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Research article

Multi time scale influence of dams on bedload transport

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ABSTRACT

Dams are ones of the main sources of anthropogenic disturbance to the ecology and geomorphology of rivers. The aim of the present study is to understand the mechanisms underlying their influence on downstream bedload transport in three gravel-bed rivers in the Morvan massif, France. The hydrological disturbance caused by four dams is examined at a short (2.4–2.7 years) and longer (21–28 year) time scale. At the short time scale, bedload displacement was monitored (RFID) at 8 study sites around the dams. Morpho-sedimentary characterization of the bed substrate was performed at the study sites and combined with analyses of the long profile evolution and the current cross profile.

The flood regime has been to a varying extent durably reduced by the dams depending on their size and purpose: the mean annual maximum flood was reduced by 9 to 40% and the number of flood events by 27 to 73.5% over the 21–28 years period. Sediment availability and loose structures were found above the dams and below medium-sized dams (<10 m) with a null or moderate influence on the flood regime (configuration I). Sediment deficit, consolidated structures, bed coarsening and vegetation encroachment were observed within 20 km downstream of large dams (>15 m) influencing strongly or moderately the flood regime (configuration II). These morpho-sedimentary features significantly affect the current bedload dynamics, creating conditions more or less favorable for the mobility of the present and incoming bedload. The cumulative mean bedload distances of RFID tracers in configuration II are significantly lower (6.8–45 m) than in configuration I (78–315 m). The current flow management of the dams has only a moderate effect on the bedload distances recorded, as shown by the mean virtual bedload velocities, which confirm the different dynamics (0.42–0.91 m/d, and 0.62–6.44 m/d, for II and I respectively). Our results demonstrate how modifications of dams on flow and bedload discharge altered the downstream morphology, but also that this inherited morphology may now be the main controlling factor of bedload transport. These findings invite further discussion about the most appropriate ways to restore rivers downstream of dams when dealing with multi-decadal inherited morphological features.

1. Introduction

Dams are known to modify hydro-sediment dynamics and are consequently likely to disturb a wide range of morphological parameters including channel stability and geometry, planforms, bed texture, instream and riparian vegetation (Kondolf, 1997; Brandt, 2000; Petts and Gurnell, 2005; Csiki and Rhoads, 2010; Piqué et al., 2017). In turn, these morphological features affect channel flow characteristics and sediment transport (Petts and Gurnell, 2005; Grant, 2012; Church and Ferguson, 2015), and possibly connectivity with the floodplain and any tributaries (Gilvear, 2004; Kloehn et al., 2008). By altering hydro-sediment dynamics and hence morphological and hydraulic conditions, dams also affect river habitat and biota at the impounded site and in the downstream reaches (Assani et al., 2006; LeRoy Poff et al., 2007; Lees et al., 2016; Wright and Minear, 2019; Wu et al., 2019).

These significant consequences of hydro-sediment disturbances help explain why for the last 20 years, restoring environmental flows and sediment transfer in fluvial systems truncated by dams has become a major issue in fluvial ecology, fluvial geomorphology and river management (Gregory and Downs, 2004; LeRoy Poff and Zimmerman, 2010; Kondolf et al., 2019). Since the beginning of the 2000s, literature on engineering and management operations aimed at reintroducing

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sediment dynamics downstream of the dams (mitigation measures, dam removal) has flourished (Kondolf et al., 2014; Major et al., 2017; Gaeuman et al., 2017; Dépret et al., 2019). During these restorative operations and/or in the years following them, the quantity and propagation patterns of released sediments have been measured, and bedload discharge has occasionally been measured downstream of the dams (Draut, 2015; Gartner et al., 2015; Arnaud et al., 2017; Chardon et al., 2021). Comparing these studies indicates that the operations can cause a variety of changes in bedload mobility (increase/decrease/no change) compared to prior-operation conditions, prior-dam conditions or upstream conditions in control reaches (Cheng and Granata, 2007; Magirl et al., 2015; Dépret et al., 2019; Gilet et al., 2021). The variable effect of restorative operations on bedload mobility is a major consideration because subsequent morpho-sedimentary adjustments are themselves partly controlled by bedload dynamics. (Comiti et al., 2011; Wohl, 2014; Church and Ferguson, 2015). This is also why, in the case of dam removal, the annual solid discharge of a river can be used to help predict the duration and magnitude of the geomorphic responses (V'ratio, Major et al., 2017).

Yet, despite its major hydromorphological role, bedload transport still tends to be overlooked by restoration operations, even when these consist in sediment augmentation and dam removal. The same goes for bed characteristics (macro and micro-scale bedforms, grain size sorting, substrate arrangement, particle burial, etc.) that are yet closely linked to bedload transport and channel adjustment capacities (Petit et al., 2005; Grant, 2012; Yager et al., 2018; Gilet et al., 2020). The lack of attention paid to these key hydromorphological conditions raises questions about the effectiveness and sustainability of these restoration operations. Also, knowledge of bedload transport and bed characteristics developed over several decades of alteration of the water-sediment supply is essential to define the range of goals that can be targeted with the operation (Kondolf, 2011; Brierley and Fryirs, 2016). Thus, assessing the extent to which bedload transport can be modified and possibly restored to a pre-disturbance situation will clearly help define the range of hydromorphological conditions that can be realistically expected as a result of a restorative operation. The first step in this assessment could be to identify the drivers of bedload transport in the disturbed context, reaches below dams in this study, and to what extent they can be modified.

This paper tackles these issues through the study of several river reaches disturbed by dams that differ in size, age, and functioning. Our investigation focuses on three rivers: Yonne, Cure and Chalaux, in the Morvan massif, a medium elevation mountain range in central France. Several dams were constructed starting in the middle of the 19th century for a variety of - and changing - uses: log driving, hydro-electricity production, flood control, water sports. Most of these dams are still in use today and should not be removed because of their economic importance and their role in risk mitigation. Consequently, the eco-geomorphic issues associated with their flow and sediment management are major questions to address. The aim of the present study was therefore to provide data to help understand the specific mechanisms behind the influence of dams on bedload transport and to assess what subsequent restoration paths can be appropriate. To do so, various methods were implemented to identify the effects of the dams on the flood regime, the sediment supply, and the morphological conditions. The second step was to determine to what extent these altered hydrological and morpho-sedimentary conditions control the current bedload dynamics. We characterize the specific ways Morvan dams affect the flood regime of their respective river on the long term (21–28 years) with two analysis methods of hydrological series, Annual Maximum Flood (AMF) and Partial Duration Series (PDS). We then investigate how the multi-decadal disturbance to the water and sediment supply shaped new morphological conditions, using various field techniques implemented on 8 study sites: grain size campaigns and visual assessment to characterize the bed substrate (grain size distribution, sorting, packing), topographic surveys to obtain the cross-sectional and longitudinal geometry, the latter being compared with historical long-profiles from the 1930s. Finally, over a period of 2.4–2.7 years, we measure with Radio Frequency IDentification the current bedload mobility associated with these morphological conditions and the current flood regime. The implications of our results for river restoration below dams and in particular the restoration of channel dynamics are discussed.

2. Study sites

The Morvan massif is a Hercynian medium-elevation mountain range located in the southeast of the Seine catchment in central France (Fig. 1A). Granitic and gneissic rocks form most of its substratum. The

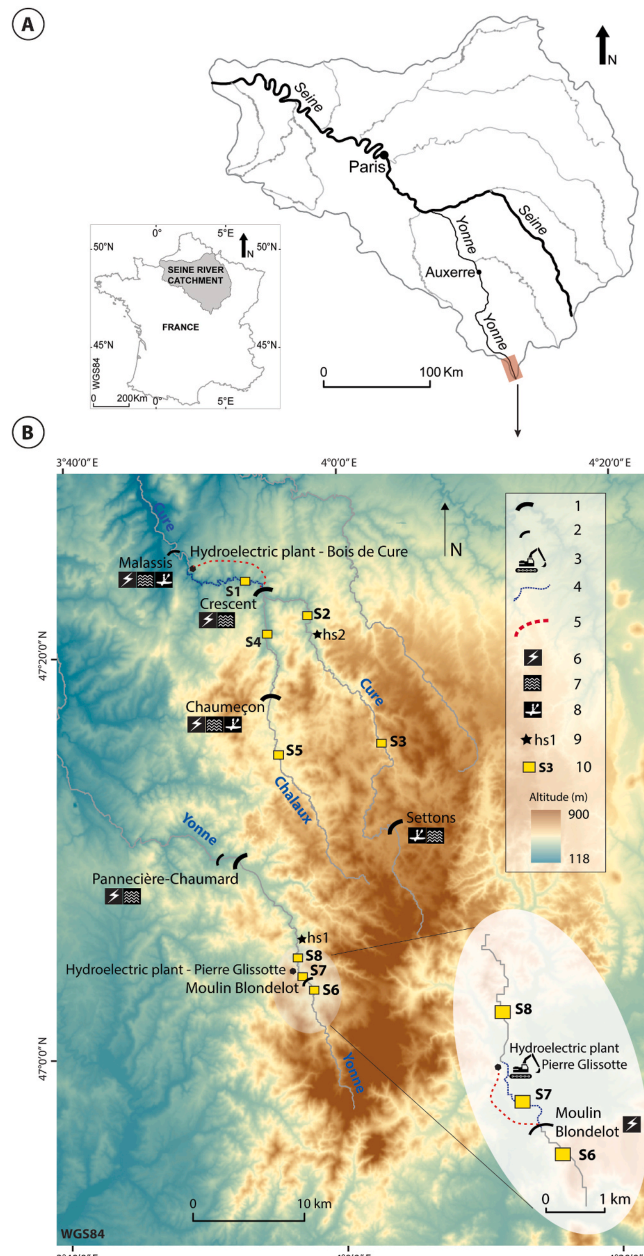


Fig. 1. Location of the study sites (A) in the Morvan massif in the Seine river catchment, (B) on the Yonne and Cure rivers. 1. Large dam (>15 m); 2. Medium size dam (<10 m); 3. Removed dam; 4. By-passed reach; 5. By-pass canal; Functions of the dams: 6. Hydroelectric production; 7. Flood control. 8. Water sports; 9. Gauging station; 10. Study site. **S1**: 47°23′36″ N, 3°53′21″ E; **S2**: 47°22′9″ N, 3°57′36″ E; **S3**: 47°17′22″ N, 4°2′17″ E; **S4**: 47°20′51″ N, 3°54′43″ E; **S5**: 47°15′17″ N, 3°55′40″ E; **S6**: 47°3′44″N, 3°57′27″ E; **S7**: 47°4′7″ N, 3°57′10″ E; **S8**: 47°5′1″ N, 3°56′41″ E.

climate is temperate oceanic with pluviometry influenced by the orography. The average rainfall in the region is 1000 mm/year (Vaucoulon and Chiffaut, 2004). Given the imperviousness of the substratum, this has led to the formation of a densely developed hydrographic network. We studied eight river reaches (S1 to S8) of three gravel-bed rivers in the region: three on the Yonne, three on the Cure river and two on one of its tributaries, the Chalaux (Fig. 1B.). These study sites are located both upstream and downstream of dams built on their respective river. We investigated four dams that function in four different ways.

The Chaumecon dam works by water releases that run a small electric plant located at its bottom (Fig. 1B, Table 1). Turbined water is returned to the bed of the Chalaux river and subsequently supplies the Crescent reservoir located 7.4 km downstream. The mean discharge passing through the Chaumecon turbines is 5 m^3/s, to which is added a permanent minimum discharge of 0.3 m^3/s (Asconit consultants and Aralep, 2006). Therefore, in July and August, to produce electricity while sustaining the low flows, 5.3 m^3/s are released for 9 h/day almost every day (EDF, personal communication). This is well above the mean annual discharge (2.15 m^3/s) at Chaumeçon dam. During the rest of the summer and in the spring, the same discharge is released on Wednesdays, weekends and public holidays to enable water sports to be practised downstream of the dam (Léger, 2006). During high-flow periods (in the fall and winter), the dam also has the function of flood control. Thus, the reservoir is emptied in spring and summer (for water sports and low flows support) to be at its lowest water level in the middle of October in order to be fully capable of absorbing fall and winter flood water (Léger, 2006; EDF, personal communication).

The Crescent dam was built and is still used for the production of hydroelectricity, to mitigate low flows, and for flood control (Fig. 1B, Table 1). Like the Chaumecon dam, flood control is particularly effective in winter, as the reservoir is managed in such a way to start filling in the middle of October (Léger, 2006; EDF, personal communication). The dam is equipped with two 11-m^3/s turbines located 5.5 m below the water intake. The water is then directed into a tunnel along the hillslope towards a second power plant ("Bois de Cure", Fig. 1) located 7.3 km downstream and equipped with three 11-m^3/s turbines. This bypass implies a drop height of 82 m (Asconit consultants and Aralep, 2006). The minimum and most frequent discharge released by the dam in the bypassed reach of the Cure is 0.9 m^3/s, which represents about 10% of the mean annual discharge flowing into the Crescent reservoir (EDF, personal communication).

The Settons dam was originally built for log driving (Bardonnet, 2008; Héry, 2015), but today its main function is to enable the practice of water sports in the lake and the downstream reach (Fig. 1B, Table 1). This means respecting a water filling schedule in the reservoir and water releases for about 30 days/year. These water releases are operated to reach an average discharge of 5 m^3/s, and very occasionally, 7–8 m^3/s, several kilometers farther downstream (IRAP, 1999). These discharges remain under the critical threshold for bedload motion at our study sites (Gilet et al., 2020). The rest of the year, exiting discharge is managed based on the water filling schedule and incoming discharge (DDT, personal communication). During flood events, as long as the water in the reservoir does not go beyond a defined maximum height, a maximum of 4 m^3/s is released from the dam. When the maximum water level in the reservoir is reached, the discharge of water releases equates incoming flow (transparency). Since 2008, the dam has been incorporated in the wider Seine basin flood management plan, although less definitively decisively than the Chaumecon and Crescent dams (DDT, personal communication).

The Moulin Blondelot dam on the upper Yonne River is a much smaller dam (Fig. 1B, Table 1). A by-pass canal runs from the dam to bring water to the Pierre Glissotte hydroelectric plant located 1200 m downstream (Fig. 1B). The maximum bypassed discharge is limited to 2.3 m^3/s, provided that a minimum discharge of 300 l/s remains in the river. This diversion capacity is significant for low flow and also in the case of small floods, considering that the bankfull discharge is close to 6 m^3/s. Also, the mobile sluice gates of the dam, that open automatically during flood events, help allow high flows and sediments to reach the by-passed reach (Gilet et al., 2021).

Until July 2015, the Pierre Glissotte hydroelectric plant was associated with a 7.29 m high and 40 m wide dam also built in the mid-1920s to produce hydroelectricity (Fig. 1B). However, from the early 2010s and until July 2015 when the dam was removed, its reservoir (≈40,000 m^3) was almost completely filled with sediment and consequently unable to retain any flood discharge (Gilet et al., 2021).

Of our 8 study sites, 5 are located downstream of the above-mentioned dams (Fig. 1B). The real and reconstructed mean discharge, and the bankfull discharge were calculated for each site using data provided by dam management records, two public gauging stations (Fig. 1B) and field observations (Table 2). Details on the data and equation that were used are provided in section 3.1.1.

S1 is located 2.5 km below the Crescent dam in the by-passed reach (Fig. 1B). At this point, without regulation by the dam, the Cure would have a mean discharge of 9.5 m^3/s, and the bankfull level is reached at 32.8 m^3/s (Table 2). S2 and S3 are located respectively 33.3 km and 18.2 km from the upstream Settons dam, and their respective bankfull discharge is 20.5 m^3/s and 16 m^3/s. S4 is located 6.1 km downstream of the Chaumecon dam. Without flow regulation, its mean discharge would be 2.77 m^3/s. S7 is located on the by-passed reach, 0.3 km below Moulin Blondelot dam (Fig. 1B). The mean reconstructed natural discharge at S7 is 1.93 m^3/s and the bankfull level is reached at 5.5 m^3/s (Table 2).

The 3 other study sites are located in river reaches that are not influenced by the dams (Fig. 1B). S5 is located 1.6 km upstream of the Chaumecon reservoir tail while S6 is located 0.6 km upstream of the Moulin Blondelot dam. S8 study site is located 2.5 km downstream of the Moulin Blondelot dam. At this point the discharge is no longer influenced by the dam because the tail race of the Pierre Glissotte hydroelectric plant brings back the diverted discharge into the Yonne 1.3 km downstream of the Moulin Blondelot dam (Fig. 1B).

The rivers we studied are medium energy streams with a specific stream power for bankfull discharge fluctuating between 45 and 167 W/m^2 for slopes ranging from 0.0056 m/m to 0.015 m/m (Table 2). The

Table 1
Characteristics and functions of the studied dams.

Dam	River	End of construction	Functions	Height and width (m)	Size of the reservoir (hm^3)
Chaumecon	Chalaux	1933	Hydroelectric production Flood control Water sports Low-flow support	35.5–196	19.3
Crescent	Cure-Chalaux junction	1932	Hydroelectric production Flood control Water sports	31.5–332	14.2
Settons	Cure	1858	Log driving (until 1920s) Water sports Flood control	19–267	22.7
Moulin Blondelot	Yonne	1927	Hydroelectric production	3.49–23	0.0007

Table 2
Characteristics of the study sites.

Site number and river	S1 Cure	S2 Cure	S3 Cure	S4 Chalaux	S5 Chalaux	S6 Yonne	S7 Yonne	S8 Yonne
Catchment area (km^2)	410	234	160.5	126	69	71	74,5	83
Mean annual discharge (m^3/s)	3.13	4.76	3.51	2.3	1.65	1.84	0.84	2.15
Reconstructed natural mean annual discharge (m^3/s)[a]	9.5	4.55	3.42	2.77	1.65	1.84	1.93	2.15
Bankfull discharge (m^3/s)	32.8	20.5	16	12	6.2	6	5.5	9.5
Specific stream power for bankfull discharge (W/m^2)	139.9	78	166.7	48.2	48	45.2	77.1	67.7
Bankfull width (m)	18	18.05	14.12	14.4	7.1	9.5	10.5	11.7
Bed slope (m/m)	0.0078	0.007	0.015	0.0059	0.0056	0.0073	0.015	0.0085
D_{50} (m)	0.261	0.133	0.265	0.091	0.080	0.074	0.108	0.083
D_{84} (m)	0.813	0.224	0.699	0.164	0.142	0.105	0.247	0.175
D_{16} (m)	0.036	0.051	0.041	0.033	0.023	0.034	0.038	0.037

[a] Reconstructed natural discharge in the absence of flow regulation.

grain size distribution of the bed matches this slope value range quite well (Table 2). Beds D_{50} and D_{84} range from respectively, 0.074–0.265 m and from 0.105 to 0.813 m, revealing riverbeds dominated by cobbles or small boulders (Table 2). Except for S3, the study sites are rather similar with a plane-bed morphology. At S3, the grain size distribution is wider (S1 excepted) and a light step-pool system or a transverse rib system tend to successively characterize the bed morphology.

The morphology of the Morvan rivers is also greatly influenced by almost 350 years of log driving. The hydromorphological consequences of this activity on the Morvan rivers are well studied (Poux et al., 2011; Jacob-Rousseau and Gob, 2020). In the middle of the Yonne river valley, log driving resulted in a major input of cobbles and pebbles from headwater streams. In addition, water courses have been considerably straightened and river banks riprapped to secure the efficient transport of the logs.

3. Methods

3.1. Hydrological analysis

3.1.1. Available data

Two public hydrometric stations provide instantaneous discharges and daily discharge. One is located on the Yonne river, 4.5 km downstream of the Moulin Blondelot dam and the other on the Cure river, downstream of the Settons dam (labeled hs1 and hs2 in Fig. 1B). They were installed on the Cure river in 1962 and on the Yonne river in 1990. In addition, water sensors (Diver, ©Schlumberger) were installed at the upstream and downstream limits of the 8 study sites and record variations in water level at 15-min intervals. Data on the flow entering and exiting the Crescent and Chaumeçon dams were provided by *Electricité de France* (EDF): series of mean daily discharges from 1995 to 2017 (data for the years 1995 and 2017 are not complete) and instantaneous discharges for several flood events. Mean daily discharges exiting the Settons dam were also provided by EDF for the period 1995–2017 (data for 1995 and 2017 are also not complete). These data enabled us to reconstruct a theoretical natural discharge at the hydrologically influenced study sites (concerning the S1 Cure site, we call it semi-natural discharge because the discharge that would flow in the absence of the Crescent dam is already modified by the upstream Settons and Chaumecon dams). To evaluate the hydrological effects of the dams, we compared discharges among the study sites and between the real and theoretical natural configuration, at two time scales. At the long time scale, the reconstructed natural discharge was estimated using the discharge entering the Crescent and Chaumecon dams extrapolated to our study sites with the catchment area-discharge relationship found in Bravard and Petit (1997). For the sites located downstream of the Settons dam, the same relation was used with the data provided by the public hydrometric station (hs2 in Fig. 1B), after subtracting the influence of the dam on the real discharge. Then, in the Bravard and Petit (1997)'s relationship below:

$$q = Q\left(\frac{a}{A}\right)^{0.8} \quad (1)$$

q is the reconstructed natural discharge at the study site, Q is the discharge extrapolated from hydrometric station (hs2) to our study site minus the input exiting the Settons dam; a is the catchment area at the study site, and A is the catchment area at the study site minus the subcatchment upstream of the Settons dam.

The series for the years 1995 and 2017 for the Cure and Chalaux rivers are not complete; and the same applies to the 1991 series for the Yonne river. The data are nevertheless interesting to compare natural and regulated discharges in the Annual Maximum Flood analysis (AMF), but should not be compared to the other years. The same goes for the Partial Duration Series analysis (PDS). In this paper, discharge episodes reaching and exceeding the critical threshold for bedload mobilization (section 3.2) are termed "floods". Related terms (flood magnitude, flood frequency, flood duration, etc.) are also based on this definition.

Daily discharge series were used to measure the long term influence of the dams on the flood discharge (instantaneous discharge data from the management records for Crescent and Chaumecon dams were too fragmented). Except for the S2 and S3 Cure sites, instantaneous discharges (at 15 min and hourly intervals) were used for all sites to study this hydrological influence at a short time scale throughout the period of the bedload monitoring. At this short time scale, regulated and natural reconstructed discharges (only calculable with daily discharge on S2 and S3) were compared to measure the influence of the dams on the loss of flow energy and hence on bedload transport capacity.

3.1.2. Short time scale analysis

The 15 min and hourly discharge data were used to compare instantaneous real regulated discharge and reconstructed natural discharge at the short time interval of our bedload monitoring period (2014–2017).

A partial duration series analysis (PDS) was performed to measure the influence of the dams on the cumulative amount, frequency and duration of flood events during the same bedload monitoring period. The PDS analysis consists on focusing on the discharges above a given threshold, hence the frequent use of "Peak Over Threshold" or POT, to refer to it (Madsen et al., 1997; Lang et al., 1999; Pfaundler et al., 2011). For our analysis, the threshold used corresponds to the critical discharge for bedload incipient motion (see section 3.2). This method has the advantage of considering every flood event and the overall flow competence duration. It makes it possible to study the intensity, the frequency, and the individual and cumulative duration of independent flood events each year.

In addition to PDS analysis, the energy of the flow along our bedload monitoring (2014–2017) was assessed by calculating the stream impulse developed by Gilet et al. (2020). The stream impulse (SI) is expressed in Ws/m^3 and its equation is written as follows:

$$SI = \int_{ts}^{tf} \frac{(\omega - \omega c)dt}{D50}, \omega > \omega c \quad (2)$$

where ω is the specific stream power described by Bagnold's equation (1980):

$$\omega = \rho g Q S / w \quad (3)$$

where ρ is the density of water (kg/m^3), g the acceleration due to gravity (m/s^2), Q the discharge (m^3/s), S the slope (m/m) and w the width of the water-surface (m). In Eq. (2), D_{50} is the median grain size of the tracers, *ts* and *tf* are the starting and finishing times of the period considered during which the critical specific stream power for bedload mobilization (ω_c) is exceeded. These excess values are multiplied by the duration (dt) they are supposed to last and normalized by the D_{50} of the tracers mobilized. In this way, the intensity and duration of the mobilizing flow as well as the particle size are taken into account to examine the river energy consumed for particle transportation. This energy indicator, which combines flow magnitude and flow competence duration, is largely inspired by the dimensionless impulse (I*) introduced by Phillips et al. (2013) and Phillips and Jerolmack (2014) (Gilet et al., 2020). The slope and width required for the calculation of stream power were both obtained from topographical surveys: the first corresponds to the reach averaged bed slope and the second to the reach averaged bankfull width. Critical stream power was then calculated from the critical discharge. A unique critical threshold for incipient bedload motion was set at 0.7 Q_{bf}. This value was the result of a review of the literature (see Gilet et al., 2020) and of observations made during gauging campaigns at several of our sites that indicated that the bed material began to move at discharges ranging from 0.5 to 0.7 Q_{bf}.

3.1.3. Long time scale analysis

The analysis of regulated and reconstructed natural discharge was performed over the longest possible period based on the available data: 1995–2017 for the Cure and Chalaux rivers, and 1990–2018 for the Yonne River. The results presented here are focused on the flood regime. Two standard analysis methods were used: Annual Maximum Flood (AMF) and the Partial Duration Series (PDS) (Roche et al., 2012).

Based on Gumbel's works (Gumbel, 1958), the AMF method isolates the annual maximum discharge (in our case, daily discharge). The AMF therefore focused on the maximum flow magnitude. The discharge for a given recurrence interval (RI) can be estimated using the graphical adjustment method. The value of reference floods (Q2, Q10, etc.) from our analysis should be taken with caution as the complete hydrological series we have is limited in time (21 years for the Cure and Chalaux rivers, 28 years for the Yonne river).

3.2. Bedload transport monitoring

Bedload transport was studied using Radio Frequency IDentification (RFID) technology (Piégay et al. (2016); Gilet et al. (2020). The tags we used were 23 and 32 mm long. 50 tagged particles, tracers, were first injected on each site between August and October 2014 (Table 3). Tracers were positioned along cross sections with a minimum distance of 1.25 m between them. At the study sites with the most intense bedload transport, 25 additional tracers were injected in the same way in October 2015. The particles to be tagged were selected in the riverbed using Wolman's sampling method (Wolman, 1954). Because of technical constraints (tracers not equipped on site), there is a slight discrepancy between the D_{50} injected and the D_{50} of the bed at the sites with the largest grain size distribution. However, as explained in Gilet et al. (2020), overestimation of travel distance is rather low: at these sites with a very coarse substrate, regularly transported D_{50} and D_{84} particles are actually smaller than the D_{50} and D_{84} of the bed.

Surveys of the positions of the tracers were undertaken with a round 0.5 m-diameter antenna between November 2014 and April 2017. The distances travelled by the marked particles were measured using a flexible tape measure unrolled along the bank. As suggested in the literature (Bright, 2014; Houbrechts et al., 2015; Olinde and Johnson, 2015) and except if otherwise mentioned, the displacements recorded during the first survey after injection are not included in the results below (to avoid a possible artificial protrusion effect). Details of these methodological specificities can be found in Gilet et al. (2020). Finally, the bedload data presented at the inter-survey scale (section 4.4.2) come from a total of 29 surveys: three surveys at the Yonne sites (S6, S7, S8) and S1 Cure site, four at the Chalaux sites (S4, S5) and S3 Cure site, and five at the S2 Cure site.

3.3. Morphological data and grain size distribution

The current longitudinal profiles and cross-sectional geometry of the study sites were surveyed with a Trimble total station S6. At least 13 cross sections spaced 1–1.5 times the bankfull width were made at each site. This resulted in a transversal survey that covers a total reach length ranging from 120 m to 302 m depending on the study site. The long profile was measured on a longer reach (between 120 and 1200 m long).

The grain size distribution of the riverbed was determined using Wolman's pebble count method (1954). A decameter was unrolled along the river bed including several diagonal crossings. At least 300 particles per site were randomly sampled and measured. From these measurements, we also estimated a Grain Size Sorting Index (GSSI), the ratio D_{84}/D_{16}, to assess the heterogeneity of the substrate (Robert, 2003).

3.4. Historical data

In order to examine the evolution during the last decades of the long profile of the rivers studied, we compared the current and long-profile from the beginning of the 1930s. The historical long profiles were extracted from the "*Atlas des Grandes forces hydrauliques*" (geodesie.ign.fr), part of a general survey of French rivers and streams that aimed to identify sites for hydroelectricity production. The precision of the tacheometer used for this work was 0.1 m and about 4 points per kilometer were measured (Liébault et al., 2013). The method used to calculate the overall propagated uncertainty surrounding the comparison between current and historical long-profile is given in Liébault et al. (2013). One source of uncertainty results from the difference in the water level between the surveys. Indeed, the historical long-profile only gives the elevation of the water surface, and not of the river bed. As discharge for the historical period is often not known, a cautious error margin of 50 cm was suggested by Liébault et al. (2013). For two of our study sites, the current channel slope was used for the comparison because it was impossible to measure the water surface elevation precisely. In this case, an error margin was calculated based on the water height generally observed on the occasions the historical long profile was realized (low flow period). In the end, total error margins fluctuated between 0.52 m and 0.96 m, with a mean of 0.67 m.

Table 3
Details of the injected PIT tag tracers.

Site and river	S1 Cure	S2 Cure	S3 Cure	S4 Chalaux	S5 Chalaux	S6 Yonne	S7 Yonne	S8 Yonne
Total number of tracers	50	75	50	75	75	75	75	75
D_{50} injected tracers (mm)	67	63	60	68	62	58	58	63.5
D_{50} injected tracers/D_{50} riverbed	0.26	0.47	0.23	0.74	0.78	0.82	0.55	0.76

4. Results

4.1. Long-term influence of dams on flood regimes

4.1.1. Annual maximum floods

Overall, AMF analysis showed that the Crescent (Fig. 2, S1) and Chaumecon dams (Fig. 2, S4) are responsible for a significant reduction in annual maximum floods. Under regulated discharge, the mean AMF is respectively, 62% (S1) and 60% (S4) of the value without regulation (Table 4). The mean and biggest discharge differences between regulated and reconstructed AMF below the Crescent dam (S1) and Chaumecon dam (S4) are significant for the flood regime of these reaches (Table 4). The reduction in annual maximum floods downstream of the Settons dam (Fig. 2, S2, Table 4) and the Moulin Blondelot dam (Fig. 2, S7, Table 4) is lower.

Management of the volume of water in the reservoir of the Settons dam (S2) respects a schedule (scaled filling) to allow the practice of water sports during specific periods. Flood control itself is secondary. This explains the very limited reduction in the annual peak discharge (Table 4). The small 700 m^3 impoundment (i.e., almost no flood storage capacity, Table 1), and the automatically opening sluice gates at the Moulin Blondelot dam mainly limit the peak reduction to the diversion capacity of the by-pass canal (2,3 m^3/s). This capacity is significant for the general flood regime of this reach of the river (59% of the critical discharge, Table 4) but has less impact on annual maximum peak discharges.

Considering sediment transport, it is particularly interesting to note the differences in excess critical discharge created by the dams. At S7 (Yonne site) (Fig. 2, S7), non-exceedance of the critical threshold because of the Moulin Blondelot dam only happened in one year (1997). At S2 (Cure site), the limited flood regulation by the Settons dam allow the critical threshold to be exceeded each year (Fig. 2, S2). Here, the impact of the Crescent (S1) and Chaumecon (S4) dams is significant. The Crescent dam massively reduces the number of years when the critical discharge is reached and exceeded (only 10 years out of the 21 complete years, Fig. 2, S1). The Crescent dam also lessens small and medium floods more intensively (Table 5). In line with the average values listed in Table 5, the maximum reduction was reached for moderate floods: 80% in 2017, 83% in 2009, 93% in 2005, and 95% in 1997, all for reconstructed flood peaks under the 1.5-year flood (Fig. 2, S1).

The Chaumecon dam reduces the frequency of morphogenic floods less significantly (only 1 year under the critical threshold) but Fig. 2 (S4) clearly shows that, in many years, critical discharge is barely exceeded: in the series, 43% of the annual maximum flow value exceeds the critical threshold by less than 1.5 m^3 (i.e., 25% of the critical discharge). In addition, unlike Crescent, the lessening effect of Chaumecon dam on floods does not vary as much with flood intensity (Table 5). Beyond the average values, the Chaumecon dam can retain floods at a high proportion for different flow magnitudes: it reduced the downstream maximum discharge by 56% in 1996 and 2007 (<2-year flood), by 63% and 64% in 2003 and 2012 (<5-year flood), and again by 63% in 1999 (>100-year flood) (Fig. 2, S4).

The lessening effect with growing flood intensities increases very progressively for the Settons dam, reflecting its only moderate role in flood control, and logically, the effect decreases gradually for the Moulin Blondelot dam, whose storage and diversion capacity remains limited and stable (Table 5).

Table 6 uses the results of the AMF to summarize the hydrological impacts of the dams over several decades: the Crescent and the Chaumecon dams strongly attenuate the flood regime in their downstream reaches. The influence of the Settons and the Moulin Blondelot dams on controlling the flood regime was more moderate, with the notable exception that the Moulin Blondelot dam had more impact on the exceedance (or non-exceedance) of the critical discharge.

Table 4
Influence of the dams on the magnitude of annual maximum floods.

	Crescent	Chaumecon	Settons	M. Blondelot
Ratio of regulated discharge to reconstructed discharge based on the mean AMF value for the entire hydrological series studied	0.62	0.60	0.91	0.82
Mean difference between reconstructed and regulated discharges (m^3/s), based on the difference in discharge in each year	12.3	6	2.4	2.3
- normalized with the critical discharge	0.54	1.02	0.17	0.59
Biggest difference between reconstructed and regulated discharges (m^3/s) (year)	26.4 (1997)	25.5 (1999)	7.4 (1996)	2.3 (multi-years)
- normalized with the critical discharge	1.15	4.33	0.51	0.59

Table 5
Influence of the dams on the magnitude of annual maximum floods according to flood intensity. The value of reference floods is based on the reconstructed natural regime.

	Mean reduction rate of annual maximum floods (%) (number of complete years it is based on)				
	AMFs < Q_2	Q_2<AMFs < Q_5	Q_5 < AMFs < Q_{10}	Q_{10} <AMFs < Q_{50}	AMFs > Q_{100}
Crescent	68 (9 y)	33 (6 y)	8 (5 y)	4 (1 y)	–
Chaumecon	37.5 (11 y)	38 (8 y)	–	22 (1 y)	63 (1 y)
Settons	2 (10 y)	11 (5 y)	12 (3 y)	16 (3 y)	–
M. Blondelot	25 (13 y)	17 (10 y)	14 (2 y)	11 (2 y)	9 (1 y)

4.1.2. Partial duration series

All the dams reduce the frequency of independent flood events and confirm their influence on the exceedance of the critical threshold (Fig. 3). However, once again there are significant differences in magnitude: on the data series, the total number of independent flood events is reduced by a maximum of 73.5% by the Crescent dam, and by a minimum of 27% by the Settons dam (Table 7). These numbers represent the reduction in independent flood events caused by the dams relative to the total number of independent flood events that would have occurred in a semi natural (S1) or natural (S2, S4, S7) flow regime. The absolute numbers of impeded events (Table 7, rows 2 and 3) do not necessarily follow this relative hierarchy, as the number of reconstructed natural events differs downstream of each dam.

The annual cumulative flood duration was also noticeably reduced by the Crescent and Moulin Blondelot dams (Fig. 3, S1 and S7): respectively 84% and 69% of the total flood duration (Table 7). However, downstream of the Chaumecon dam, cumulative flood duration is often higher with the regulated discharge (Fig. 3, S4, Table 7) reflecting flood management by the dam. The number of independent flood events and their magnitude are lowered (Fig. 2, S4 and Fig. 3, S4, Table 7). However, the gradual controlled release of a flood from the reservoir means it lasts longer in the downstream reach (i.e., the released discharge is smaller but remains above the critical discharge longer than it would have in a natural regime).

Like for flood magnitude, the influence of the Settons dam on flood duration is significantly lower (Fig. 3, S2, Table 7). In fact, whereas the frequency of flood events is clearly reduced (Fig. 3, S2, Table 7), there are 7 out of the 21 complete years during which the number of "flooded"

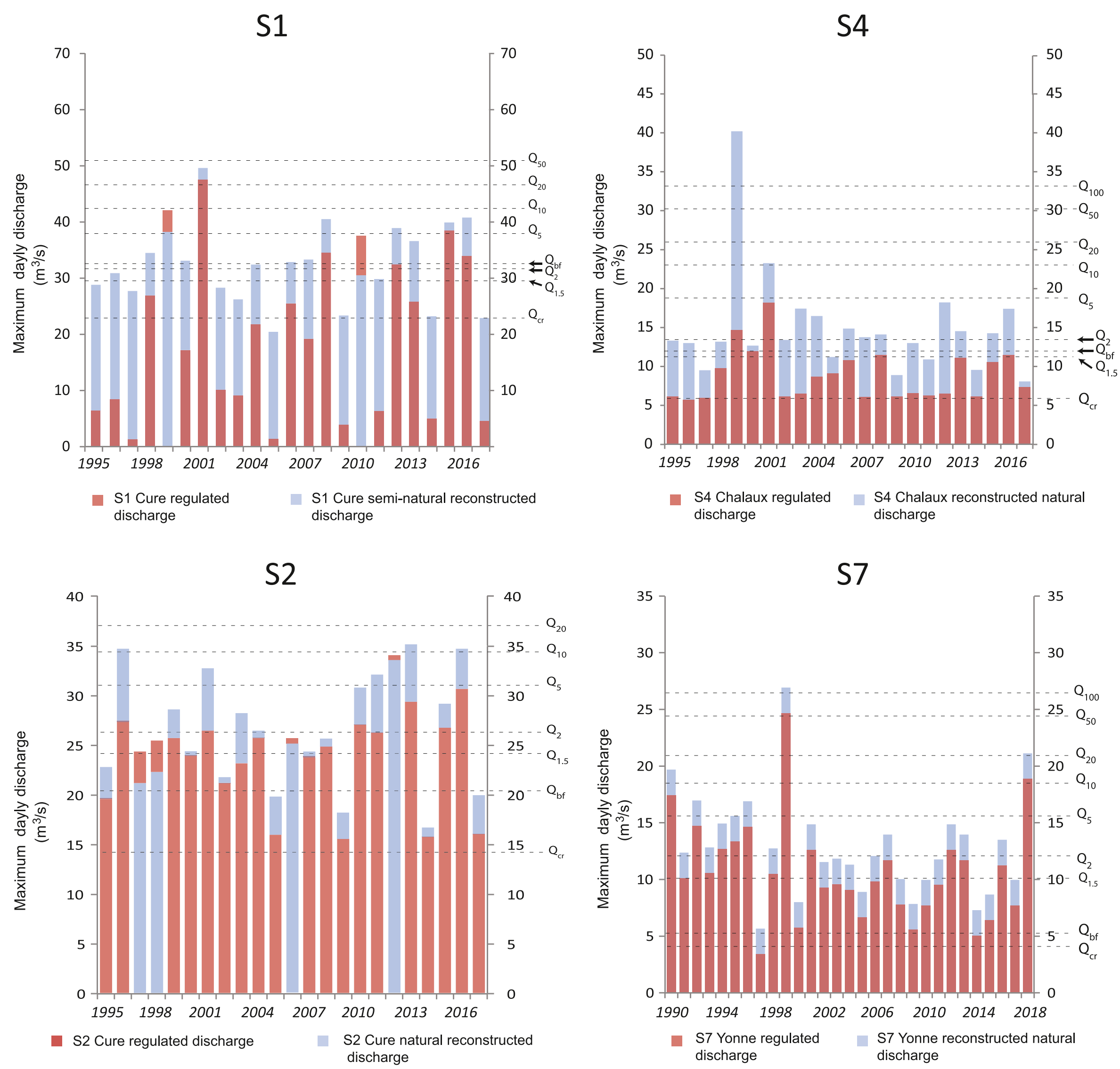


Fig. 2. Comparison of annual maximum floods for influenced and reconstructed natural discharge. The location of each study site (S1, S2, etc.) is shown in Fig. 1. Please note the differences in the discharge scale in the graphs. $Q_{1.5}$ ....Q_{100} = 1.5-year flood … 100-year flood; Q_{cr} = Critical discharge for bedload mobilization; Q_{bf} = Bankfull discharge.

Table 6
Influence of the dams on the frequency and duration of annual maximum floods according to flood intensity.

	Crescent		Chaumecon		Settons		M.Blondelot	
	Frequency	Duration	Frequency	Duration	Frequency	Duration	Frequency	Duration
Very large and exceptional event (>Q10)	No change	No change	Disappearance	Disappearance	Decrease	No change	Slight decrease	No change
Large events (Q10, Q5)	Decrease	Decrease	Disappearance	Disappearance	Decrease	No change	Slight decrease	No change
Medium events (Q2, Q1.5)	Marked decrease	No change	Decrease	No change	Slight decrease	Slight increase	Decrease	Decrease
Small events (Q1, Qcr)	Marked decrease	Decrease	Slight decrease	Increase	No change	Slight increase	Slight decrease	Decrease

days with regulated discharge is slightly higher than with natural reconstructed discharge (Fig. 3, S2). Although the difference in duration is generally slight, it nevertheless means that some of the (less numerous) independent flood events last slightly longer than in a natural regime.

PDS analysis at the long time scale confirmed the major influence of the Crescent and Chaumecon dams on the flood regime, as well as the moderate impact of the Settons dam. It also highlighted more clearly the specific influence of the Moulin Blondelot dam on the exceedance of the critical discharge. The dam considerably reduces the cumulative flood duration and prevents a significant absolute number of flood events from occurring (Fig. 3, S7, Table 7). However, its relative impact remains lower than that of the Crescent or Chaumecon dams, because a significant number of independent floods are still allowed by the dam

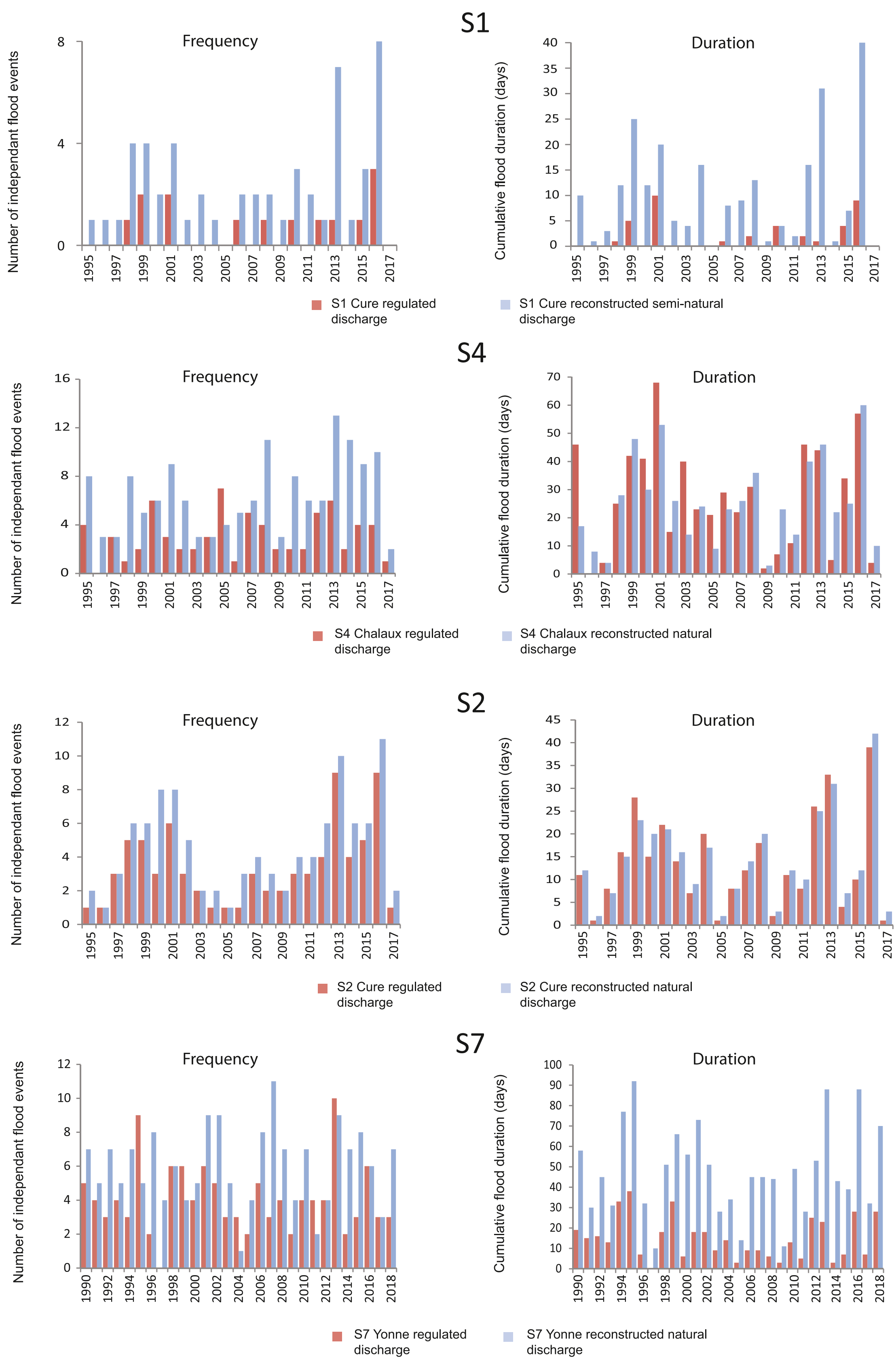


Fig. 3. Frequency and duration of the flood events in the case of influenced and reconstructed natural discharge. The location of each study site (S1, S2, etc.) is shown in Fig. 1.

Table 7
Influence of the dams on the frequency and duration of flood events.

	Crescent	Chaumecon	Settons	M. Blondelot
Percentage reduction in the number of independent flood events, based on the total number of independent flood events over the entire period	73.5	52	27	32
Average number of independent flood events prevented (per year)	1.7	3.3	1.2	1.9
Highest number of independent flood events prevented in a year	6 (2012)	9 (2014)	5 (2000)	8 (2007)
Percentage modification of the total flood duration (negative = reduction; positive = increase)	−84	+5	- 5	−69

due to its limited attenuation capacity, and also to the more intense natural flood regime (S7 is the site with the most reconstructed natural flood events).

4.2. *Bed substrate (grain-size, packing, sorting) around the dams*

The consequence of the discharge disturbances is visible in the bed substrate in the vicinity of the dams. Figs. 4 and 5 show micro-scale morpho-sedimentary characteristics indicative of sediment supply and bedload transport activity.

4.2.1. *Substrate characteristics above the dams (S5, S6) (non-regulated reaches)*

S5 (Chalaux) and S6 (Yonne) sites (Fig. 4E and 5) are the two sites located upstream of all dams. The substrate is relatively homogeneous (GSSI ≤3.1 and ≤6.2 respectively) and the bed particles are not constrained by stable bed structures. At these sites, no consolidated clusters or armoring process are observed. Their substrate also have the lowest D_{50} (0.080 mm for S5, 0.074 mm for S6) and D_{84} (in the same order, 0.142 and 0.105 mm) (Fig. 5, Table 2) despite their upstream location on their respective rivers. At these sites, the river bed is flat and the medium-sized sediment load is abundant. The same configuration is also found on the tributaries of the Cure that are not truncated by dams and has been shown to be a consequence of the multi-century log driving industry that took place in the Morvan massif (Poux et al., 2011; Jacob-Rousseau and Gob, 2020). This is also an indication of what the morpho-sedimentary conditions were in the rivers of the Morvan middle valleys before the construction of the dams (space for time substitution).

4.2.2. *Substrate characteristics on reaches <5 km downstream of medium-sized dams (S7, S8)*

S7 Yonne site (Fig. 4F) is located downstream of the Moulin Blondelot dam in a steep and confined reach, which helps explain the relatively coarse D_{50} and D_{84} of the riverbed (108 mm and 247 mm, Table 2). However, no highly protruding large grains or consolidated clusters are visible, and the grain size distribution remains homogeneous (Table 2 and Fig. 5, GSSI = 6.5). No small cobble and pebble deficits are observed (Fig. 4F). Based on what was described at the S6 study site (2.5 km upstream), the quantity and exposure of this available bedload shows the sediment continuity through the Moulin Blondelot dam located 300 m upstream. At S8, 1.3 km below the Pierre Glissotte dam, which has since been removed, the substrate presents neither an armored bed nor a very consolidated structures (Fig. 4F). Like at S7, there is no deficit of medium grain-sized sediment and existing large cobbles or boulders do not protrude significantly from the surrounding smaller particles.

4.2.3. *Substrate characteristics on reaches <20 km downstream of large dams (S1, S3, S4)*

The characteristics of the bed substrate of another group of sites are completely different from those of the two previous groups. This group is composed of the downstream sites located relatively close to the large dams on the Cure and Chalaux rivers. At these sites, bed coarsening and a deficit of medium grain-sized sediment is observed. These two conditions are accompanied by morpho-sedimentary configurations (armoring, consolidated clusters, imbricated structures) that indicate weak past mobility of the particles forming the bed.

At S3 Cure site, located 18.2 km below the Settons dam, very wide grain-size distribution (the second largest GSSI = 17.2) and the lack of medium-sized particles (small cobbles and pebbles), is easy to see (Fig. 4C and 5, D_{50} = 265 mm). Very stable interlocked particles between boulders and bedrock outcrops are also visible (Fig. 4C). The configuration is not strictly a pavement or a static armor because the smaller particles are not covered by the coarsest elements. They are in the surface layer too (in fact there is no clear subsurface layer at this site) but hidden/sheltered by neighboring larger particles. These medium-sized sediments (from cobbles to granules) are imbricated in such a way that it is often impossible to separate them by hand. The black color of the particles and their poor abrasion (asperities of the particle are easily visible) are also notable (Fig. 4C).

At S1 Cure site, located 2.4 km below the Crescent dam, a similar deficit of medium-sized sediment (D_{50} = 261 mm) and wide grain size distribution (GSSI = 22.7) can be observed compared with S3 (Fig. 4A, C and 5, Table 2). However, the few medium-sized particles that are present are generally not imbricated like they are at S3 (Fig. 4C).

An almost sediment starved situation is also observed 6.1 km downstream of Chaumecon dam at S4 Chalaux site, where there are no inputs of medium grain-sized sediments comparable to groups S5–S6 and S7–S8 (Fig. 4D). A sort of stable armoring layer made of cobbles and some small boulders can be seen in some areas, with signs of their rare mobility, i.e. they are black in color, and moss grows on the surface exposed to the flow (Fig. 4D). The same signs of limited mobility can be observed - but less homogeneous - in areas where there is no armoring layer. Here, it is interesting to note that the features (moss, black color of the sediments) are also observed immediately downstream of the Crescent dam. At S4, the deficit of medium grain size fractions in the sediment load is particularly noticeable compared with the substrate at the Chalaux site (S5) located upstream of the Chaumecon dam (Fig. 4E and 5). This sediment deficit and bed coarsening makes the riverbed at S4 more homogenous and coarser than at the upstream S5 site (GSSI = 6.2 and 5 for S5 and S4 respectively, Fig. 5, and D_{84}, D_{50} and D_{16} are all higher at S4, Table 2).

The morpho-sedimentary configurations (substrate coarsening, a deficit of medium grain-sized sediment, an armor layer, consolidated and imbricated structures) at these three sites very likely result from the reduced sediment supply and attenuated flood regime (for S1 and S4) caused by the large dams.

4.2.4. *Substrate characteristics >30 km downstream of a large dam (settons) (S2)*

S2 is regulated by the Settons dam but is located 15 km farther downstream than S3 (Fig. 1B). Even if the substrate is coarse (D_{50} = 133 mm, Table 2), at S3, we did not observe the same lack of medium grain-sized fractions and the same heterogeneity (GSSI = 4.4) (Fig. 4B and 5). In addition, the boulders do not protrude as much, although they do protrude sufficiently to hide cobbles and pebbles (Fig. 4B). Moreover, at S2 Cure site we observe pebble clusters (Fig. 4B) like those found in the Yonne river (Fig. 4F). The clusters are sometimes slightly imbricated but way less consolidated than the stable imbricated structures observed at S3 (Fig. 4C) and there is no noticeable black color on the particles. These pebble clusters often developed against very stable large cobbles or boulders.

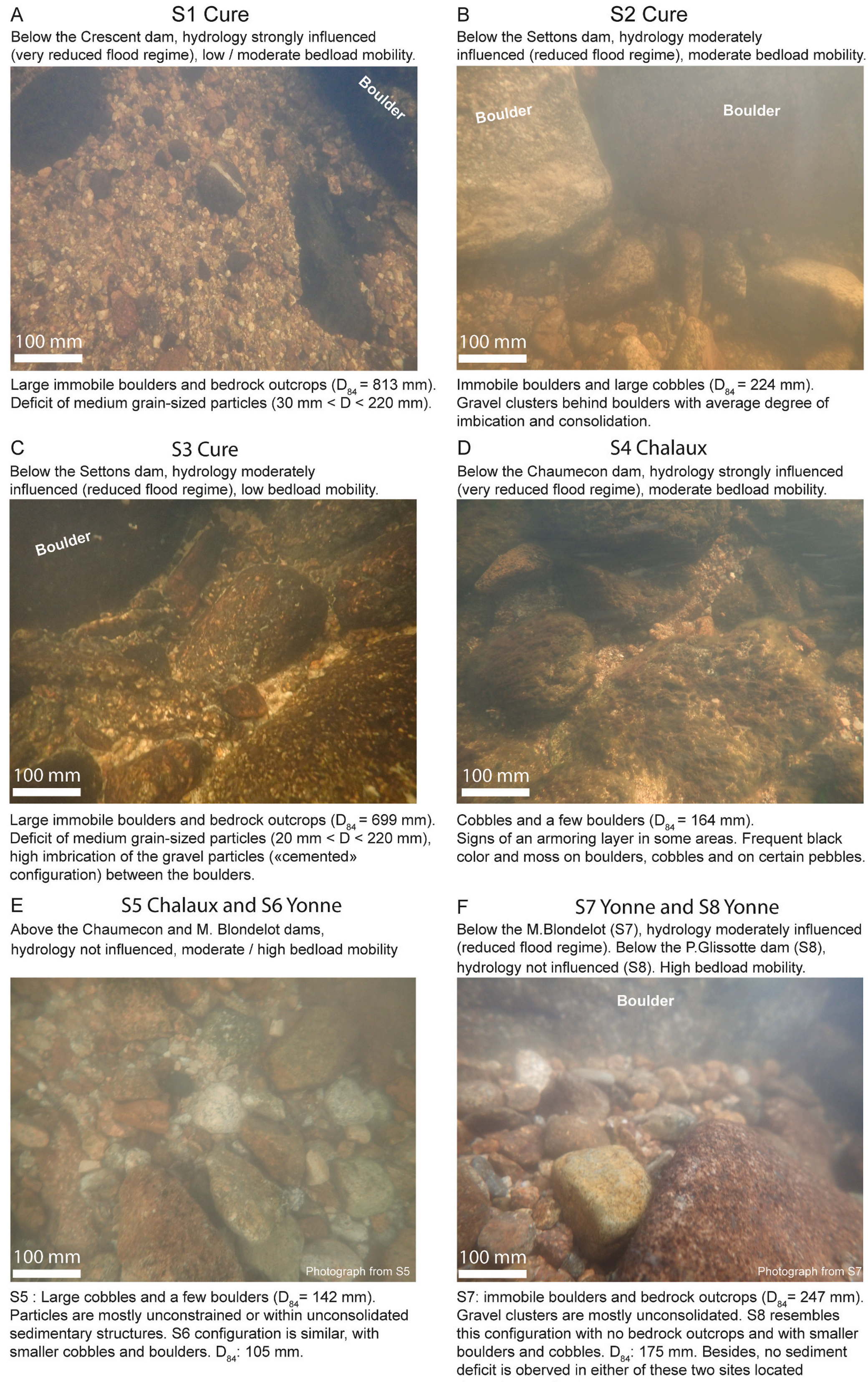


Fig. 4. Characteristics of the river bed substrate at the study sites.

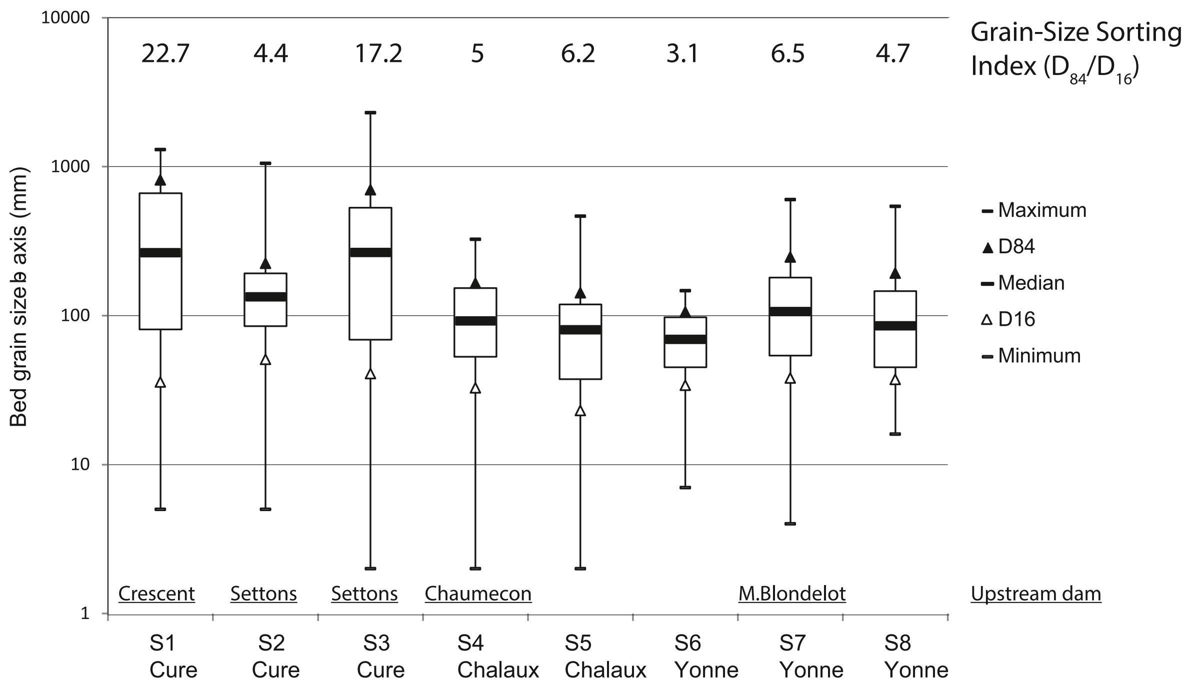


Fig. 5. Characteristics of the grain size distribution at the study sites.

4.3. Long-profile evolution and transversal planforms

Fig. 6 shows the change in the river's long-profile few kilometers downstream of the different dams (but not necessarily in the immediate downstream reach). Most of the historic long-profiles were surveyed in 1933 (only a limited section downstream of the Crescent dam was surveyed in 1930, s), meaning that, except for the Settons dam (built in 1858), the dams still have not had the time to significantly modify the longitudinal profile of the rivers (the construction of the Chaumeçon dam was completed in 1933, that of the Crescent dam in 1932, and that of the Moulin Blondelot dam in 1927, Table 1). It should also be noted that the error bars on the historic long-profile correspond to the total error margin, not only to the uncertainty calculated for the historic profile.

No significant generalized vertical evolution is clearly visible below the large dams of the Cure and Chalaux rivers but some incised reaches can be seen. For instance, 1 km downstream of the Settons dam (Fig. 6.1), the bed degradation may be a local response to the reduced sediment supply caused by the Settons dam. The low density of surveyed points on the historical long-profile downstream of the Crescent dam (Fig. 6.3) makes the comparison with current data more difficult. However, there is a noticeable incision near the Lingoult mill (0.5 m above the error margin at the point surveyed in 1933), and the incision is followed by a local aggradation downstream of the new Chastellux bridge.

Below the Moulin Blondelot dam, the long-profile of the Yonne shows no incision but does show aggradation on its most downstream part in the tail of the former Pierre Glissotte reservoir (Fig. 6.5). The vertical stability observed in the Chalaux river downstream of the Chaumecon dams must also be underlined (Fig. 6.4). The same vertical stagnation is visible in the Cure river downstream of Montelesme bridge (Fig. 6.1).

The limited incision of the rivers in Morvan below the large dams may suggest that the response was rather through lateral erosion. However, it should be noted that the banks of these rivers from middle valleys have been protected (rip-rap) on an important part of the river course (more than 70% at our study sites) to facilitate log driving between the mid-16th and early 20th centuries. Potential lateral adjustment of the rivers was therefore limited. Nonetheless, an interesting evolution of the cross-section can be observed at S1 Cure site and more generally in the by-passed reach downstream of the Crescent dam (Fig. 7), particularly in comparison with S4 Chalaux site located below the Chaumecon dam (Fig. 8).

The survey of the river bed shows that channel bed at low flow is narrower than it used to be before the dam was built (Fig. 7). Trees are indeed able to grow in areas that were immerged before the flow was regulated.

Generally, some patches with grass and trees tend to stretch out the floodplain in what used to be the riverbed (Fig. 7). Some "isolated" trees, apparently disconnected from the floodplain, also grow in the wet river bed. All these observations are evidence for the stability of the deposit on which the vegetation is growing.

S4 Chalaux site is located below a large dam that strongly attenuates the flood regime (Figs. 2 and 3, Tables 4–7). However, small and medium floods are more frequent than at S1 (Figs. 2 and 3, Table 6), and the reach is regularly supplied through water releases (≈5 m^3/s) well above the reconstructed mean annual flow (2.8 m^3/s) (Table 2). This management coincides with an armoring process (section 4.3, Fig. 4D) but maintains a current low flow width close to the pre-dam one (Fig. 8). This also prevents vegetation encroachment, as at S1, and a significant increase in flow resistance. Nonetheless, in a few areas, stabilization of the bed substrate tends to facilitate the development of herbaceous vegetation on shallow fine patches (granules, sand) deposited on top of pebbles and cobbles (Fig. 8).

Finally, through a direct influence (hydrology and sediment supply, bedload transport) or through the textural and larger morphological adjustments they entail, the large dams have led to major stabilization of the substrate but also to a sort of closure of the riverbed in vertical and lateral dimension (vegetation encroachment). These closures also help stabilize the channel and bedload dynamics.

4.4. Bedload displacements around dams

4.4.1. A specific influence of each dam on the reduction of the flood regime during our bedload monitoring

Fig. 9, Table 8, and Fig. 10 reveal the variety of ways the flood regime is influenced depending on the upstream dams during the period of bedload monitoring (2014–2017). At this time scale, the effects of the

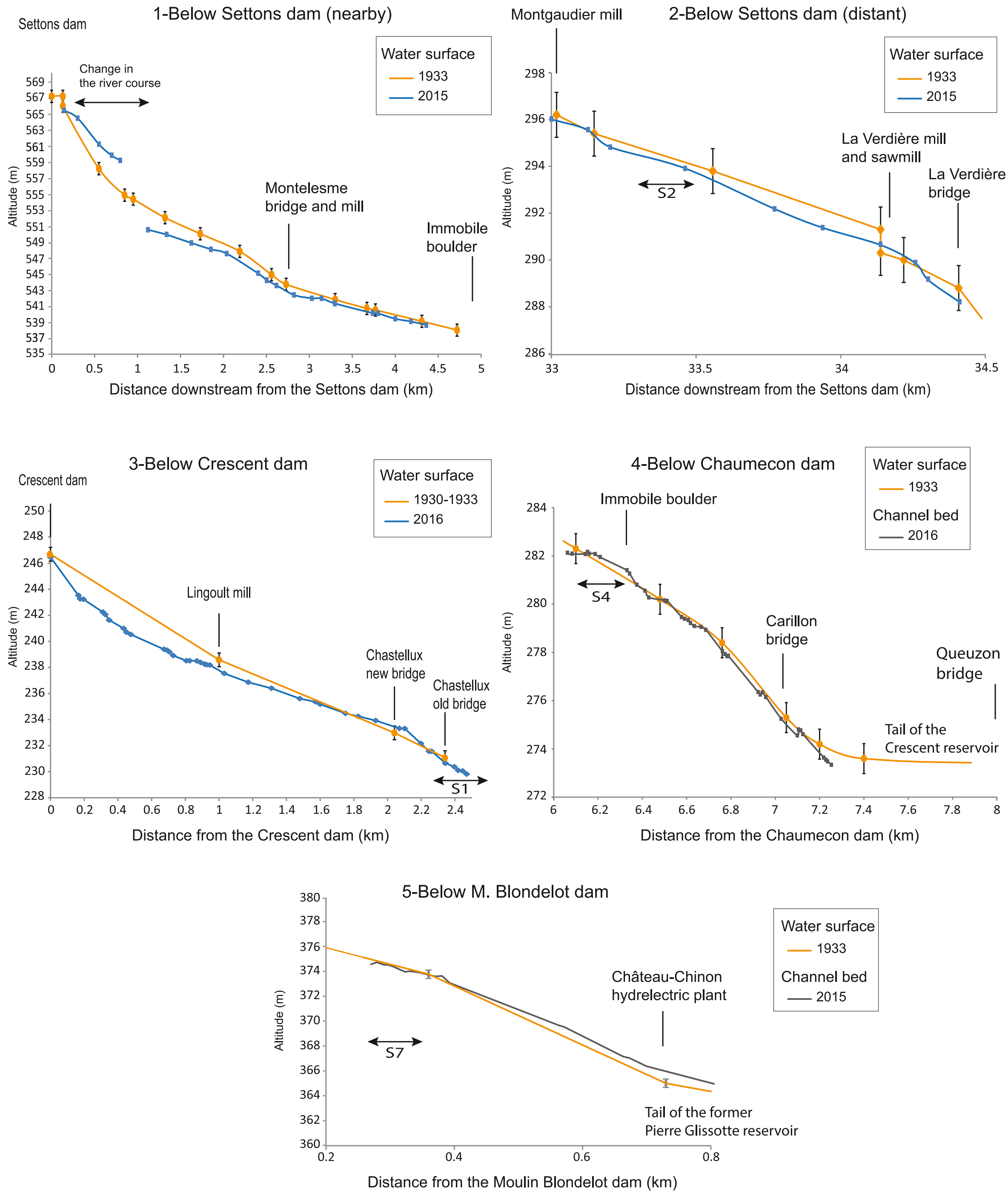


Fig. 6. Comparison of historical and current partial long-profile below the dams (Please note, the scale of the horizontal and vertical axes are not the same in all the graphs).

dams appear to be in line with the impacts described at a longer time scale in section 4.1.

S1 and S4 clearly show a reduction in the frequency and magnitude of the flood events under the current management of the Crescent and Chaumecon dams (Fig. 9). At S1, the frequency of independent flood events is reduced by 75% and their cumulative duration by 95% (Table 8), leaving only 3 full days above the critical discharge. Only one very big flood (>10-year flood), in May 2015 (57 m^3/s), is close to and even higher than the reconstructed semi-natural discharge (47 m^3/s) downstream of the Crescent dam (S1). Graph S1 (Fig. 9) also underlines the uniformity of the base flow in the by-passed Cure reach (S1), and its low value compared with the reconstructed semi-natural regime and its mean annual discharge (9.5 m^3/s). Examination of the cumulative frequencies shows that the discharge is less than 6.8 m^3/s for 95% of the study period, and less than 1.07 m^3/s for 80% of the study period.

Because of hydropeaking, variations in discharge downstream of the Chaumecon dam (S4) are much more frequent than downstream of the Crescent dam (S1) (Fig. 9). However, uniformity can be noted in the pattern of timing (speed and occurrence of the flow increase and flow decrease each day) and in the peak discharge (near 5 m^3/s) reached by the water releases (excepting water releases due to flood events). The modification of the summer low-flow regime caused by almost daily water releases is also clearly visible. In July and August 2015, the real mean discharge was 1.39 m^3/s whereas the reconstructed natural flow

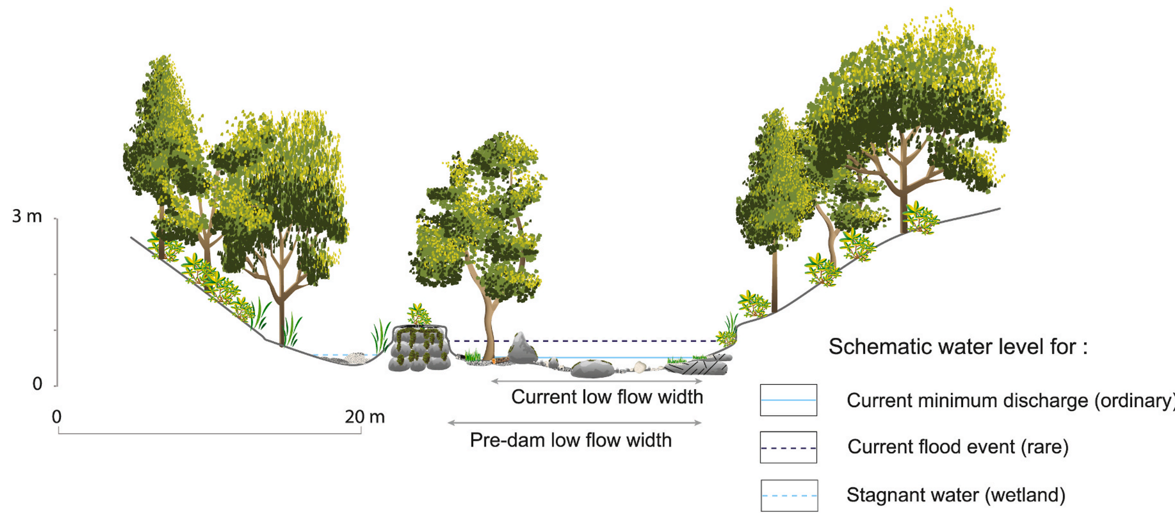


Fig. 7. Example of cross-sectional morphology in the by-passed Cure reach (downstream of the Crescent dam).

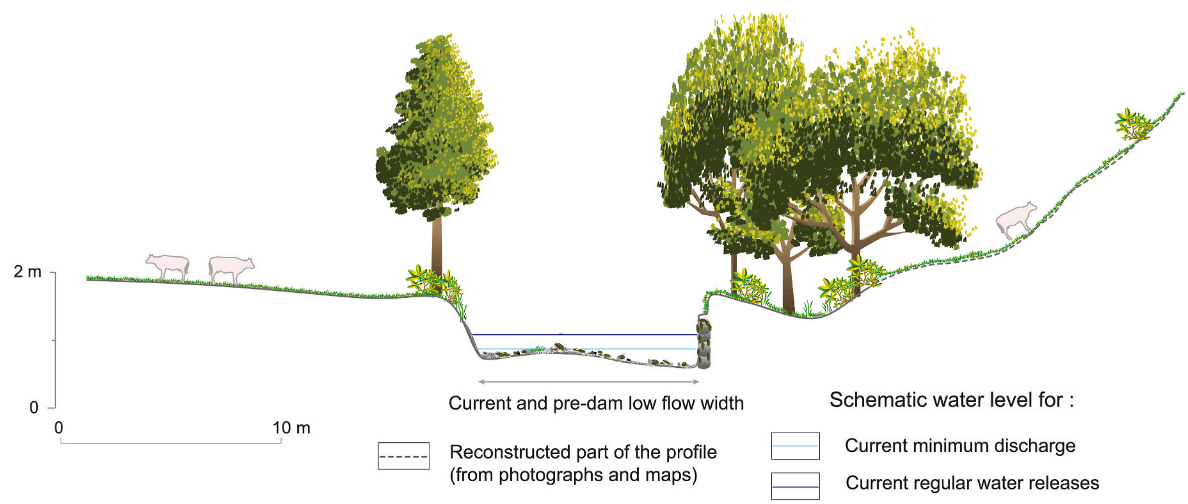


Fig. 8. Example of cross-sectional morphology downstream of the Chaumecon dam.

Table 8
Reduction in the flood frequency and flood duration due to flow regulation (August 2014–April 2017).

Site, river and upstream dam	S1-Cure Crescent	S2-Cure Settons	S3-Cure Settons	S4-Chalaux Chaumecon	S7-Yonne M. Blondelot
Reduction in the number of independent flood events (%)	75	17	25	54	15
Reduction in flood duration (%)	95	13	27	40.5	63.5

suggests a mean discharge of 0.27 m^3/s.

Like in the Cure S1 reach, the two biggest flood events downstream of the Chaumecon dam during our bedload monitoring period occurred in May 2015 and June 2016 (Fig. 9). At the beginning of May 2015, a reconstructed flood event peaking at 19.7 m^3/s was only moderately retained by the dam since the real recorded discharge reached 13.9 m^3/s. In June 2016, the attenuation of the flood by the dam was greater: the recorded peak discharge represented only 52% of the reconstructed natural peak (26.6 m^3/s). The Chaumecon dam was also responsible for significant decrease in flood frequency and cumulative flood duration: more than half of the flood events are “cancelled” or at least sufficiently reduced to not exceed the critical threshold, and the number of flooded days is reduced by 40.5% (Table 8).

S3 (Fig. 9) confirms the more limited impact of the Settons dam on the magnitude of the flood discharge along the downstream reach. Many flood peaks are only weakly attenuated with sometimes a released discharge that is even slightly higher than the reconstructed natural discharge. However, during our bedload monitoring period, the 5 largest flood events occurring in the series of reconstructed natural discharge (between 21,6 m^3/s and 28.45 m^3/s) are still reduced by an average of 22% by Settons dam. The maximum decrease was achieved for the flood event in late June 2016: the regulated peak discharge (19.5 m^3/s) reached only 68.5% of the reconstructed natural peak (28.45 m^3/s). The more moderate impact of the Settons dam is also reflected in the relatively small reduction in flood frequency (17–25%) and in flood duration (13–27%) caused by the dam (Table 8).

The Moulin Blondelot dam on the Yonne river (Fig. 9. S7) does not artificialize the discharge regime in the same way as the Crescent (S1) and Chaumeçon (S4) dams. The lessening of the peak flood discharge is moderate, due to its limited storage and diversion capacities, the relative impact of which decreases with an increase in the magnitude of the

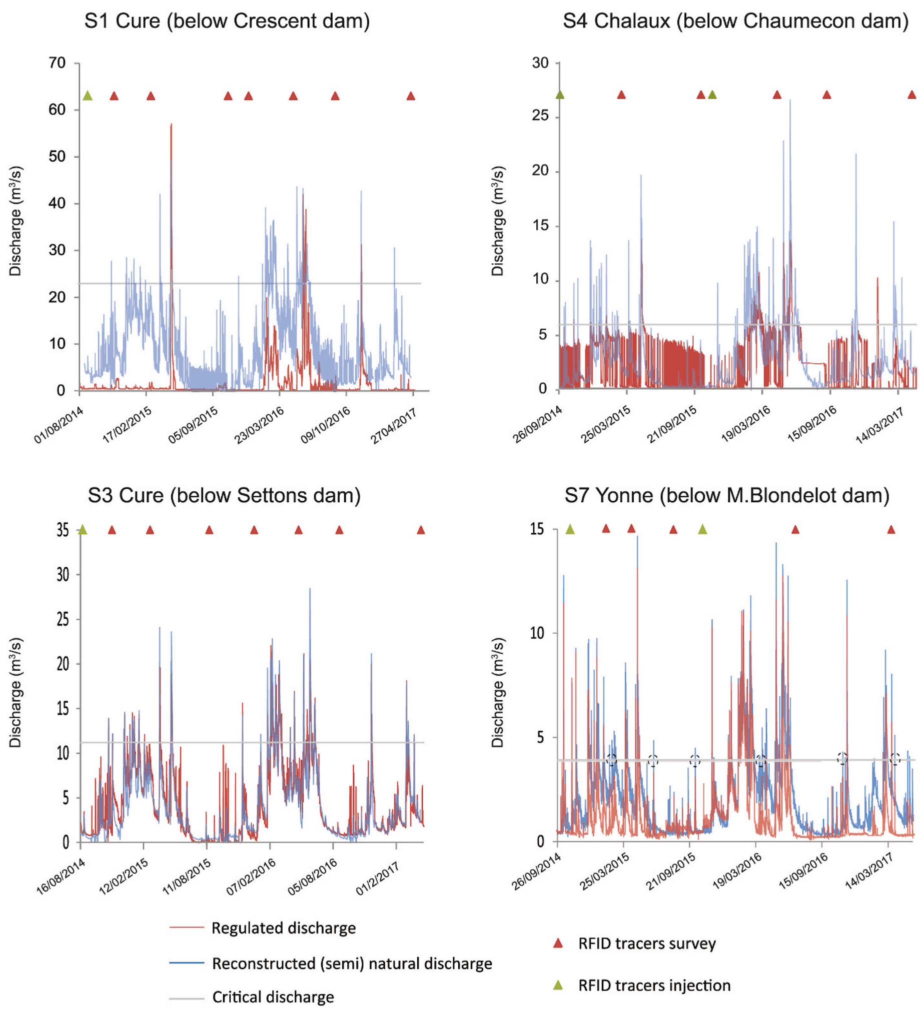


Fig. 9. Regulated discharge and reconstructed natural discharge at S1 Cure, S3 Cure, S4 Chalaux, S7 Yonne during the course of the study. S1, S4 and S7 show instantaneous discharge, S3 shows mean daily discharge.

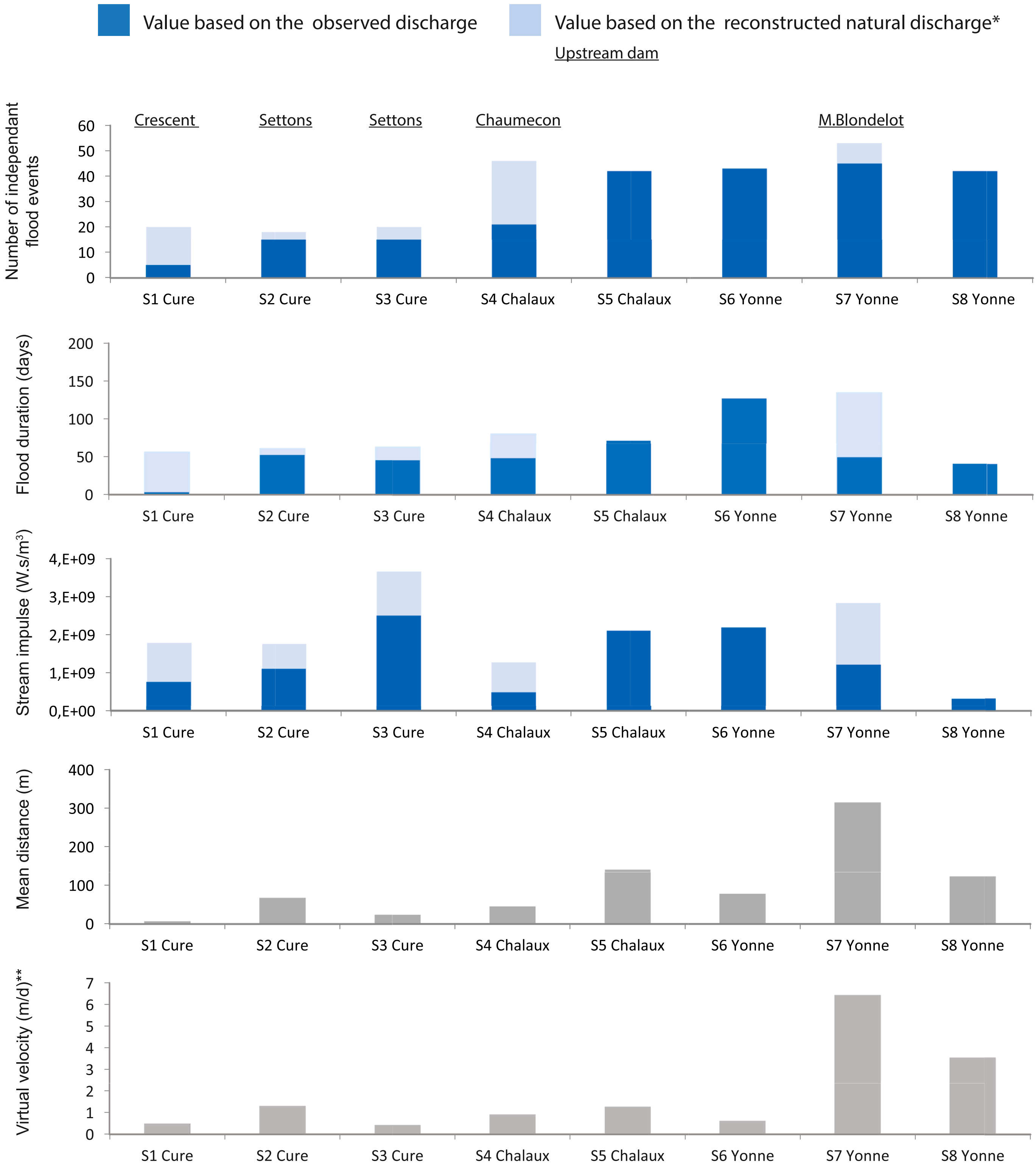
flood. Thus, in the reconstructed natural flow series, for the five largest floods that occurred during our bedload monitoring (between 14.4 and 12.5 m^3/s), the reduction in the peak discharge caused by the dam averages 12%. However, for several small and medium flood events, the discharge remains below the critical threshold (black dotted circles on the S7 graph, Fig. 9) or does not remain above it for as long because of the influence of the dam. This does not affect the frequency of flow events much (only a 15% decrease), but significantly alters the cumulative flood duration, which is reduced by 63.5% (Table 8). It should also be noted that the influence of the dam is less obvious in the 2015–2016 winter season as the flow was not diverted during this period due to maintenance works on the dam. Finally, as the S7 reach is located in a by-passed section, the discharge at low flow also tends to be lower than the reconstructed natural discharge (Fig. 9, S7): in July and August 2015, the mean regulated discharge was 0.310 m^3/s whereas the mean reconstructed natural discharge was 0.783 m^3/s.

4.4.2. Transport data for the overall study duration and at the inter-survey timescale

The reduction in the frequency, magnitude and total duration of flood events (Fig. 9, Table 8) brought about by the dams helps reduce the cumulative stream impulse in the regulated reaches by 32 (S3) to 61% (S4) (Fig. 10). In a given river, the stream impulse is lower than that of the sites located upstream of the dams (S5, S6). However, the consequences for bedload transport appear to be very different and neither the cumulative and inter-survey bedload data perfectly match the hydrological disturbances (Figs. 10 and 11).

4.4.2.1. Bedload transport upstream of the dams (S5, S6). With no flood control, S5 Chalaux site and S6 Yonne site present a high cumulative stream impulse (Fig. 10). This time-integrated energy variable contributes to the important cumulative mean distance, 141 m at S5 and 78 m at S6 (Fig. 10 and Table 9). It should be added that the S6 bedload mean cumulative distance is almost certainly underestimated because of difficult and uncomplete PIT tag survey conditions beyond 120 m (it also explains the lower virtual velocity, 0.62 m/d for S6, whereas it reaches 1,27 m/d at S5). Otherwise it would be equally – if not more - dynamic than S5, as suggested by the bedload distance per inter-survey period (Fig. 11).

4.4.2.2. Bedload transport in reaches <5 km downstream of medium-sized dams (S7, S8). Despite a low to moderate cumulative stream impulse (which at S7, is greatly reduced by the Moulin Blondelot dam), S7 and S8 present the longest mean cumulative distance (respectively 315 and 123 m) and highest virtual velocity (respectively 6.44 m/d and 3.55 m/d). The same upper bedload transport activity can be seen at S7 and S8, for a comparable range of stream impulses when mean distances per inter-survey period are considered (Fig. 11). Nonetheless, the S8 stream impulse could be slightly underestimated (in Figs. 9 and 10) because of slight overestimation of the critical discharge. The river scoured a part of its reach at this site, hence critical discharge is possibly a little under the threshold we used (0.7 bankfull discharge, section 3.2). This explains the



* Reconstructed discharge is semi-natural for S1 Cure (only the Crescent dam's influence has been removed).
** Based on cumulative mean distance and cumulative flow competence duration.

Fig. 10. Cumulative stream impulse and mean cumulative displacement of bedload tracers over the whole duration of the study. *Distance and velocity values are based on the results of the last monitoring survey only and the mean values include tracers that did not move.*

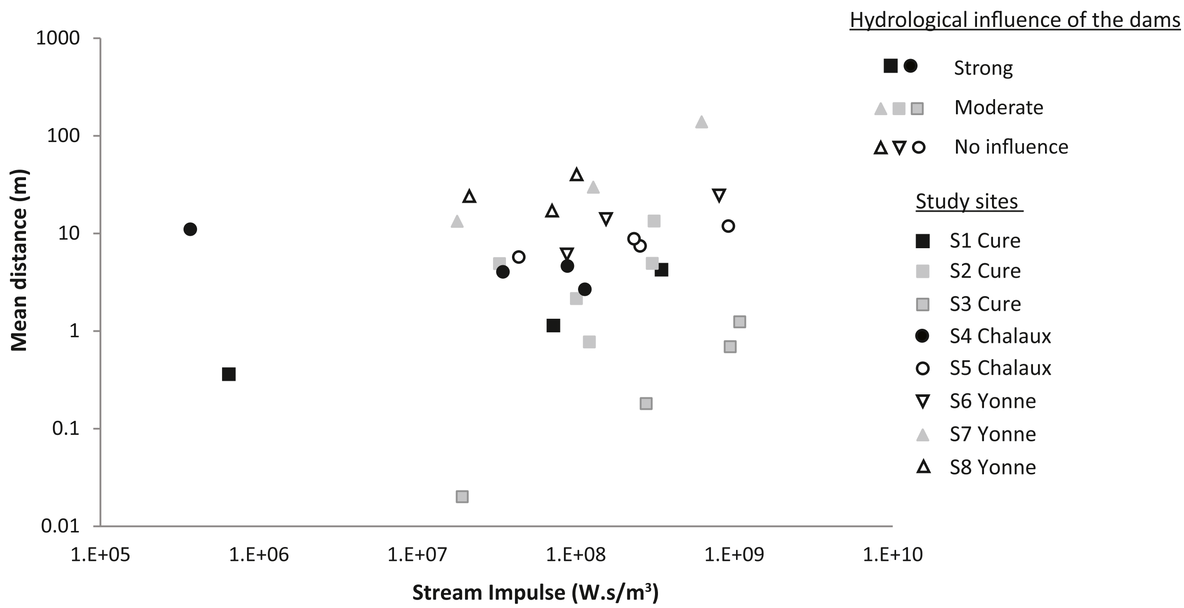


Fig. 11. Relationship between the mean distance (per inter-survey period) and the stream impulse.

Table 9
Cumulative data on bedload transport in Morvan rivers.

Site and river	S1-Cure	S2-Cure	S3-Cure	S4-Chalaux	S5-Chalaux	S6-Yonne	S7-Yonne	S8-Yonne
Mean distance (m)	6.8	67.5	24	45	141	78	315	123
Mean velocity (m/y)[a]	2.5	25	9	17.3	55	33	132	50
Max velocity (m/y)[b]	31.9	162	143	123	212	101	294	179
Mean virtual velocity (m/d)[c]	0.49	1.30	0.42	0.91	1.27	0.62	6.44	3.55
Di_{max} mobilized (mm)	129	144	139	166	128	148	175	122
D_{50} tracers (mm)	67	62.5	70	45	58	69.5	58	68
Mobilization rate	0.49	0.69	0.50	0.67	0.80	0.91	0.97	0.94

[a] Based on the cumulative mean distance and the whole duration of the study.
[b] Based on the cumulative maximum distance and the whole duration of the study.
[c] Based on the cumulative mean distance and the whole flow competence duration (= flood duration in this study).

possible overestimation of the virtual velocity of S8 tracers, due to underestimated flow competence duration.

Bedload transport at S7 might be slowed down by the Moulin Blondelot dam's influence on the flood regime (Fig. 9, Table 8 and Fig. 10), and the bedload distance would perhaps be even longer without the dam. However, the hydrological influence of the dam cannot be said to threaten bedload mobility.

4.4.2.3. Bedload transport <20 km downstream of the large dams (S1, S3, S4). Bedload transport downstream of the large dams located on the Cure and Chalaux rivers is generally less intense. S1 Cure site has a low mean distance (6.8 m) which is not surprising considering its low stream impulse (Fig. 10, Table 9). Here the massive reduction of the flood regime by the upstream Crescent dam may contribute directly to the low bedload mobility. The mean distance is nonetheless much shorter than at S7 and S8 Yonne river sites at a comparable stream impulse (S8 in particular), even when bedload distance per inter-survey period is considered (Fig. 11). Incorporated in the stream impulse, the flow competence duration of S1 ("flood duration" in Table 8 and Fig. 10) is the lowest of all sites (which also explains the virtual velocity of 0.49 m/d, which is not that low compared to the other sites). This low flow competence duration is logical considering the rarity of flood events at S1 (Figs. 9 and 10, Table 8). Thus, the fact that S1 Cure site has a cumulative stream impulse that is close to that at S7 and S8 Yonne sites despite a largely lower flow competence duration, shows that the excess energy at this site is very high considering the small number of flood events that occurred (Fig. 9. Table 8). However, the low cumulative distance at S1 suggests that the frequency of flood events is as important as their intensity for long-term bedload displacements. The effect of reduced flood frequency may not be the only explanatory variable. On a shorter time scale, i.e. that of the inter-survey period, when this effect may be attenuated, the bedload mean distance at S1 remains low or very moderate (Fig. 11). The fact S1 data are in the low tail end of the "intermediary group", composed of S2, S5 and S6, indicates that when energy is available for sediment transport, particles move (Fig. 11). They do not move as much as at most of the other sites, but they still move farther than those at S3 Cure site at a comparable or lower stream impulse (Fig. 11).

S4 Chalaux site presents a surprisingly long cumulative mean distance (45 m) relative to its low cumulative stream impulse (Fig. 10). With a lower stream impulse, its mean virtual velocity (0.91 m/d) is for instance higher than that at S1 and S3 Cure sites (0.49 m/d and 0.42 m/d) and the S6 Yonne site (0.62 m/d, even if this rate is probably underestimated, as explained above). The reduction in the magnitude and frequency of flood discharge at this site (Fig. 9, Table 8) explains the low stream impulse compared to that at the S5 non-influenced Chalaux site, for example (Fig. 10). The active bedload mobility reflects the efficiency of the transport process at S4: bedload tracers appear to move whenever they have the opportunity (a flood event) and despite only moderate excess energy. In addition to a rather high cumulative mean distance for a low cumulative stream impulse (Fig. 10), an apparently negative correlation between mean bedload distance and the stream impulse at the inter-survey scale even appears (Fig. 11).

In contrast to S4, S3 Cure site presents a low cumulative mean distance (24 m) despite a markedly higher stream impulse (hence the lowest virtual velocity, 0.42 m/d) (Fig. 10). At this site, the moderate hydrological effect of the Settons dam is not followed by "proportional" bedload transport activity. It is also interesting to note that the cumulative stream impulse differs from that at S2 Cure site, located 15 km downstream, despite the same hydrological regime. Morphological features (slope, width) explain this different energy for a same hydrological influence (Table 2).

4.4.2.4. Bedload transport >30 km downstream of a large dam (settons) (S2). Tracers from S2 travelled a medium mean cumulative distance (67.5 m) despite a limited stream impulse, and their mean virtual velocity (1.30 m/d) was the third highest after the Yonne sites S7 and S8 (Fig. 10). Therefore, not only can the time integrated energy indicator (stream impulse) vary between two sites (S2 and S3) along a relatively short segment downstream of the same dam, but the bedload dynamics can also differ considerably.

Our analysis of current hydrological and energy conditions around the dams only partially explain the scattered bedload dynamics we recorded. In Gilet et al. (2020), we reported that morphological features (relative size, slope) represent other significant controlling factors that explain bedload movements.

5. Discussion

The current characteristics of the bed morphology and sediment structure (Figs. 4 and 5) show traces of the mobility/immobility trends in recent decades that are consistent with the degree of influence of dams on the flood regime and on the sediment supply on a long time scale (Figs. 2 and 3). Where the flood regime or sediment supply have been more significantly reduced (below large dams), we found the most stable and constrained morpho-sedimentary structures (S1, S3, S4) (Fig. 4). Where the influence of dams on flow and sediment supply has been moderate or absent, we observed loose sedimentary arrangements and significant sediment inputs (S5, S6, S7, S8). An intermediate situation (S2), with coarse substrate and variously consolidated clusters is found below a large dam (Settons) that only moderately disturbed the flood regime but significantly reduced the downstream sediment supply. The distance between S2 and the dam (33.3 km) explains its specific morpho-sedimentary conditions (e.g., no sediment structures related to sediment deficit).

The substrate characteristics inherited from 100 years of flow regulation and disturbed sediment supply influence the current entrainment and transport of bedload particles differently: S3 has the shortest bedload distances and S1/S4 low to medium mobility, whereas S5/S6 show medium to high mobility and S7/S8 have the longest bedload distances. At S2, an intermediate situation is again observed, with medium bedload distances.

5.1. The multiple influence of dams on flood regime and transport capacities

The magnitude and frequency of floods are relevant and widely used indicators (Assani et Petit, 2004; Wang et al., 2011; Xiong et al., 2019) and in our study, they turned out to be very instructive to measure in particular, the hydrological effect of the Crescent (S1) and Chaumecon dams (S4) (Figs. 2 and 3). However, our work on the Moulin Blondelot dam underlines the fact that it is also important to assess other parameters such as the flood duration or a time integrated energy excess indicator such as the stream impulse to render the hydrological impact of the dams more perceptible (Table 8, Fig. 10). The Moulin Blondelot example shows that a medium-sized dam (3.49 m high) with a permanent by-pass canal can significantly affect the cumulative flood duration while only moderately attenuating the intensity of flood events.

Our comparative study also highlights three main factors that determine the degree of influence of the dams on the flood regime and the mechanisms involved (intensity, occurrence frequency, flow duration): (i) the size of the dam and the related structures (reservoir, diversion canal) that determine its storage and diversion capacities; (ii) the functions of the dam (hydroelectricity production, flood control, low flow support), perfectly illustrated by the comparison between the Crescent and the Settons dams, two large dams with different uses and different hydrological consequences; (iii) the "natural" flow regime of the river on which the dam is located (Mori et al., 2018). Indeed, Crescent dam was built and operates to significantly reduce the magnitude and frequency of flood events, but its impact is all the greater because the natural flow regime of the Cure produces less frequent floods than the Chalaux and Yonne rivers. Conversely, the significant effect of the Moulin Blondelot dam on the flow competence duration and stream impulse (Fig. 10) has less impact on bedload transfer because a moderate amount of competent flow is still allowed by the dam (Fig. 10).

5.2. Morphodynamic processes in the long term influence of dams on bedload transport

Our results reveal the many different types of influence dams can have on bedload transport, both in the processes involved and in the time scale. The stream impulse presents a certain relationship with bedload distance, but is not sufficient to enable us to fully understand the different bedload dynamics we measured (Figs. 10 and 11). This observation supports the hypothesis that, alone, the current flood regime controlled by the dams, even if it differs, does not explain bedload displacements. On the same rivers, Gilet et al. (2020) emphasized, like many before them in other contexts (Petit et al., 2005; Mao et al., 2008; Gob et al., 2010; Houbrechts et al., 2012; Parker et al., 2011; Prancevic and Lamb, 2015; Lamb et al., 2017; Yager et al., 2018), that other hydro-morphological parameters (relative grain size, slope, flow depth) would also have a significant influence on bedload mobility. In the present study, we show that the presence of dams, in particular on the Cure and on the Chalaux, may have deeply modified the hydro-morphological characteristics of these rivers and hence also their transport capacity and bedload dynamics. Some of our study sites indeed present imbricated and armored structures, consolidated clusters, heterogeneous and coarse substrate, and vegetation encroachment that reduce bedload mobility (Figs. 4, 10 and 11); while in the other reaches sediment availability, relative substrate homogeneity, loose clusters highlight and favor more intense bedload displacements. The first conditions are often reported in the literature to occur in sediment-starved contexts and/or under a highly regulated flow regime (Kondolf, 1997; Petts and Gurnell, 2005; Grant, 2012). In the rivers studied here, it is therefore not surprising to find these conditions downstream of large dams (Crescent, Chaumecon and Settons).

The long presence of the Crescent, Chaumecon and Settons dams (from 93 to 156 years), acting as an obstacle to sediment transfer and the long term influence they have had on the flood regime (Figs. 2 and 3) have largely shaped the currently stable morpho-sedimentary conditions. Grant (2012) indeed underlined the frequent armoring or at least bed surface coarsening that occurs in the reaches below dams owing to changes in the water and/or sediment supply. In this regard, our results also provide evidence that, on the contrary, a medium-sized dam such as Moulin Blondelot can allow bedload connectivity, recalling the recent studies on sediment connectivity around weirs (Pearson and Pizzuto, 2015; Peeters et al., 2020; Casserly et al., 2020; Magilligan et al., 2021). The conditions of the Yonne river, with significant inputs of important medium-sized sediment (pebbles and cobbles) (Fig. 4E and F), inherited from the log driving era, do not appear to be disturbed by the dam.

Bed coarsening and armoring tend to stabilize the bed, not only by increasing the energy needed to move the particles of the subsurface layer (breakup of the armor), but also by increasing the proportion of large immobile and protruding grains in the bed. Those are shown to greatly favor the general stability of the substrate, to decrease the energy available to move finer particles and to indicate reduced sediment availability for transport (Yager et al., 2007, 2012; Mackenzie and Eaton, 2017). These processes directly echo what we observed downstream of the Chaumecon (S4), the Crescent (S1) and the Settons dam (S3) (Fig. 4). By extension, the imbricated/"cemented" structures, consolidated clusters, etc. that we describe can also be considered as being favored by the modification in flow regime as well as by the reduction in sediment supply (Venditti et al., 2017). The attenuation of the flood regime (Reid et al., 1985) and the bed coarsening partly caused by sediment starvation from dams can support the development of very stable medium and micro morpho-sedimentary features. The settlement and consolidation of these components is indeed greatly favored by the structuring and immobile coarse sediments (large cobbles, boulders) against/among/around which they develop (Petit, 1989; Church et al., 1998): this process is well established at S3 and appears to be underway at S4 (Fig. 4). Stable bed structures have even been shown to develop in parallel with the armoring process (Church et al., 1998; Venditti et al., 2017). A wide grain size distribution combined with the deficit of medium-sized fractions (obvious at S1 and S3, and starting at S4, Figs. 4 and 5) may also act in favor of the consolidation of the structures when small gravels and sand begin to settle durably and cement the interstitial spaces between coarser particles.

Ultimately, these different stable morpho-sedimentary configurations indicate weak past mobility of the particles that form the bed and may now act as stabilizing structures ("stability-promoting mechanisms", Church et al., 1998). Indeed, they appeared to reduce the bedload dynamics of our freshly introduced tracers, although these may slide or roll "on" it in the initial stage (S4) especially when no very coarse and protruding elements are present. This effect recalls what Vericat and Batalla showed in the case of the Ebro River downstream of the Flix dam (2007). Bed coarsening due to a limited sediment supply and downstream evacuation of fine and medium-sized particles entailed an armoring process. This process modifies sediment entrainment conditions by increasing particles hiding by larger grains. The mobilized grains are then moved with a dimensionless shear stress that diminishes with an increase in their size, reducing the sheltering effect. However in the regulated Ebro River, the armor layer does not seem to be as solidly established as the morpho-sedimentary configurations we describe here (Vericat and Batalla (2007) notably underline an "armor reformation" process). Also, a solidly armored riverbed can favor incoming bedload mobility when the bed is particularly flat and hermetic (Gilet et al., 2021).

Our study shows that the impacts of dams on downward bedload transport rely on a complex pattern of interactions and feedback between water and/or sediment supply and fluvial morphology, the latter being itself gradually shaped on a longer time scale by the flow and bedload transport. At S4, the gradual shaping of new geomorphic conditions (bed armoring) may first have reflected the active transport of the finer gravel particles (selective downstream mobility). However, the more the development of the armoring structure advances, the less the finer gravel particles would be mobilized (vertical winnowing), as already suggested by the moss colonizing hidden particles and small particles in the bottom of the substrate (Fig. 4D). At S1, below the Crescent dam, the ongoing vegetation encroachment on the active bypassed river bed will continue to modify general hydraulic flood conditions (increased rugosity, back waters), cause local accumulation of wood debris and create low flow energy areas where sediments will be deposited and less easily remobilized in the future (Fig. 7). The lack of medium-sized sediments has made the numerous boulders protrude even more. These very coarse elements help reduce bedload distances at S1 by generating hiding effects and flow resistance (Gilet et al., 2020).

Below the Settons dam, the poor to moderate mobility observed today is mostly due to the coarse bed surface (that also favors imbricated structures) partly due to the reduced sediment supply and perhaps to an initially enhanced flood regime in periods of log driving (evacuation of medium-sized sediments) (Héry, 2015). A pre-dam incision favored by straightening and bank rip-rapping (mainly implemented for log driving) may also have exposed the underlying coarse particles. Poeppl et al. (2015) and Vázquez-Tarrío et al. (2019) also underline the increased complexity of geomorphic response to dam construction and dam removal when other engineering structures (channel and bank protections, other dams) produce additional interactions in fluvial processes.

5.3. *Gradual "immobilization" of the rivers?*

The limited evolution of the long profile (in a context of limited lateral mobility due to rip-rap) and the stabilization and deficit of medium-sized alluvial substrate below large dams raise several specific issues for river restoration. Indeed, in this field, perhaps more attention has been paid to re-enhancing lateral mobility and erosion from the floodplain ("erodible corridor", Piégay et al., 2005), than from the channel riverbed, especially in bed coarse surface configurations. Yet, actions supporting lateral mobility are subject to several conditions: the availability of the flood plain in terms of land use and the absence of bank protection infrastructure, and sufficient energy for the river to have morphogenetic dynamics (Kondolf, 2011; Dépret et al., 2023). Moreover, a geomorphic and ecological problem may arise when materials from the floodplain are very different from the usual bedload. In our fieldwork, immediately downstream of Settons dam, the Cure River appears to erode laterally when its banks are not protected. However, this only adds silt and sand to the already fine particles released from the dam, and does not resolve the gravel deficit.

Other possible ways to compensate for sediment starvation and/or to try to re-activate gravel bedload transport below dams include: adjusted discharge management (Kondolf, 2011; Dépret et al., 2019), sediment by-passing (Kantoush et al., 2011), sediment flushing or sluicing (Kondolf et al., 2014), gravel augmentation (Arnaud et al., 2017; Gaeuman et al., 2017). The interest and realistic possibilities of these mitigation measures, in particular renewed flow management and sediment augmentation, for the study reaches concerned, merit more in-depth investigation. While the ecological stakes of Morvan rivers are high (spawning grounds, sources of coarse sediments), for certain of the reaches located below dams (Chalaux and Cure rivers), the morphological evolution (vertical stagnation, stable width or encroached vegetation), current substrate characteristics (bed coarsening, armoring, solid imbricated structures) and bedload dynamics (low or moderate) may, in the most extreme pattern, produce "fossilized bed forms" (Kondolf, 2011). Kondolf (2011) linked these in-active, immobilized channels to low floodplain habitat diversity but surely ecological issues involved in channel bottom habitat conditions (renewal, diversity) are also at stake.

Ultimately, given the multi-decadal shaping of certain very stable morpho-sedimentary configurations, the possible irreversibility of some river adjustments must be questioned. For example, it is far from guaranteed that not attenuating exceptional flood events at the S3 Cure site would be sufficient to destabilize the very solidly imbricated structures at this site. Also care should be paid to not overestimate our ability to predict future behaviors and adjustments based on our understanding of past adjustments (Brierley and Fryirs, 2016). The modification of the factors (sediment supply and flow regulation) that have played a key role in the development of current bed structures does not automatically abolish their initial effect. On the Yonne River, 5 years after the removal of the Pierre Glissotte dam and successful reestablishment of bedload continuity, the coarse and armored bed structure in the reach located immediately downstream had still not been modified (Gilet et al., 2021). These "long term" inherited morphologies thus clearly add to the inherent uncertainty and absence of guaranteed outcomes in river restoration (Downs and Gregory, 2004; Darby and Sear, 2008).

6. Conclusion

This study emphasizes the fact that the influence dams have on current bedload transport, and hence on river morphodynamics, needs to be accounted for at several time scales. Most immediately, dams contribute to determine bedload transport by defining the quantity of water supplied to the downstream reach. On this point, it was shown that, depending on the purposes and on the storage capacity of the dam, flow management can differ significantly: over a series of 21–28 years, the reduction in the mean annual maximum flood ranges from 9 to 40%, frequency of flood events is reduced by 27 to73.5% and flood duration is reduced by 5 to84% or slightly increased (5%). Specific implications for the energy excess, in terms of intensity, occurrence frequency, and duration, directly affect the bedload transport capacity of regulated rivers. During the 2.4–2.7 years of bedload monitoring, the cumulative stream impulse was reduced by 32 to61% due to flow regulation. On a longer time scale, water management and the degree of sediment trapping help shape fluvial morphology, which, in our case, further influences bedload mobility. Less than 20 km below large dams, most morphological adjustment was to textural elements with a change in substrate grain size (bed coarsening) and re-arrangement of the bed particles (armoring configuration, consolidated clusters, imbricated sedimentary structures), both supported by the apparent medium-sized sediment deficit (pebbles cobbles) and substrate heterogeneity ($D_{84}/D_{16} \geq 17.2$ on two of the three study reaches). In these strongly adjusted reaches, the mean cumulative virtual bedload velocities range from 0.42 to 91 m/d. The bedload mobility is much higher (0.62 to 6.44 m/d) in the reaches located above the dams or below medium-sized dams where sediment availability, homogeneous substrate ($3.1 \leq D_{84}/D_{16} \leq 6.2$) and loose clusters can be observed. Our study also suggests that sediment starvation alone (without intense flow regulation) seems able to modify and create morpho-sedimentary conditions that reduce bedload dynamics (e.g., the Cure reach below the Settons dam).

The fluvial response to dam-induced disturbances also appears to interact with the influence of previous uses (e.g., log driving) of the river, whether this influence consists of inherited morpho-sedimentary conditions (e.g. sediment load quantity, former vertical adjustment), or material constraints that still exist (rip-rap). This historic in the former anthropogenic influences on the river may make the influence of the dam on fluvial morphology harder to distinguish and to weigh.

Ultimately, three major lessons can be drawn from this study: (i) the weight of the past and the hydro-geomorphological context in which dams evolve need to be integrated to grasp their specific impact; (ii) because of this context and because of the specific characteristics (size, diversion structures) and functioning (purpose, schedule for filling the reservoir), the effect of each dam on flood regime and sediment continuity is specific and merits individual assessment (iii) a dam's influence on current bedload transport may first be determined by solid morphological conditions shaped partly by their multi-decade modifications of morphodynamic processes, rather than by the immediate flow management. This last fact is particularly important when considering possible action aimed at re-establishing bedload dynamics below a dam: a "simple" change in flow and even in sediment management from the dam would not necessarily guarantee re-activation of the "stabilized bed load" already in place, or bedload transport similar to that in pre-dam conditions.

Further studies would therefore be worthwhile to test mitigation measures. It would be useful to assess more definitively whether certain flood magnitudes are capable of destabilising the very consolidated sedimentary structures that "freeze" the riverbed, under current hydroclimatic conditions, and if so, to delimit this range of morphogenic floods. In addition, the analysis of the particle mobility in a sediment augmentation would still be of interest. This operation implies a much larger quantity of new incoming sediments than the quantity of tracers used in this study and possibly different bedload dynamics as well.

CRediT author statement

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Declaration of competing interest

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

Data availability

Data will be made available on request.

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