were more often favorable for detection surveys (low water depth) than
219 on the U and D sites. The sites are also equipped with water pressure sensors (Diver ©Schlumberger) that
220 record the water level at 15-minute intervals (Fig. 2). The water levels were transformed into discharge using
221 stage-discharge relationships built from our own discharge measurements made with an electro-magnetic
222 current-meter and extrapolations from data recorded at the Corancy hydrometric station (using a formula to
223 adapt the calculated discharge to the size of the basin, Bravard and Petit, 1997). The Corancy hydrometric
224 station is located only a few kilometers downstream from the study sites (from 4.5 to 1 km) (Fig. 1C). It
225 drains the first 106 km² of the Yonne catchment and is not influenced by the Pierre Glissotte hydroelectric
226 complex.

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4.2 Morpho-sedimentary characterization of the Yonne riverbed

4.2.1 Topographic surveys

The morphology of study site was characterized using a Trimble S6 total station. At sites U and D, the longitudinal profile and cross-sectional geometry were measured from a series of cross-sections (n: 13 on U, n: 20 on D) to allow characterization of the channel geometry (Fig. 2). Several topographic survey campaigns including longitudinal and cross-sectional profiles to assess the morphological changes following the removal stages, were conducted in the former impoundment (Ri), and in its immediate upstream (Ru) and downstream (Rd) reaches (Table 2). The cross-sections were carried out on a different stretch of the river length depending on the area to be surveyed (upstream, reservoir, downstream) but always targeting intervals between cross-sections of 1.5 times the bankfull width. 13 cross-sections were carried out on Ri and 15 on Rd, and two series of 3 and 13 cross-sections were surveyed on Ru (the interval left between the two series is due to the impracticability of the fieldwork). A mean distance of 0.92 cm was left between each point of a cross-section within the channel. On the sections where only the long profile was surveyed, one point was measured on average every 1.5 m. In addition, a historic long-profile of the Yonne River (water surface) was available. It was surveyed in 1933, only a few years after the dam was completed in 1927. A study of the longitudinal changes in the Yonne River after 1933 and the methodological precision of the comparison with the current long profile are detailed in Gilet et al. (2018).

270 **Table 2. Overview of the fieldwork campaigns and methods used in the former Pierre Glissotte**
 271 **impoundment (Ri), its immediate upstream (Ru) and downstream (Rd) reaches, and in the more**
 272 **distant U and D study sites.**
 273

		RFID monitoring					Topographic surveys					UAV	Grain size measurements					
		U	Ru	Ri	Rd	D	U	Ru	Ri	Rd	D	Ri	U	Ru	Ri	Rd	D	
Before removal	07/14																	
	08/14																	
	10/14	■																
	11/14																	
	12/14	■																
	02/15	■																
	04/15	■																
After 1 st stage	07/15			■														
	08/15																	
	09/15			■														
	10/15	■		■				■										
	02/16			■														
	03/16								■									
	04/16			■									■					
	05/16	■		■														
	06/16			■														
	08/16			■														
	11/16																	
	02/17			■														
	03/17	■											■					
	04/17																	
	06/17								■									
	07/17			■														
10/17			■															
After 2 nd stage	12/17			■														
	05/18			■								■						
	08/18			■														
	09/18			■														
	02/19											Lidar						
	07/19			■								■						
	10/19																	

■ Survey ■ Tracers injection

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 276 **4.2.2 Aerial photographs taken by an unmanned aerial vehicle and SFM photogrammetry**

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 278 To more accurately assess the volumes involved in the two dam removal stages, a 3D reconstruction of the
 279 entire reservoir was also carried out using aerial photographs taken by an unmanned aerial vehicle (UAV).
 280 The use of photogrammetry is increasing to characterize river responses in restoration or rehabilitation
 281 projects (Ritchie et al., 2018; Marteau et al. 2020, a, b). At Pierre Glissotte, four overflight sessions of the
 282 site were conducted, in April 2016, March 2017, May 2018 and July 2019. In 2019, a large area was covered
 283 by vegetation during our overflight session, so we used Lidar data to survey our study site. The data are from
 284 an airborne Lidar campaign that was carried out in winter 2019. The first drone sessions were carried out

285 with a Sony RX1 camera mounted on a hexacopter UAV and the last three with a DJI Mavic Pro. The
 286 reconstruction was based on the structure from motion (SfM) photogrammetry method (Fonstad et al., 2013).
 287 Agisoft Metashape (v1.5.2) software was used to process the photographs. This produces a 3D point cloud
 288 (about ten million points preserved after decimation of the point cloud) from which a very high resolution
 289 (0.05 m) digital surface model (DSM) is generated directly in Agisoft Metashape. The Canupo algorithm
 290 (Brodu and Lague, 2012) was then used to filter out the areas colonized by dense vegetation. The number of
 291 ground control points (GCPs) in each flight session is listed in Table 3. For practical reasons, it was
 292 impossible to keep fixed GCPs in the field but GCPs were surveyed by a Trimble Total Station. Particular
 293 attention was paid to respecting a homogeneous spatial distribution of GCPs (Rangel et al., 2018), and 30%
 294 were used as independent checkpoints (Sana-Ablanedo et al., 2018). The characteristics of each flight session
 295 and the associated errors after bundle adjustment are given in Table 3. Checkpoints' vertical RMSE were
 296 used to evaluate uncertainties in calculating volumes and minimum levels of detection (Schaffrath et al.,
 297 2015) at the 95% confidence interval ($LoD_{95\%}$) of the DSMs of difference according to the formula

$$298 \quad LoD_{95\%} = \pm 1.96 \times \sqrt{RMSE_{Year}^2 + RMSE_{Year-1}^2}.$$

299
 300 **Table 3. Characteristics of the UAV campaigns in the former Pierre Glissotte impoundment and**
 301 **details of the respective SFM processing.**
 302

Date	UAV	Ground Sample Distance (GSD) (cm)	Number of GCPs	Number of checkpoints	RMSE V (m)	RMSE H (m)
20/04/2016	Hexacopter with Sony RX1 camera	1.07	12	5	0.01	0.025
20/03/2017	DJI Mavic Pro	1.1	11	5	0.04	0.025
02/05/2018	DJI Mavic Pro	1.1	17	8	0.033	0.055

304
 305 As the topography of the reservoir was not available just before it was emptied, the pre-removal topography
 306 was reconstructed by virtually filling in the newly opened channel and the volume of this infilling was

307 calculated. To this end, the slope of the valley was detrended using the average slope of the new channel
308 bottom and a plane with an elevation corresponding to that of the bankfull level was created (Thommeret et
309 al., 2016). By subtracting the bankfull level from the detrended DSM, the volume of sediment evacuated
310 between July 2015 and April 2016 was calculated. For subsequent surveys, the DSM in year T was
311 subtracted from the DSM in year T-1. This meant the deposition and erosion zones could be located and the
312 corresponding volumes calculated with the associated estimated error. In 2019, Lidar data comes with a
313 vertical accuracy of 10 cm. Another uncertainty associated with the sediment volume in general is due to the
314 fact that sediments under the water surface are not included in the calculation of volume. Considering our
315 aerial photographs were always taken during low flow and the bypassed configuration of the former
316 impoundment since March 2016, water height was similar in each campaign and can be considered as close
317 to the profile of the river bed. Consequently, significant sediment dynamics under water could still be
318 identified when the water surface altitude varied. However, slight local sediment dynamics may not have
319 modified the water surface altitude and consequently may have gone unnoticed. In all cases, we considered
320 the volume of sediment underwater to be negligible.

321 Finally, using the DSM obtained after each session of aerial photography by UAV, the longitudinal profile
322 (water surface) of the river in the former impoundment could be reconstructed each year between 2016 and
323 2019.

324

325 **4.2.3 Grain size distribution**

326

327 At all the study sites, the grain size distribution of the riverbed was determined using the surface sampling
328 method proposed by Wolman (1954). Between 2016 and 2019, at the Pierre Glissotte impoundment, three
329 gravel bars were sampled at least eight times (100 particles per bar on each occasion). The bars sampled are
330 located in the upstream, intermediate and downstream parts of the old reservoir (supplementary material, Fig.
331 S4). In 2018, a sampling site was added about 160 m downstream from the Pierre Glissotte dam. There, 100
332 particles were sampled and measured in September 2018 and October 2019.

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337 **5. Results**

338

339 **5.1 Adjustments in the former reservoir**

340

341 **5.1.1 Channel morphodynamics**

342

343 Monitoring first highlighted the rapid response of the river as soon as emptying began. Although performed

344 at low discharge, it carried away a large quantity of fine sand and silt sediments. Barely more than a week

345 after the water level was lowered, a first steep slope failure (knickpoint) was identified 40 meters upstream

346 of the dam (supplementary material, Fig. S5, July 28, 2015). Within eight days, the incision had already dug

347 a channel more than 1.50 m deeper downstream of the knickpoint. A lesser incision (average 0.45 m) was

348 also cut into the reservoir deposits upstream of the knickpoint for approximately 160 m. By March 2016, the

349 knickpoint had already passed the tail of the reservoir and reached the bypassed section upstream, reaching

350 more than 400 m up the Yonne in the space of eight months. At that point in time, the width ranged between

351 6.5 and 19.5 m and the maximum bankfull height was over 4 m (median value: 2.1 m) (Figs. 3 and 4, and

352 supplementary material, Fig. S5). The formation of an average 16-m wide and 2.3-m deep channel resulted

353 in the remobilization of 26% of the volume of sediment contained in the reservoir, i.e. 11,039 m³ of mainly

354 sandy material (Fig. 4, Table 4) (Gilet et al., 2018).

355 From summer 2016 on, we observed a weakening of the intensity of the erosive processes and the

356 progressive stabilization of the new morphological and sedimentary conditions shaped in the reservoir (Figs.

357 3 and 4).

358 During this period, channel widening continued at a lower rate, mainly through lateral erosion and bank

359 undermining. The slowing down of vertical erosion is accompanied by the coarsening of the material in the

360 new riverbed (see section 5.1.3) but also by the revealed presence of local grade controls in the longitudinal

361 profile. The main control was obviously the remaining 4 meters of the dam that controlled the entire new

362 profile formed (“New local base level” (1), Fig. 3) but there were also an outcrop of bedrock and many

363 multi-decimetric boulders (“Grade controls”, Fig. 3) that prevented or slowed down bed incision.

364 Ultimately, a total volume of 951 m³ was released into the system between April 2016 and March 2017,

365 much less than the 11,039 m³ eroded in the preceding nine months (Fig. 4, Table 4). The calculation of

366 volumes even showed the formation and stabilization of certain deposits (263 m³ accumulated sediment)

367 mainly corresponding to three large gravel bars on which the sediment size was measured (supplementary
 368 material, Fig. S4). This stabilization was accompanied and potentially favored by plant colonization of the
 369 deposits during this period.

370 After the second stage of the removal (October 2017), significant vertical and lateral erosion occurred again
 371 (Figs. 3 and 4). Seven months later, 4,180 m³ of gravel-sand sediment had been eroded and reinjected into
 372 the river system (Table 4). A significant proportion of this release was the result of both river action and
 373 mass movement that affected the banks. Figure 4 shows that erosion was particularly concentrated in a
 374 stretch 170 m in length immediately upstream of the former dam. Nevertheless, small areas of significant
 375 erosion can also be seen in the middle of the former reservoir. Also, the important aggradation that can be
 376 seen on Figure 4 near the dam (dark green area) is artificial. Sediments were excavated to form the new
 377 channel passing through the hole in the dam and stocked against the right hillslope of the valley (also visible
 378 in supplementary material, Figs. S2 and S5, photograph taken on November 16, 2017). A comparison
 379 between the 2018 and 2019 profiles shows that the bed was not completely fixed (Fig. 3). Some sectors were
 380 incised and others were in a state of aggradation, even if the differences in altimetry were moderate (a few
 381 tens of centimeters). These moderate changes were confirmed by the differential DSM between 2018 and
 382 2019 (Fig. 4). The sediment volumes calculated from it were 597 m³ of eroded sediments for 603 m³ of
 383 aggraded sediments (Table 4). These numbers suggest a slowdown of morphogenic activity but not the
 384 complete stabilization of the fluvial system. Eventually, 34% of the reservoir fill was eroded and exported
 385 downstream of the dam (Table 4).

386

387 **Table 4. Sediment budget in the reservoir between each photogrammetry campaign.**

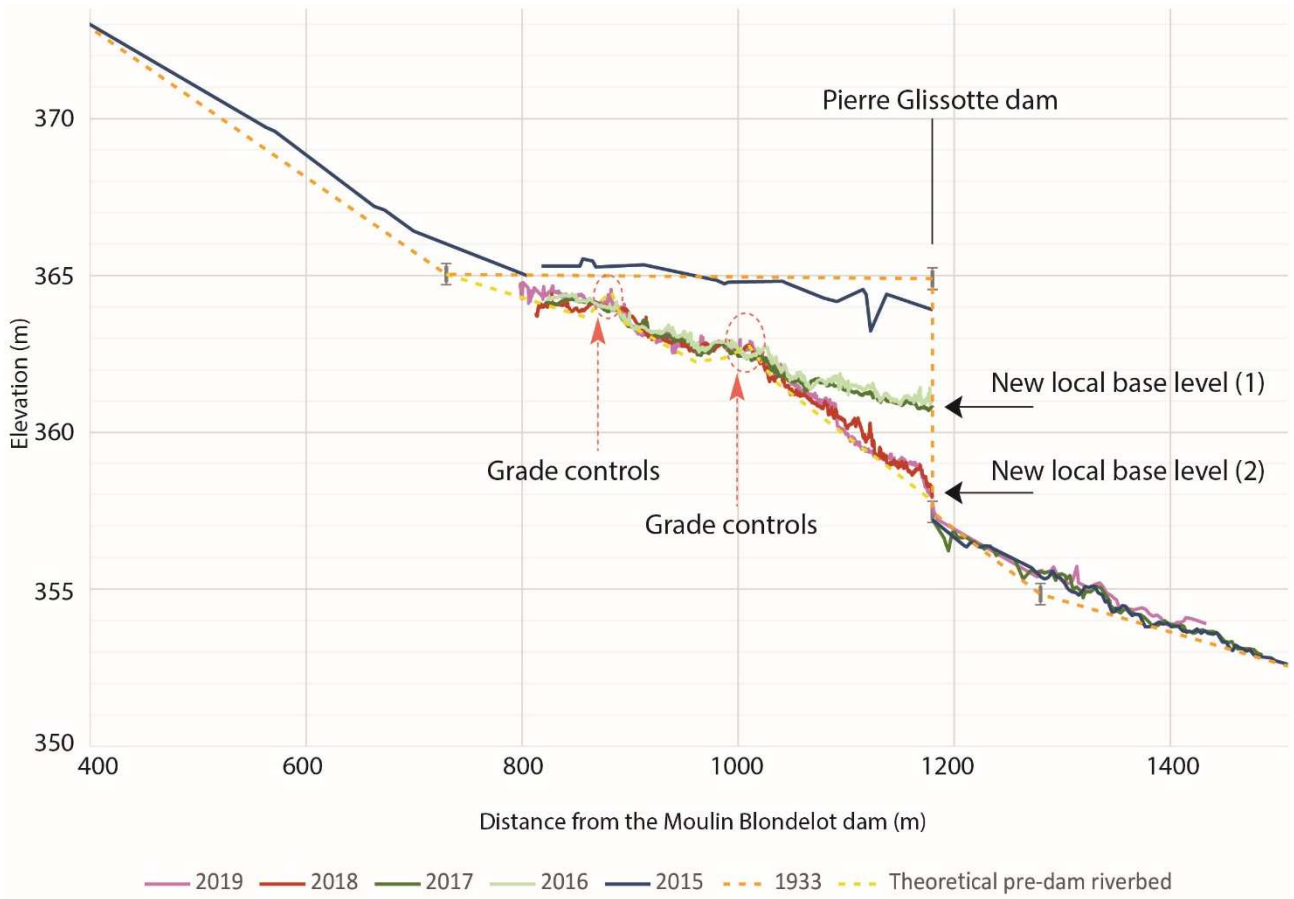
Difference of DSM (DoD)	Eroded volume (m³)	Deposited volume (m³)	Sediment budget (m³)	Rate (m³/d)	Part of reservoir fill¹ exported downstream the dam (%)
DoD ₂₀₁₆₋₂₀₁₅	11 039±59	0	-11 039±59	-40	25.9
DoD ₂₀₁₇₋₂₀₁₆	951±154	263±77	-688±231	-3	1.6
DoD ₂₀₁₈₋₂₀₁₇	4 180±195	1355±76	-2825±271	-7	6.7
DoD ₂₀₁₉₋₂₀₁₈ (2019 from Lidar)	597±173	603±375	6±548	0.01	-

388 1: based on the sediment volume (42 600 m³) calculated in Gilet et al. (2018).

389

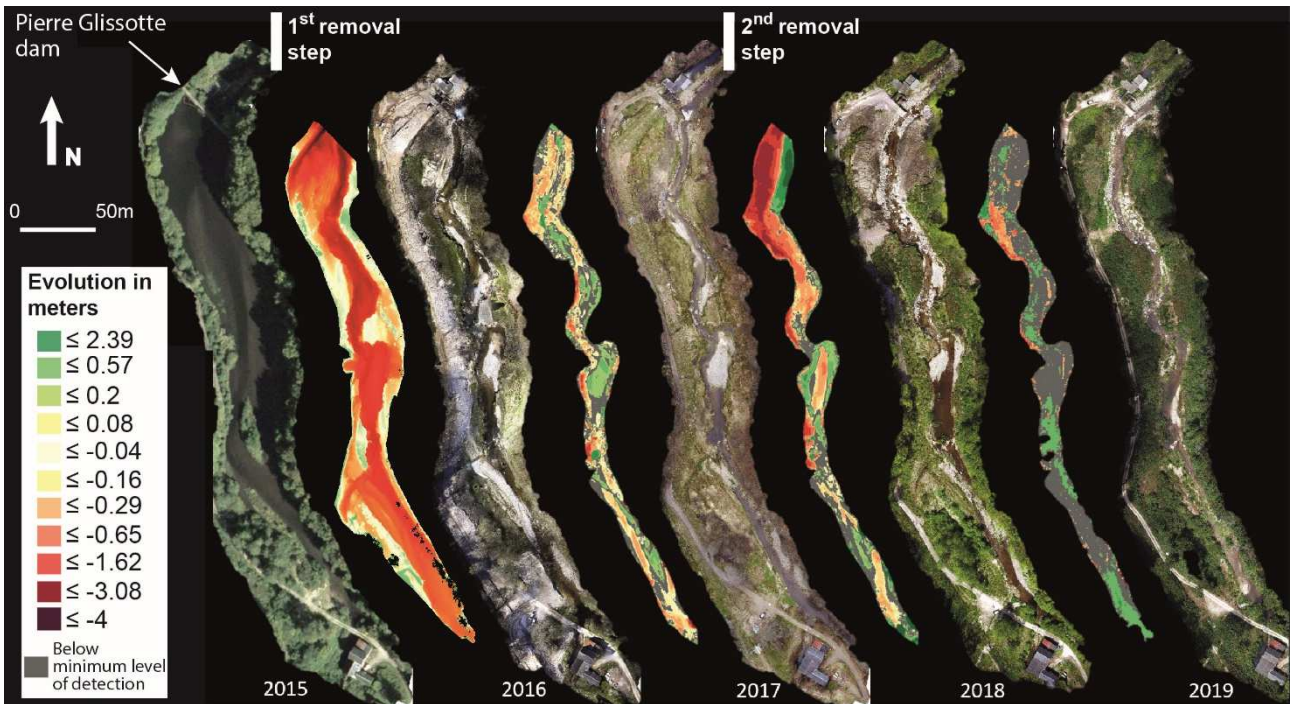
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Fig. 3 Development of the new Yonne long profile around the Pierre Glissotte dam.



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Fig. 4 Planimetric and vertical changes in the former reservoir (DSM) between each aerial photograph campaign by UAV (except 2015, IGN, ortho database). The minimum level of detection is set at the 95%

402 confidence interval (LoD_{95%}) of the DSMs of difference, described in section 4.2.2. The intervals of the
403 vertical evolution correspond to a manual classification.

404 **5.1.2 Coarse bedload transport**

405
406 Figure 5 shows the movement of the tracers over time and with respect to the hydrology. For each survey,
407 the mean inter-survey distance (Fig. 5A) of the detected tracers corresponds to the mean distance traveled
408 since the previous survey (or to injection in the 1st survey). Mean inter-survey velocity (Fig. 5B) is the ratio
409 between the mean inter-survey distance and the time elapsed since the previous survey.

410 RFID tracking showed that the coarse load (pebbles and cobbles) stored at the tail end of the reservoir was
411 very quickly set in motion again during and after the first removal step. The first two tracer displacement
412 surveys were carried out two and three months after the start of the removal (emptying phase included). They
413 revealed very high bedload displacement rates, with a mean inter-survey velocity equal to 138 m/year and
414 347 m/year respectively. This very rapid movement was observed despite the absence of a noticeable peak
415 flow.

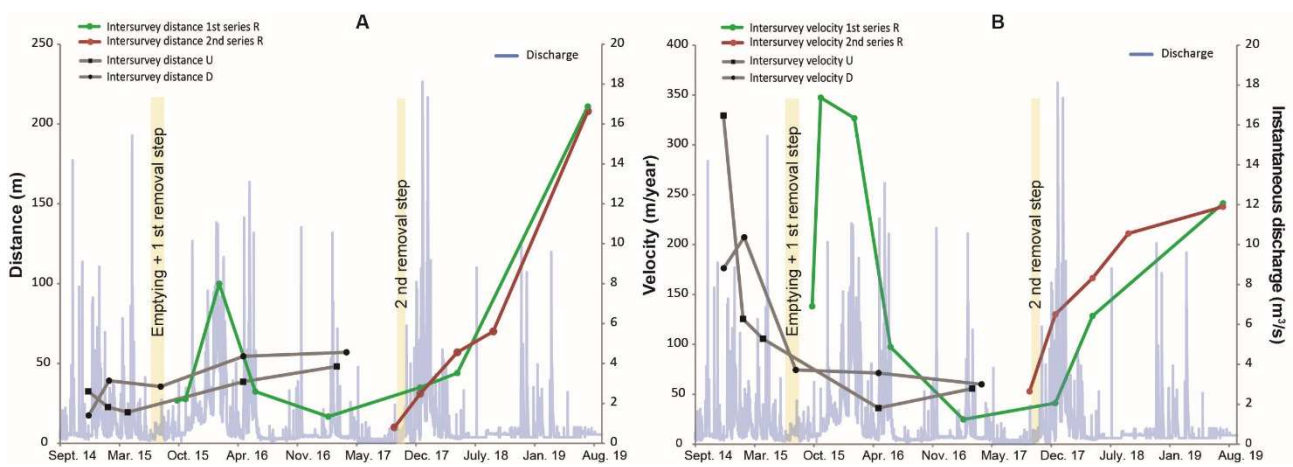
416 The remarkable morphogenic activity in the first nine months following the first removal phase is clearly
417 visible when the results of the bedload tracers at Pierre Glissotte are compared with those at the undisturbed
418 sites, U and D (Fig. 5A-B). The distance is shorter and the velocity recorded at the control sites in the same
419 period is significantly weaker: e.g., the bedload velocity was 36 m/year at U, and 71 m/year at D, between
420 April 2015 (U) - August 2015 (D) and May 2016. Also, for comparable hydrological conditions during the 9
421 months following the first removal step, bedload displacements appear more important at Pierre Glissotte.
422 Between February and June 2016, a first decrease in the mobility of the Pierre Glissotte tracers was observed
423 but the mean displacement velocity was still high (Fig. 5B). In total, between the 1st injection and June 2016,
424 the mean distance travelled by mobile tracers was 123 m (134 m/y) (Fig. 6, photographs 1-2).

425 The relative morphological stability observed from summer 2016 was accompanied by a major slowdown of
426 the bedload transport (Fig. 5): the mean distance covered by the mobilized tracers between June 2016 and
427 February 2017 was 17 m (25 m/year), despite the occurrence of multiple flood events during that time
428 interval (Fig. 5).

429 The bedload was again significantly mobilized following the second removal step. The new tracers injected
430 (2nd series) into the channel a few months before the complete opening of the dam were mobilized and some
431 travelled several hundred meters in about 13 months (Fig. 6, photographs 3-4). Between October 2017 and

432 August 2018, the inter-survey particle velocity increased again (for the 3 RFID surveys in this time interval,
 433 a mean value of 169 m/year for the mobile tracers of the second injection and 67 m/year for those of the
 434 first). However, it remained lower than those recorded after the first removal step (up to 340 m/year) (Fig.
 435 5B). This time, the high velocity of bedload did not slow down after the first year following the removal step
 436 but continued for at least one more year, despite the exit of the fastest tracers from the survey area (Fig. 5B).
 437 Our final survey carried out in July 2019 revealed displacement of 209.5 m on average for the tracers
 438 mobilized since August 2018 (considering the two series of injections together). This corresponds to a mean
 439 velocity for the two injections of 241 m/year (series 1) and 238 m/year (series 2).

440

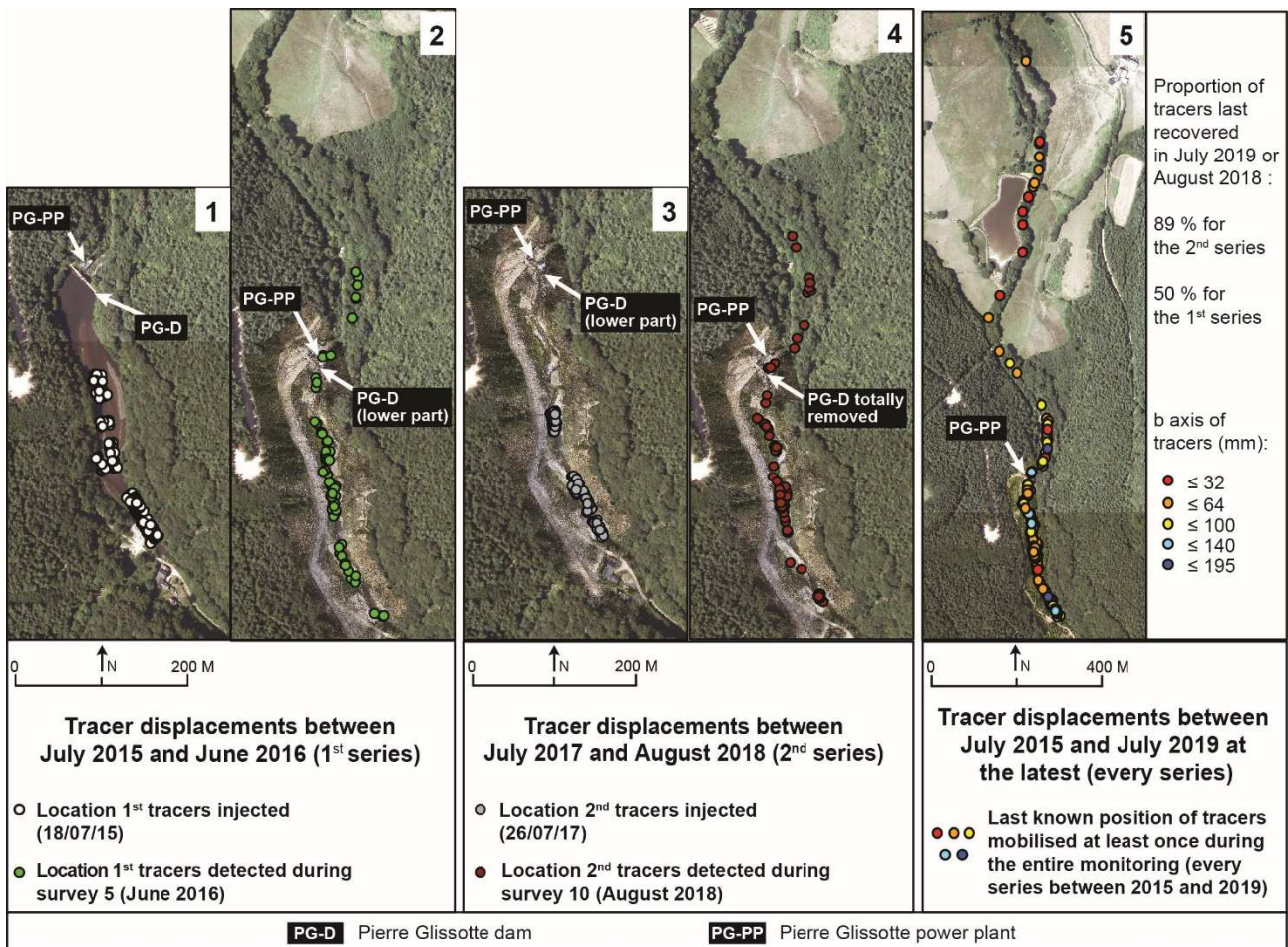


441

442 **Fig. 5 Bedload displacements at Pierre Glissotte (R) and at the study sites undisturbed by the removal**
 443 **(U, D). A. Mean inter-survey distance covered by the mobile tracers. B. Mean inter-survey velocity of**
 444 **the mobile tracers. For each survey, the mean inter-survey distance (A) of the detected tracers corresponds**
 445 **to the mean distance traveled since the previous survey. For each survey, mean inter-survey velocity (B) is**
 446 **the ratio between the mean inter-survey distance and the time elapsed since the previous survey.**

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Fig. 6 Positions of RFID tracers at different phases of the Pierre Glissotte removal.

452 5.1.3 Bed texture

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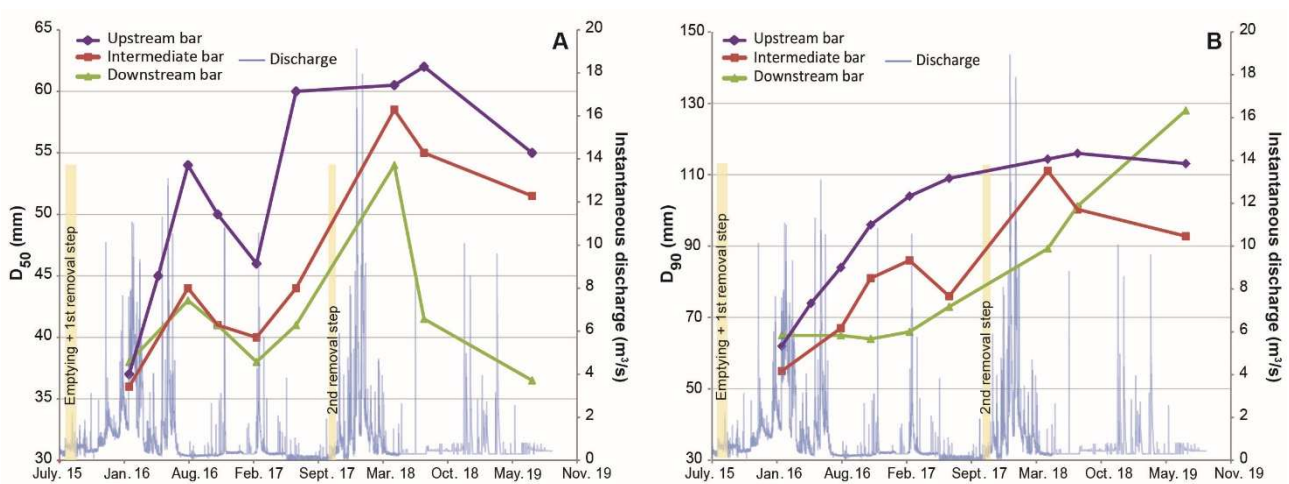
464

The riverbed of the new channel that formed after the first removal works was rapidly covered with coarse sediments coming from the reservoir tail and the upstream reach. By February 2016, the sandy bed had completely turned into a gravel bed ($D_{50} = 37$ mm) (Fig. 7A). The bed adjustments and the size of the substrate particles (D_{50} and D_{90}) continued to increase until August 2016 (Fig. 7), confirming the gradual restoration of coarse bedload transport in the former reservoir. A change in sediment dynamics was then recorded as a reduction of the median size of the particles was measured on the three main bars in the former reservoir between August 2016 and February 2017 (Fig. 7A). After the second removal step, the changes in the size of the particles comprising the gravel bars were less uniform (Fig. 7); the increase in the D_{50} was generally maintained until May 2018 (August 2018, in the upstream part), after which there was a decrease in the D_{50} in the sampled bars until July 2019. This is similar to the decrease measured between August 2016, about one year after the first removal step, and February 2017. It should be noted that the 2018

465 decrease in median diameter was particularly strong in the case of the downstream bar (Fig. 7A) when its
 466 D_{90} , which had changed very little after the first stage of work, increased very rapidly from September 2017
 467 on (Fig. 7B). This downstream bar thus appeared to be becoming more heterogeneous, probably due to the
 468 departure of its intermediate size fraction.

469 All indicators suggest that in summer 2019, the bed was not yet stabilized and still in search of equilibrium
 470 conditions. Indeed (i) the size of the pebbles on bars was still evolving and remained below the D_{50} of the
 471 uninfluenced sites (U and D) (Table 1); (ii) the transport velocities recorded in spring-summer 2018 and
 472 summer 2019 were still high; and (iii) certain bars apparently stabilized before the second removal stage was
 473 in erosion again. Finally, the active adjustment observed after the second step was less spectacular but lasted
 474 longer than after first removal step.

475



476

477 **Fig. 7 Changes in grain size distribution of three gravel bars located in the former Pierre Glissotte**
 478 **reservoir. A. Changes at D_{50} ; B. Changes at D_{90} .**

479

480

481 5.2 Changes in the downstream reach

482

483 5.2.1 Fine deposits

484

485 In July 2015, the butterfly valve got stuck in open position as soon as the reservoir began to empty, very
 486 quickly releasing a massive amount of sand and silt even before the top part of the dam was removed. The
 487 resulting centered flow of highly suspended sediment significantly affected the aquatic biocenosis for at
 488 least 3.5 km downstream, and probably as far as Pannecièrè reservoir, 5.5 km further downstream. Sandy
 489 deposits up to 40 cm thick formed along the river course, primarily on the channel margins. Even if this

490 event probably had a strong impact on the aquatic communities, from a morphological point of view, the
491 impact was slight. Indeed, the sand bars were ephemeral as they were rapidly evacuated during the following
492 2015-2016 high waters of the hydrological season. By June 2016, they had almost disappeared, and the
493 thickness of the remaining patches had been greatly reduced.

494

495 **5.2.2 Bedload continuity**

496

497 Due to the high bedload dynamics mentioned in the previous sections, sediment continuity was quickly
498 restored. As early as June 2016, about ten tracers injected (5% of the injection) into the former reservoir
499 were found scattered over more than 100 m downstream of the former Pierre Glissotte dam (Fig. 6,
500 photographs 1-2). The number of tracers found downstream then increased slightly until the beginning of the
501 second stage of removal (12 tracers were detected downstream the dam in February 2017). After this stage
502 and the renewed sedimentary dynamics it triggered, an increasing number of tracers continued to be detected
503 in the downstream section. By August 2018, at least 29 tracers (13% of all the tracers recovered) had gone
504 beyond the former dam, spread over a distance ranging from 4 to 420 m downstream of the old structure.
505 One year later, in July 2019, this figure reached a minimum of 53 tracers (26% of the recovered tracers),
506 over a river course extending up to 850 m downstream of the dam (Fig. 6, photograph 5), at the exception of
507 one isolated head tracer located 1400 m downstream of the dam. These tracers were distributed fairly evenly.
508 No preferential storage areas really emerged, except for a local sector located 95-125 m downstream of the
509 former dam, immediately downstream of the confluence with the hydropower plant tail race, where the
510 channel widens. Apart from this specific area and a few tracers that appeared to be stuck behind blocks, the
511 particles that passed through the former reservoir remained highly mobile and did not settle downstream of
512 the structure.

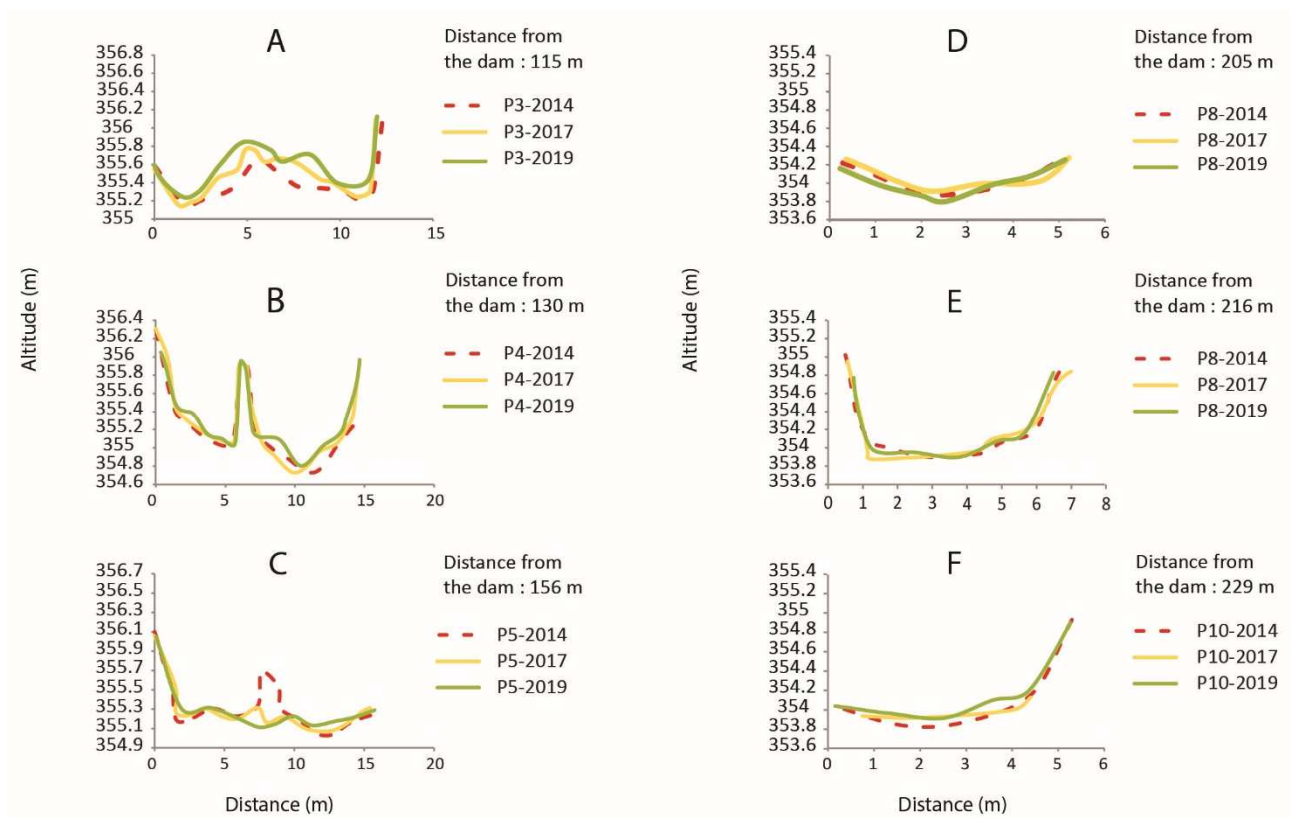
513

514 **5.2.3 Morpho-sedimentary adjustments**

515

516 A comparison of the long profile before the removal of the dam with those surveyed in 2017 (after the 1st
517 stage) and in 2019 (after the 2nd stage), over a length of 315 m downstream from the dam, confirmed the
518 absence of significant deposits and generalized bed elevation (Fig. 3). The vertical variations are rather
519 positive, indicating the formation of small gravel deposits. However, in the last survey in 2019 they were still
520 fairly limited (< 30 cm). These small bars, or rather gravel and pebble patches, were actually more present

521 between 2017 and 2019 than after the first stage of the restoration operation. Comparison of cross-sections
 522 surveyed in 2014, 2017 and 2019 confirm our observations up to 2019 (Fig. 8, see also Fig. 2 for location).
 523 The morphological changes consisted mainly in a few areas of limited aggradation (< 40 cm). These
 524 aggraded sections were mainly either on median or mid-channel bars that already existed before the dam was
 525 removed (Fig. 8A), or near the banks (Fig. 8F). Also, like the long profile, some vertical adjustments appear
 526 to have continued between 2017 and 2019 (Fig. 8A, 8C, 8F). Some changes are still complex to interpret as
 527 cross-sections show both aggradation and bed degradation (Fig. 8C), changing dynamics (Fig. 8D) or an
 528 almost unchanging situation (Fig. 8E). Considering the substrate, the comparison of two surface grain size
 529 campaigns carried out 160 m downstream of the former dam, in September 2018 and October 2019, tends to
 530 underline the limited nature of the textural adjustments: the D_{50} only increased from 73.5 to 79.5 mm and the
 531 D_{90} decreased from 250 to 241 mm.



532
 533 **Fig. 8 Series of cross-sectional profiles downstream of the former Pierre Glissotte dam (Rd sub-reach)**
 534 **in 2014, 2017 and 2019.**

535
 536
 537 **6. Discussion**

538
 539 **6.1 Adjustments in the former reservoir**

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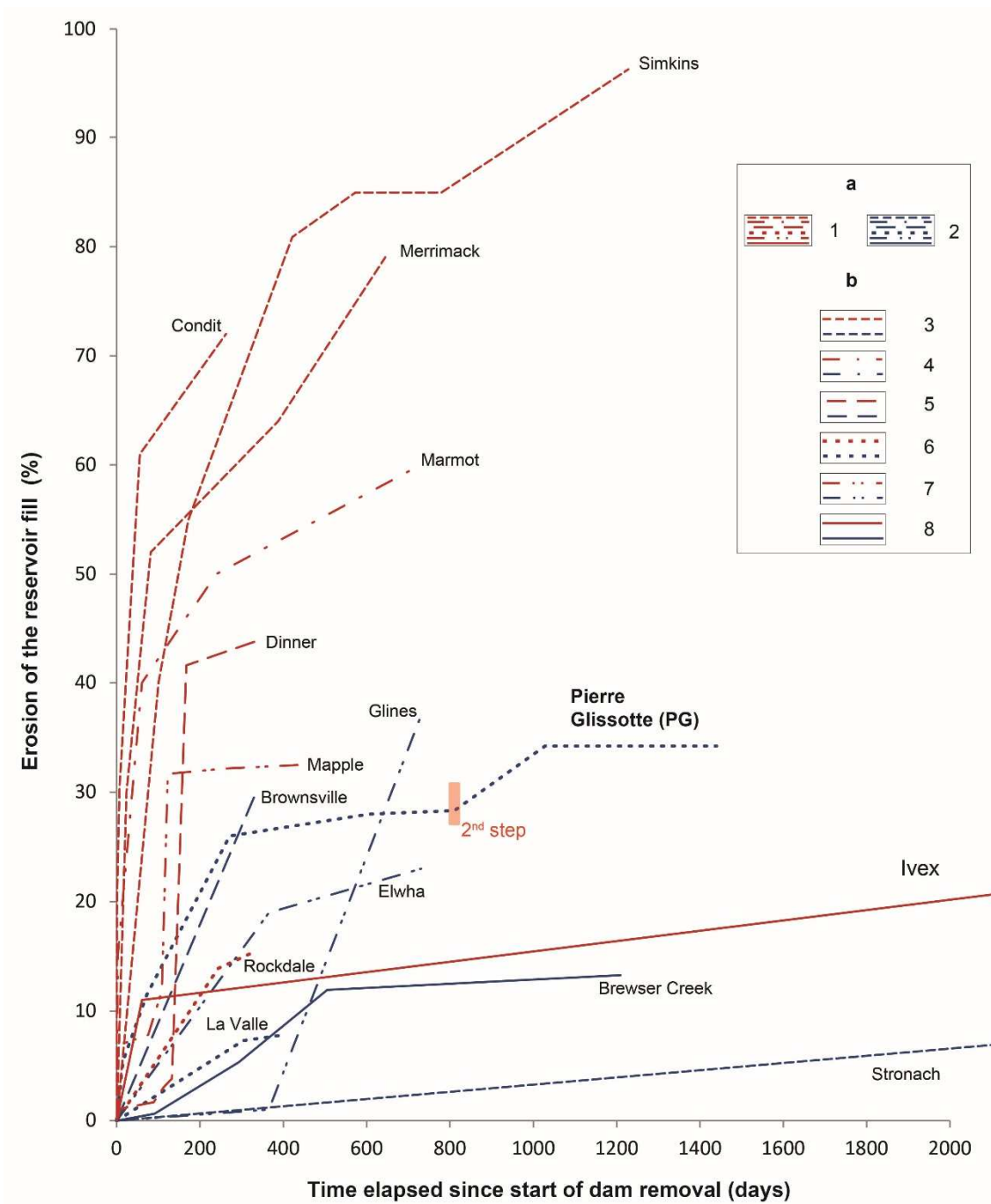
541 Figure 4 shows that most of the morphological changes mentioned above were observed over a fairly short
542 period of time, with the most important morpho-sedimentary adjustments occurring after the first step of the
543 removal operation. A comparison of the adjustments observed on the Yonne river with those of other
544 removal operations underlines the speed of the erosive process at work at Pierre Glissotte (Fig. 9). Over the
545 first 9 months following the start of the dam removal, the erosion rate measured at our study site (26%) was
546 higher than almost all the cases corresponding to a multi-stage removal in Figure 9 (except the one in
547 Brownsville), much faster than that of the two other reservoirs with comparable grain size composition
548 (Rockdale Dam and La Valle dam; Doyle et al., 2003), and very close to the Brownsville dam removal
549 characterized by much coarser sediments ($D_{50} = 59$ mm) (Walter and Tullos, 2010). After this first very rapid
550 erosion phase that lasted a little less than a year, the evolution of the erosion rate is non-linear. The
551 readjustment of the newly formed channel in the former reservoir corresponds indeed to a transient system
552 that Bellmore et al. (2019) associated with “dynamic and non-linear recovery trajectories”. The morphogenic
553 acceleration phases are the direct consequence of the two deconstructing works that lower the control base
554 level by several meters. Once the equilibrium profile is almost restored, the system slows down and the
555 morphogenic activity decreases. This relay phenomenon has been described in the literature notably by
556 Pizzuto (2002) and by Pearson et al. (2011). The intense erosive phase, a process-driven system due to
557 morphological instability, is then followed by a gradual transition leading to a more classical functioning of
558 the river system with a larger role played by the hydrological episodes (“event-driven system”) (Pearson et
559 al.; 2011; Collins et al., 2017). In Pierre Glissotte, close to what Pearson et al. (2011) had already noticed,
560 large floods appeared to play a major role in the most incised sections, in mobilizing the impounded
561 sediments that emerged during base flow, and in maintaining bank undermining in the widest areas.

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Fig. 9 Comparison of the erosional velocity of reservoirs following removal projects (Sawaske et Freyberg, 2012; Lewis et Grant, 2015, modified). After: Doyle et al., 2003; Stewart, 2006; Evans, 2007; Straub, 2007; Burroughs et al., 2009; Walter & Tullos, 2010; Pearson et al., 2011; Major et al., 2012; Randle et al., 2015; Collins et al., 2017).

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a. Type of dam removal: 1. Rapid removal; 2. Staged removal; b. Main sedimentary composition of the reservoir; 3. Dominance of sands; 4. Non-cohesive mixed sediments (sands and coarse material); 5. Coarse material (> 2mm); 6. Mixed fine sediments (sand, mud); 7. Mixed sediments (mud, sands and coarse material); 8. Mud.

576

577

A closer look at the Pierre Glissotte situation shows that the very rapid erosion that occurs in the reservoir directly after the lowering of the 3 upper meters of the dam is favored by the non-cohesive nature of the

578 sediments. The rather young (less than 40 years old) filling of the reservoir was indeed characterized by an
579 alternation of sandy deposits with finer layers rich in organic matter. This allowed the rapid formation of a
580 channel that enlarged due to the upstream displacement of a mobile knickpoint. These types of knickpoint
581 have frequently been described in the literature (Pizutto, 2002; Doyle et al., 2003; Stewart, 2006; Major et
582 al., 2012; Magilligan et al., 2016; Ibisate et al., 2016). They allow regressive erosion and favor the incision
583 of the bed despite low flows, such as that observed on the Yonne River in summer and autumn 2015.
584 Consequently, the hydraulic capacity of the channel increases and the peak flow of the following hydrologic
585 season continued the vertical and lateral erosion processes. The process of bank destabilization (widening)
586 after the first stage of incision is also consistent with what is reported in the literature (Cantelli et al., 2004;
587 Pizutto, 2002; Pearson et al., 2011; Major et al., 2012; Randle et al., 2015; Ibisate et al., 2016). Until autumn
588 2016, the morphological response in the former impoundment may for instance partially be integrated in the
589 five-stage readjustment model proposed by Doyle et al. (2003): A) pre-works; B) lowering of the water level
590 and differentiation between the new bed and the outlet channel; C) incision; D) incision and widening; E)
591 aggradation and widening. F) state of near equilibrium. The first 4 stages clearly took place during the first
592 year of monitoring at Pierre Glissotte, but stages E and F were not achieved. A slower and more local
593 incision and some local widenings continued until the second removal step in October 2017. Our
594 observations comfort the proposals made by Evans (2007) to adjust the model of Doyle et al. (2003) by
595 adding a phase E' corresponding to the stabilization and revegetation of the deposits. Indeed, this stage
596 started to occur in late spring 2016, on some stable gravel bars, and fine deposits collapsed or slumped from
597 the banks. As in the Ivex reservoir (Evans, 2007), these stable deposits were located near the foot of a
598 previously unstable bank and often faced the opposite bank subject to undermining and prone to erosion
599 and/or collapse (i.e. in places where the channel widened).

600

601 Following the reactivation of bedload transport, the formation of the channel was accompanied by an
602 increase in the particle size of the bed substrate, again in accordance with what has been observed in other
603 cases of dam removal (Pearson et al., 2011; Major et al., 2012). A shift from fine (< 2 mm) or slightly coarse
604 (< 8 mm) grain size to a gravel bed was, for instance, observed in the Souhegan River (Pearson et al., 2011)
605 following the removal of Merrimack Dam. Though at the Merrimack Dam, a stage of refinement was
606 initially observed over the 300-350 m stretch upstream of the dam. At Pierre Glissotte, all the coarse

607 fractions present at the tail and in the reservoir were very quickly remobilized and travelled the entire length
608 of the reservoir (400 m) in just a few months (Fig. 6, photographs 1-2).

609 When considering these high transportation rates recorded at Pierre Glissotte (R), one could argue that they
610 were also recorded at the control sites (U and D) just after the injection of marked particles (Fig. 5B). Indeed,
611 the literature suggests that the mobility of tracers after their injection may be favored by an artificial
612 protruding or unconstrained position (Gintz et al. (1996) in Lamarre and Roy, 2008 and Houbrechts et al.,
613 2015). Some studies over longer time scales (several years), have also shown that the propagation rates of
614 marked particles diminished over time (Ferguson and Hoey, 2002; Haschenburger, 2011, Houbrechts et al.,
615 2015). However, at Pierre Glissotte (R), it is important to note that: (i) the first bedload displacements
616 occurred with the absence of a flood event; (ii) the high transport rate lasted much longer and (iii) the
617 cumulative distance reached in the former reservoir (123 m in 9 months for the first tracer series) increased
618 much faster than at the control sites (50 m in 6 months at U, and 60 m in 9 months at D, following the tracer
619 injections and under hydrological conditions that are comparable or even more favorable to mobility). In this
620 case the rapid bedload displacements were clearly favored by the removal and specific conditions of the
621 reservoir. First the lowering of the base level and the migration upstream of the knickpoint that destabilized
622 the bed. Second, the sandy nature of the bed facilitated the incipient motion of the pebbles and cobbles
623 because of a protrusion effect and the reduction of the friction angle (Wilcock et al., 2001; Miwa and Parker,
624 2017; Dépret et al., 2020). This highlights once more the important role of sand in the river response. Even
625 though this study is intentionally focused on the bedload of the Yonne River (pebbles and cobbles), it may be
626 worthwhile to further assess the sand dynamics and transport rates. Finally, it is interesting to note that the
627 intense morphogenic activity is responsible for the rapid incipient motion of coarse bedload and changes in
628 bed texture (coarsening) that eventually induced a retroactive loop that slowed down the system. The
629 coarsening of the bed progressively limits the sediment transport and decreases the morphogenic activity.

630 The same cycle of intense adjustments followed by the slowing down of erosive activity was observed after
631 the second step of the removal (Fig. 9), though the adjustments recorded were more limited and the active
632 phase was shorter. This may be explained because the channel substrate was coarser but also because of the
633 appearance of large boulders that play the role of local base level. These blocks are multi-decimetric to
634 metric and, together with some bedrock outcrops, slowed down the vertical erosion. Indeed, other studies
635 have shown that these hard areas (or other materials that are more cohesive and resistant than the previously

636 eroded layer) can limit incision and regressive erosion (Pearson et al., 2011; Wilcox et al., 2014; Gartner et
637 al., 2015; Warrick et al., 2015; Ibisate et al., 2016), and by fixing the bed, may isolate the surrounding
638 sediments of the reservoir (Major et al., 2012).

639 These results, like those of Straub (2007) on Brewster creek, emphasize the fact that to understand the multi-
640 stage changes consecutive to the removal of the dam, high frequency measurements are needed (Table 2).
641 This is clearly visible on Figure 9. On one hand, the volume eroded from the Ivex (Evans, 2007) or the
642 Stronach (Burroughs et al, 2009) was assessed over 10 and 12 years respectively but only from one
643 (Stronach) or two (Ivex) surveys. In consequence, the erosion in these reservoirs may not have been as
644 regular as it may seem, despite the fact that these dams were removed in one step. On the other hand, the
645 non-linear dimension of the recovery trajectory in the former Pierre Glissotte reservoir is well shown on
646 Figure 9. Our study emphasizes the gradual establishment of the regenerative processes that are targeted in
647 river restoration (Hart et al., 2002). Indeed, the succession of different stages with changing morphogenic
648 activity corresponds to the progressive shaping of a new channel along a 400-m long stretch, with lotic
649 conditions and varying width, depth and slope. It also corresponds to new sediment deposits of variable
650 stability, and to the discovery of bedrock outcrops and boulders. All these changes in geometry and textural
651 conditions lead to clearly diversified plan forms (channel side, mid-channel and point bars, sinuous sections,
652 straight and plane bed sections), changes in substrate grain-size and sedimentary units, and in hydraulic
653 conditions (pools, runs, two 15-m long rapids). In the former Pierre Glissotte reservoir, the restoration of
654 sediment continuity and bedload transport is clearly associated with the restoration of hydromorphological
655 and ecological functioning, which was one of the objectives of the project.

656

657 **6.2 Very weak adjustments in the downstream reach showing poor resilience of the system**

658
659 Except for the temporary deposits of sand following the first step of the removal in July 2015, no significant
660 change in the bed geometry, in the fluvial planforms or in the substrate grain size appeared downstream of
661 the former Pierre Glissotte dam during the first three years of this study. This absence of reconfiguration
662 contrasts with the intense morphogenic activity described in the reservoir.

663 The initial deposits of fine sediment in the center of the channel were quickly evacuated and, as already
664 described in the literature (Doyle et al. 2003; Draut and Ritchie, 2015), only the lateral margins of the

665 channel remained covered for a few months by centimeters-thick deposits. This constitutes only a “short-
666 term response” (Foley et al., 2017a) to the first step of the dam removal and the absence of other deeper
667 morphological changes was unexpected. Grant and Lewis (2015) have for instance underlined that
668 downstream of the Marmot dam, if sands were rapidly evacuated over tens of kilometers, the gravels were
669 massively deposited only a few kilometers downstream of the dam (Major et al., 2012). Pierre Glissotte is
670 smaller but the rapid transfer of bedload towards the downstream reach suggested that something similar
671 could happen here. The reaction time downstream of the dam is already rather long given the fact that the
672 bedload supply was reactivated years ago and that the fastest particles are now located hundreds of meters
673 downstream. The weak evolution shown by the last topographic surveys raises the question of whether the
674 limited morphological changes may be the result of limited bedload supply (despite the sediment continuity
675 being restored) or the result of its high dispersion.

676 Thanks to the volume of coarse sediment stocked in the reservoir tail (2,300 m³), the bedload discharge of
677 the Yonne River was calculated. It is 77 or 177 m³/year depending on whether we consider that the bedload
678 transport stopped in 1985 (the second watering of the dam) or in 2002 (the definitive closing of the bottom
679 outlets), corresponding to a bedload yield of 1.6 or 3.6 t/km²/yr respectively (i.e. values consistent with those
680 of Houbrechts et al. (2006) in similar Belgian environments). Then, one may consider that between 2,600
681 and 3,000 m³ of pebbles and cobbles were reintroduced to the system since the reopening of the river course
682 (bedload trapped in the former reservoir + sediment supplied from upstream). Figure 7 shows that a part of
683 this volume spread out along the entire former reservoir in less than 6 months and UAV photographs allow
684 us to measure the surface of the gravel bars in April 2016, March 2017, May 2018 and July 2019. They are
685 relatively constant, ranging between 2080 and 2530 m². The thickness of this gravel deposit ranges between
686 a few centimeters in pools, up to 1 m in the thickest bars. By considering an average thickness of 0.5 m
687 (which is probably overestimated), the volume of the gravel deposited in the former reservoir would range
688 from 1040 m³ to 1260 m³ (i.e. between 33 and 50% of the total load). The remaining volume has been totally
689 evacuated from the tail of the reservoir for months and distributed in the downstream reach.

690 These calculations suggest that a sediment wave occurred consecutively to the removal of the dam.
691 According to the classification of Lisle et al. (2001), this corresponds to a dispersing wave rather than a
692 translating one. The particularity in this case, is that the load spread out in the former reservoir in a thick
693 layer but once it passed the former dam the wave disappeared as the particles were flushed away. It appears

694 indeed from the PIT tag surveys that the bedload that passes the former reservoir transits through the
695 downstream reach with very short resting times, preventing sediment accumulation and bed aggradation. The
696 same observations have been reported following dam removals from the Elwha river (Warrick et al., 2015;
697 Ritchie et al., 2018) and from the fracturing of the Barlin dam on the Dahan river (Tullos and Wang, 2014).
698 In the latter case, deposits increased and altered the longitudinal profile only when the channel lost carrying
699 capacity at the end of a very confined section (Tullos and Wang, 2014). In Pierre Glissotte, it is probably
700 also the narrowness of the valley (confinement) that facilitated the rapid evacuation of the sediment.
701 Moreover, the confinement is reinforced by ripraps present on the left bank. They date from the construction
702 of the first hydroelectric facility in 1927. The structure not only ensures a certain straightness of the river
703 course but also increases the hydraulic capacity of the channel, the water depth at peaks flow and therefore
704 the associated shear stress. Comparing several downstream decommissioning sites, Poepl et al. (2017) also
705 found that the presence of other anthropogenic developments (including bank protections) inhibit
706 adjustments and tend to preserve the configuration developed under the influence of the dams.

707 Another element, that is partly the consequence of this embankment, may also explain the rapid transit of the
708 bedload in the downstream reach of the dam. It is the fact that the river bed is clogged and paved. This
709 confers a low rugosity at the surface of the bed and favors incipient motion of the particles supplied from
710 upstream (Petit et al., 2005; Gob et al., 2010; Gilet et al., 2020). This pavement of the bed has been favored
711 by the partial channelization of the bed but is a direct consequence of the presence of the dam which limited
712 or even stopped bedload transport for decades.

713 So far, these sedimentary characteristics have not been modified by the restoration of the sediment
714 continuity, and the channel geometry and the bedforms remain almost unchanged. The recovery of bedload
715 supply without the morphological reconfiguration of the bed raises questions about the capacity of the
716 restored system to really change its hydromorphological functioning and return to a pre-dam situation (Foley
717 et al., 2017a). In particular, it calls into question whether the restoration of sediment continuity may
718 compensate for the impact of decades of sediment deficit. The morphology inherited from the dam was
719 largely the same four years after the removal started, suggesting the possible irreversibility of this influence
720 and a lack of resiliency. With this in mind, it may be more appropriate to describe the operation as a
721 rehabilitation process, rather than a restoration process (Dufour and Piégay, 2009). Downstream of the Pierre
722 Glissotte site, the paved section showing a deficit in medium-sized load is not very long and consequently

723 the absence of morphological adjustment is probably not worrying from an ecological point of view (macro-
724 invertebrate habitats, substrate and hydraulics of spawning areas, etc.). However, when the unbalanced
725 sections are more extensive, the lack of morpho-sedimentary reconfiguration may turn out to be ecologically
726 problematic.

727

728 **Conclusion**

729

730 The various morpho-sedimentary changes observed in the former reservoir during the four years of
731 monitoring underline the changing nature of the adjustments, their pace and control mechanisms. The initial
732 destabilization process associated with the propagation upstream of the knickpoint led to very rapid
733 readjustments. The new conditions (hard points, more cohesive lower deposits) revealed by the incision and
734 the achievement of more or less transient equilibrium conditions slowed down the morphological changes.

735 These changes are in line with what has been observed for other dam removals. However, in the case of
736 multi-stage removal, it is quite exceptional that 26% of the trapped sediment was re-injected into the system
737 at the end of the first year of restoration such as observed at Pierre Glissotte. This is undoubtedly linked to
738 the nature of the filling (unconsolidated sand and silt) and to the dynamic character of sediment transport in
739 the Yonne river. The reintroduction of coarse sediment into the system slowed down the morphological
740 adjustments, without completely stabilizing the system. The complete lowering of the dam during the second
741 stage of work revived the adjustment dynamics which, almost two years later, are still in progress.

742 At first glance, the absence of major morphological changes downstream of the dam, four years after the start
743 of the work, is quite surprising. It testifies to the possibility that a largely effective restoration of the coarse
744 sediment continuity will not be accompanied by significant morphological readjustment downstream. The
745 bedload reached this downstream section but did not settle there. The influence of the geomorphological
746 context (narrow valley with a steep slope) and the legacy of the dam itself (bank ripraps, straight channel and
747 paved substrate) help to explain the rapid transit of sediment in the downstream reach. The last topographic
748 measurements (2019) tend to show a slight aggradation in several sections whereas aggradation was only
749 very local in 2017. The next campaigns will enable us to see if this adjustment remains minor or is still in
750 progress. In any case, this long reaction time confirms the relevance of long-term studies after dam removal
751 as the river response needs to be clearly understood and differentiated over several time scales.

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Graphical abstract

