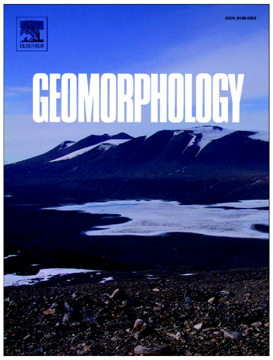

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Causes of planform stability of a low-energy meandering gravel-bed river (Cher River, France)

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Abstract

For at least two centuries, the lateral mobility of the meandering reaches of the Cher River (France) has been very low. This article aims to identify the main causes of this behavior. Two not-mutually exclusive explanatory hypotheses are proposed. Under the first hypothesis, the natural mechanisms of loop migration would have been inhibited or blocked by the presence of bank protections. Under the second hypothesis, a decrease in the frequency and/or intensity of morphogenic hydrological events since the nineteenth century would have reduced the frequency of bedload mobilization and/or reduced the capacity of the river to erode its banks. To test these hypotheses, the diachronic evolution of the planform was reconstituted at different time scales using a GIS and field surveys. Morphological transformations were characterized and quantified (eroded and vegetated areas, length of eroded banks, rates of bank retreat) and the critical discharges of bedload mobilization and of lateral erosion were estimated. Engineering works in the riverbed were identified and, when possible, dated. The results show that meander morphodynamics have been highly constrained and disrupted by engineering works, probably for over a century. However, the meanders still have noticeable potential for bedload mobility and lateral erosion, and hence for self-restoration.

Keywords: low meander mobility; diachronic evolution; river engineering works; lateral erosion rates.

1. Introduction

Most of the free meanders described in the literature are subject to quite high lateral instability (e.g., Nanson and Hickin, 1986; Gilvear et al., 2000; Leteinturier et al., 2000; Geerling et al., 2006; Gautier et al., 2007; Hooke, 2007, 2008; Magdaleno and Fernandez-Yuste, 2011). Beyond the fundamental questions about their formation and dynamics, the interest of these systems mainly lies in their associated high ecological value and the risk of erosion resulting from a shift in the channel (e.g., Lewin et al., 1977; Salo et al., 1986; Malavoi and Souchon, 1996; Piégay et al., 1997; Larsen and Greco, 2002; Ward et al., 2002; Lagasse et al., 2004; Florsheim et al., 2008; Roca et al., 2009; Ollero, 2010; Dugué et al., 2013). In contrast, meanders displaying long-term stability have been much less extensively studied — probably because their ecological diversity is assumed to be less than that of unstable meanders and also because of their limited social demand, as they do not threaten riverine buildings, engineering works (roads, bridges, pipes, etc.), or agricultural land. Nevertheless, when disturbances affect river dynamics, we need to know the cause of their stability as this will determine the definition and efficiency of any remedial actions.

At the scale of one bend or loop — here defined as a curved section of a river (seen as a section of a circular arc) for which the straight distance between points of inflexion is greater than the radius of curvature (Brice, 1974) — the retreat rate, and hence the degree of meander mobility, is determined by a combination of factors including the specific stream power, the strength and height of the banks, the radius of curvature, channel width, and the size and supply of sediments (Hickin and Nanson, 1984; Nanson and Hickin, 1986; Hickin, 1988; Howard, 1996; Constantine, 2006; Güneralp et al., 2009b, 2010; Dunne et al., 2010; Constantine et al., 2014). The rare studies of the causes of low mobility of meander systems attribute the slowness of their evolution to weak available energy and/or to excessively strong resistance to erosion by the banks. In a panel of 90 British rivers, Ferguson (1981) distinguishes, for example, between free and inactive meanders using specific stream power. Free meanders have a median value of 30 W m^{-2} (range 5 to 350 W m^{-2}), while inactive meanders have a median value of 15 W m^{-2} (range 1 to 60 W m^{-2}). Biedenharn et al. (1984) attributed the planimetric stability of the Ouachita River (USA) between 1820 and 1980 to the low available energy of the river and to the strong cohesion of its banks, composed of clays, silts, and sands and covered by dense vegetation. The quasi-absence of morphological response of the Des Plaines River (USA) to the occurrence of a 100-year flood was attributed by Rhoads and Miller (1991) to low energy and high bank resistance, in addition to the low hydrological variability of the river. According to Urban and Rhoads (2003) and Güneralp and Rhoads (2009a), the weak mobility of meandering rivers in Illinois (USA) and/or the absence of planform readjustment following channelization results from their too low specific stream power. In a study of the Holocene dynamics of two successive loops of the Red River (Canada), Brooks (2003) documented a sharp decrease in bank erosion rates from 6200 BP (0.18-0.35 m y^{-1} from 8400 to 6200 BP and 0.04-0.08 m y^{-1} since 6200 BP) interpreted as the consequence of a reduction in the sediment supply. Moreover, observing stable sections is not uncommon even on rivers subject to strong lateral activity. On the Dane River, Hooke (2003a, 2007, 2008) reported a spatial alternation of unstable and less mobile sections over a period of 140 years. The behavior of the Dane River was explained by the combined influence of at least two of the following parameters: low gradient, low sinuosity, the presence of bedrock outcrops, the proximity of valley sides or terraces (Hooke, 2007). Finally, fluvial engineering works may also directly or indirectly obstruct the growth and migration of meanders. The most striking case is bank protections whose purpose is to prevent all planform mobility (e.g., Brookes, 1985; Erskine, 1992; Steiger et al., 2000, 2001; Florsheim et al., 2008; Kiss et al., 2008, 2012; Ollero, 2010; Vandenberghe et al., 2012). By regulating the flow, the construction of dams may also lead to a sharp reduction in mobility (e.g. Bradley and Smith, 1984; Williams and Wolman, 1984; Friedman et al., 1998; Shieds et al., 2000; Dixon et al., 2012).

In this article, we focus on three meandering reaches of the low-energy Cher River — believed to have displayed very low mobility for the last 200 years. The assumption of long-term relative stability is based on observation of the superposition of the current river course on municipal boundaries, most of which date back to the French Revolution (1789). Two not mutually exclusive hypotheses are proposed to explain the low meander mobility. Under the first hypothesis, the natural mechanisms of loop migration would have been inhibited, or even blocked, by the ancient presence of bank protections. Under the second hypothesis, a reduction in the frequency and/or intensity of morphogenic hydrological events since the nineteenth century, possibly related to the end of the Little Ice Age or to the construction of the Rochebut dam upstream in the basin in 1909 (Fig. 1), would have reduced the frequency of bedload mobilization and the capacity of the river to erode its banks. These two elements, whether combined or not, would have stabilized the course of the meander.

Management issues are also important in this stream. The extraction of sediment from the active bed over a period of more than four decades that ended in the early 1990s triggered serious degradation of the river bed, leading to ecological impoverishment along numerous reaches. For this reason, assessing whether the river still has the ability to replenish its sediments through lateral erosion is crucial. This question is also linked to the need expressed by river managers for the maintenance or the enhancement of aquatic and riparian habitats. If the stability of the meander course is explained only by the second hypothesis mentioned above, the prospects of recovery would be very limited. On the other hand, if stability is mainly caused by the presence of river engineering works, the potential for restoration would be high and remediation actions possible. Broadly, dynamics of low-energy and weakly mobile systems remain largely unknown, which is detrimental to their management. In France for example, they have been the subject of very few studies, and methods or recommendations for river restoration have been mainly developed based on the dynamics of high-energy rivers (Lespez et al., 2015). This work thus had two aims: to reconstruct the planimetric evolution of these meanders from the early nineteenth century in order to accurately characterize and quantify their current mobility and to determine the causes of their relative stability.

2. Study reaches

2.1. The Cher River

The Cher River is a major tributary of the Loire River. At the downstream end, its annual average discharge is 90 m^3 s^{-1} and its catchment area is 13,615 km². The river comprises three main sections. After its source at 713 m (asl), the river flows mostly in gorges across steep slopes or in deep valleys with a very narrow floodplain (Upstream Cher in Fig. 1). This upstream portion is located at the northwest end of the low altitude mountainous area of the Massif Central, which mainly consists of crystalline and metamorphic rocks (Larue, 1981, 2011). After 63 km, the Cher alluvial plain begins (Alluvial Cher in Fig. 1). Occupying the Tertiary graben of Montluçon, the river then crosses the sedimentary domain of the Parisian Basin (Larue, 1981, 2011; Simon-Coinçon et al., 2000). In the Alluvial Cher, the bed gradient and the ratio of the width of the channel to the width of the floodplain decreases abruptly compared to the upstream section. Its course is much less laterally constrained, and the river acquires high mobility potential. In the lower valley (downstream from Selles-sur-Cher), the river is regulated and channeled by a series of weirs with locks (Serna, 2013: Channelized Cher in Fig. 1).

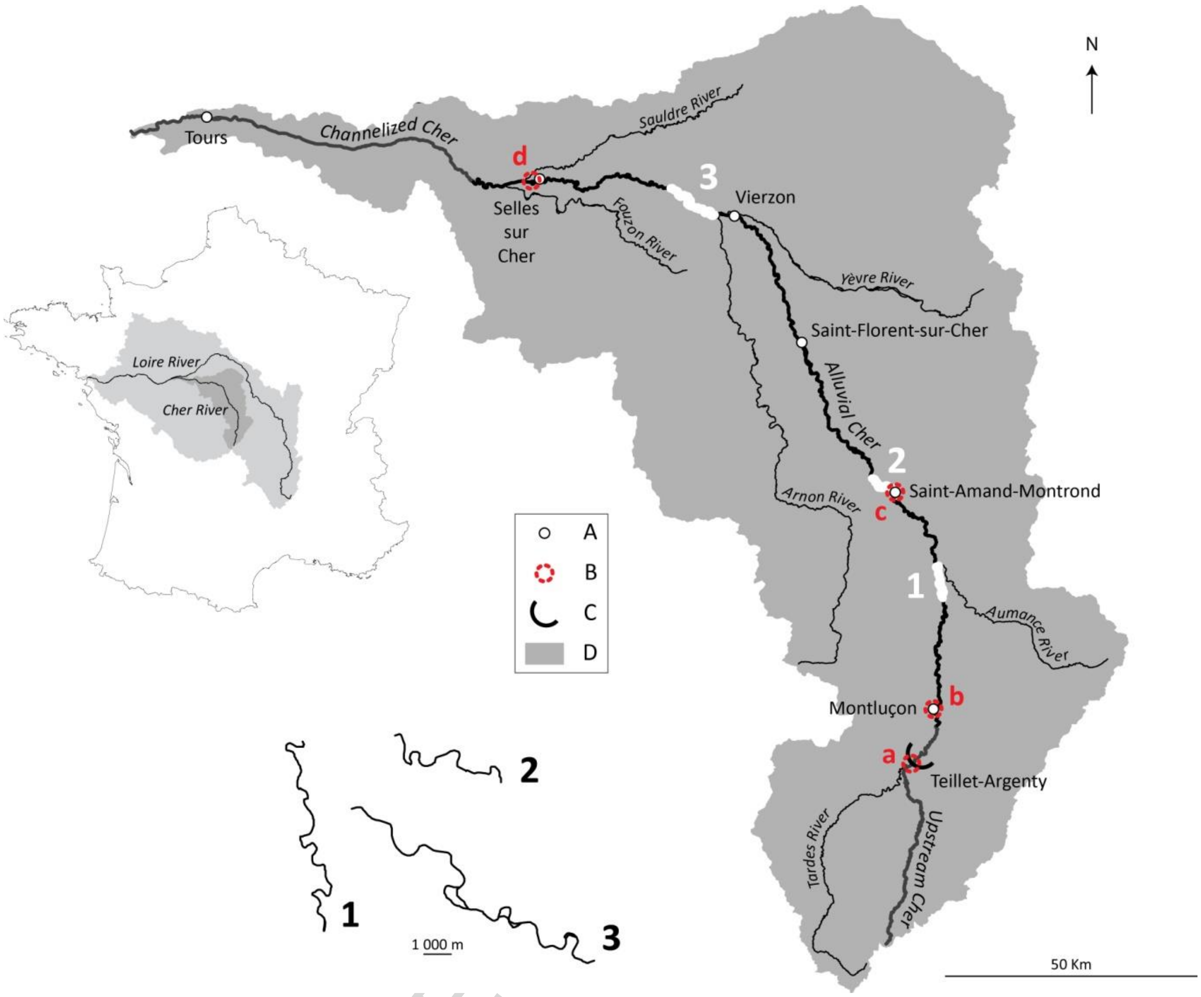


Fig. 1. Location of study reaches.

(A) Main towns; (B) Hydrological stations used in this study; (C) Rochebut dam; (D) Cher watershed; The numbers 1, 2, 3 indicate the study reaches.

2.2. The study reaches

This study focuses on three distinct meander reaches located in the Alluvial Cher (Fig. 1, Table 1). They were chosen on the basis of three criteria:

- An apparent low mobility for at least two centuries. This assumption is based on the observation of the superposition of the current river course on municipal boundaries, most of which date back to the French Revolution (1789).

- A relatively large space for lateral mobility. Meander reaches were excluded where the valley width (ratio between the width of the alluvial plain and the width of the bed is < 10) and/or the engineering works in the alluvial plain (roads, dykes, railways, artificial canal, gravel pits, etc.) have impeded the possibilities for lateral mobility over several decades.

- The recent occurrence (at least over the last 30 years) of lateral activity. The manifestation of such processes was identified through aerial photos and field observations.

The limits of the reaches studied correspond to natural or anthropogenic discontinuities or singularities. It can be valley narrowing (upstream limit of reach 1 and downstream limit of reach 2), the input of a main tributary (downstream limit of reach 1 and upstream limit of reach 3), or the presence of weirs or bridges (upstream limit of reach 2 and downstream limit of reach 3).

In reach 1, the Cher River flows in an alluvial material with a minimum thickness of 3-5 m (Turland et al., 1989a), lying on a basement mostly composed of Eocene and Oligocene sands and clays (Turland et al., 1989a, 1989b). Since 1856, bed incision has been moderate or absent, depending on the section. Maximum entrenchment reaches between 0.7 and 1.4 m locally. The hydrological gauging site is located in Montluçon. No major tributary enters the Cher between this station and the reach (Fig. 1). The Rochebut dam, located 45 km upstream of the study area, influences the hydrological regime, particularly at low flow.

In reach 2, the meanders studied are located in the Boischaut peripheral depression (Larue, 1994). The thickness of the alluvial filling is between 5.5 and 7.5 m, and the bedrock is composed of Liassic clays and shaley marls (Lablanche, 1994; Lablanche et al., 1994; Larue, 1994). The reach underwent a major incision in the second half of the twentieth century, when maximum depth reached 2 to 2.5 m (Dépret, 2014). The hydrological gauging site at Saint-Amand-Montrond is located at the beginning of reach 2 (Fig. 1). The influence of the Rochebut dam (located 80 km upstream) on the hydrological regime is weaker than in reach 1.

In reach 3, extending from the confluence with the Arnon River to the Boutet weir, the thickness of alluvial filling ranges from 7 to 9 m (Manivit et al., 1994). The bedrock is composed of Cenomanian black marls and glauconitic sands (Manivit and Debrand-Passard, 1994; Manivit et al., 1994). The vertical evolution of the bed has not been characterized owingto the lack of data, but the bed is probably incised, at least locally, because of the extraction of material from the active bed during the second half of the 20th century. No major tributary joins the river between the gauging site (Selles-sur-Cher) and the study reach (Fig. 1).

In the three study reaches, the banks are schematically composed of two or three main stratigraphic layers with pebbles, gravels, and sands overlain by overbank sandy silt (Turland et al., 1989a; Lablanche et al., 1994; Larue, 1994; Manivit et al., 1994; Dépret, 2014). With a surface D_{50} of between 25 and 34 mm, the Cher River is a gravel-bed river. Because of a bankfull unit stream power of between 7 and 32 W m^{-2} and to the composite nature of banks, the Cher River can be classified as the B3a type of Nanson and Croke (1992), corresponding to medium-energy, noncohesive floodplains whose unit stream power is between 10 and 60 W m^{-2}. We nevertheless use the term *low energy* to characterize the Cher River because the unit stream power belongs to the lowest values defining the B type according to Nanson and Croke (1992). Moreover, the values of the Cher River are close to the threshold between laterally active and inactive reaches reported in the literature. Bizzi and Lerner (2015), Brookes (1987a, 1987b), and Orr et al. (2008) proposed, for example, a limit between 25 and 35 W m^{-2}. Ferguson (1981) distinguished between active free meanders with a value of specific stream power equal to 30 W m^{-2} and inactive meanders with a value of 15 W m^{-2}.

Table 1

Hydraulic and geometric parameters and grain size in the study reaches

	A (km²)	Is	WL (m)	LL (m)	L (m)	BFw (m)	ABw (m)	APw / BFw	S $_0/^{00}$	Ws (W m^{-2})	D_{50s} (mm)	D_{84s} (mm)
Reach 1	2,232	1.55	693	508	10,700	51	31	13	0.626	12.4	26	50
Reach 2	3,898	1.55	713	401	8,300	60	49	18	0.639	32.7	34	63
Reach 3	9,043	1.45	979	688	14,900	96	69	20	0.189	06.6	29	52

A: Catchment area. Is: Sinuosity index. WL: Mean meander wavelength. LL: Mean meander loop length. L: 2005 river length. BFw: Bankfull width. ABw: Active bed width. APw: Alluvial plain width. S: Bed slope. Ws: Bankfull unit stream power ($(\rho_w gQS)/w$, where ρ_w is the density of water (1000 kg m^{-3}), g is the gravitational acceleration (9.81 m s^{-2}), Q is the bankfull discharge in m^3 s^{-1}, S is the bed slope in m m^{-1}, w is the bankfull bed width in m). D_{50s}: Surface D_{50}. D_{84s}: Surface D_{84}. In each reach, the grain size was determined through Wolman sampling realized on four riffles. The bankfull discharge was obtained by applying the Navratil et al. (2006) method (see Dépret et al., 2015 for details). The slope was computed from the low-water line surveyed in 2010-2011. The planimetric parameters were measured with a GIS (ArcGIS 9.2).

2.3. Hydrological regime

The hydrological regime is mainly influenced by a pluvio-evaporal oceanic climate and is characteristic of lowland rivers in the western part of mid-latitude regions. Maximum flow occurs in February and minimum flow in August. From upstream to downstream, the mean annual discharge of the middle Cher ranges from 16 to 75 m^3 s^{-1}. With an almost constant ratio of monthly maximum discharge to monthly minimum discharge (between 7.2 and 8.4), the regime is moderate. In the upstream part of the study area, particularly during low flow, the hydrological regime has been partly artificial since the construction of the Rochebut dam in the early twentieth century. Like the River

Loire, three main types of floods occur (Duband, 1996; Lang and Coeur, 2011). The first is the result of the passage of western depressions from the Atlantic, mostly in winter. The second type of flood — brief but intense — is caused by Mediterranean rainstorms usually in late summer and fall, but only affects the upstream (southern) part of the basin. The third type is a combination of the first two types of floods. These floods affect the entire basin. Low flows can be long and marked, especially in the upstream valley, because the substrate is impermeable and the aquifer storage is low.

3. Methodology

3.1. Evolution of the planform

The evolution of the river course was reconstituted from old maps and aerial photographs with a GIS (ArcGIS 9.2). Two main periods were considered: 1830-1950 and 1950-2005. The river course in 1830 was reconstituted using excerpts from the Napoleonic Cadaster (reach 1: 1833; reach 2: 1827; reach 3: 1825). The documents used for the period from 1950 to 2005 were vertical aerial photographs. This period was explored in more detail at intervals between 9 and 15 years, with five consecutive subperiods documented (Table 2). Aerial photos were chosen on the basis of three criteria: a discharge that was as low as possible, photographs at the same season and scales that were relatively close from one photo to another (Table 2 and 3).

Table 2

Date and discharge (m^3 s^{-1}) on aerial photos used between 1950 and 2005 for the reconstruction of planform evolution; the location of gauging station is indicated in Fig. 1 (Qd: Daily discharge. Q August: Mean discharge in August. Q mean: Mean annual discharge)

		Teillet-Argenty Station			**Saint-Amand-Montrond Station**		
	Date	**Qd**	**Q August**	**Q mean**	**Qd**	**Q August**	**Q mean**
Reach 1	10/07/1950	0.9	3.1	15.4		7.4	28.7
	26/05/1960	4.2					
	27/07/1975	0.1			1.6		
	12/07/1985	2.5			7.2		
	07/07/1995	3			7.5		
	12/06/2005	1.2			3.5		
		Saint-Amand-Montrond Station			**Teillet-Argenty Station**		
	Date	**Qd**	**Q August**	**Q mean**	**Qd**	**Q August**	**Q mean**
Reach 2	10/06/1950		7.4	28.7	3.2	3.1	15.4
	04/04/1959				8		
	03/09/1973	5.6			4		
	15/08/1983	4.3			0.8		
	07/07/1995	7.5			3		
	17/06/2005	6.4			2.6		
		Selles-sur-Cher Station					
	Date	**Qd**	**Q August**	**Q mean**			
Reach 3	13/05/1950		17.1	62.3			
	17/06/1959	22					
	15/06/1973	25.9					
	23/09/1983	40.8					
	19/07/1995	14					
	12/06/2005	14.6					

Quantification and characterization of bed modifications were based on the identification and digitization of the active bed at each date. We distinguished *vegetated areas* occupied by perennial vegetation composing lateral margins and islands from the *active bed*, formed by channels and bare gravel bars. Between two successive dates, all areas occupied by perennial vegetation at time *t* and active bed areas at time *t* + 1 were considered eroded. Conversely, all active bed areas at time *t* occupied by perennial vegetation at time $t + 1$ were considered to be stabilized. For the rest of the manuscript, they are referred to as *vegetated*. Eroded and vegetated areas were standardized in order to compare the computed changes on each of the three reaches. They were thus expressed as a percentage of the original area of the active bed. Because the lengths of all the periods are not the same, these amounts are expressed per year.

Two main types of error, inherent to the method used to generate the data, were taken into account:

- the georeferencing error (E1).

Aerial photos were georeferenced from the 2005 orthorectified photos (orthorectification made by the IGN, National Geographic Institute). We retained an error value equal to 2 RMSE. Excerpts from the Napoleonic Cadaster were georeferenced from the current cadaster (itself georeferenced by the IGN). Because the Napoleonic Cadaster presents more deformations than the aerial photos and because we wished to be sure of the reality of the planform modifications of the bed, we built the georeferencing error quite differently: for a maximum number of points different from ground control points, we measured the distance between the Napoleonic and current cadasters and finally retained the highest of these distances as the georeferencing error.

- the error of active bed digitizing (E2).

It is equal to 4 m for aerial photos. This corresponds to the maximum uncertainty in locating the boundary of the active bed under forest cover. For the Napoleonic Cadaster, we retained a value of 2 m. This corresponds to maximal thickness of the line representing the limits between the bed and the floodplain. Furthermore, we also considered a third error term for the Cadaster. It takes into account the uncertainty coming from the geometric imprecision of the surveyed objects and from their cartographic representation. We arbitrarily retained a value of 15 m.

Because the different types of errors are independent of one another, the total error is obtained following Eq. 1 (Benjamin and Cornell, 1970, cited in Gaeuman et al., 2003). It ranges from 4 to 5.7 m for the aerial photos and from 17.6 to 21.3 m for the Napoleonic Cadaster (Table 3):

$$\boldsymbol{Total\,error} = \sqrt{\boldsymbol{E1^2 + E2^2}} \qquad (1)$$

Once the total error was determined, eroded and vegetated surfaces were created. For each date, a buffer area with a width equal to twice the value of the total error was created along the boundaries of the active bed. The active bed buffers at two successive dates were merged, denoting the spatial extent within which any change was considered unproven. Subsequently, any vegetated or eroded polygon fully recorded in this merged buffer zone was excluded from the analysis.

Table 3

Date of maps and aerial photographs and range of total error for the planimetric evolution

Date	**Scale or resolution**	**Total error**
1833[a] – 1827[b] – 1825[c]	1:2,500 – 1:5,000	17.6-21-3
1950	1:2,6000	5.1-5.7
1959[bc] – 1960[a]	1:2,5000	4.9-5.7
1973[bc] – 1975[a]	1:1,5000	4.9-4.9
1983[bc] – 1985[a]	1:1,7000	4.9-5
1995	1:2,5000	4.6-4.8
2005	68 cm	4

[a] Reach 1.

[b] Reach 2.

[c] Reach 3

All changes were also quantified by calculating the total eroded bank length and the average rate of bank retreat (area of eroded polygons / length of eroded bank for each main period and each subperiod: Micheli and Kirchner, 2002; Micheli et al., 2004). Finally, because some loops have undergone some significant modifications of their course, their main planimetric changes were classified based on the typology used by Hooke on the Dane River (Hooke, 1984: Fig. 2). Previously, the meander loop limits (points of inflexion) were identified using the method developed by Hooke (1984) and O'Neill and Abrahams (1986). The method is grounded on the detection of center line direction changes at a fixed interval. An inflexion point, i.e., the limit between two successive loops, is identified when a series of direction changes of the same sign is higher than a previously determined threshold value (here chosen between 30 and 60 according to the study reach).

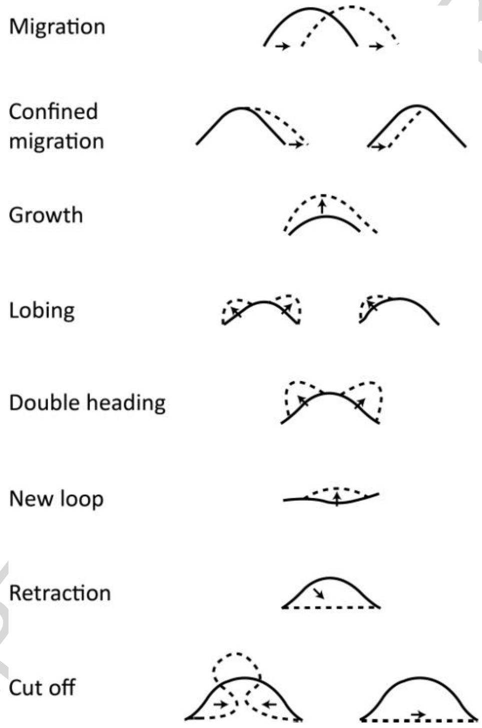


Fig. 2. Typology of meander loop changes (Hooke, 1984, modified).

3.2. Detection and localization of river engineering works

Determining the influence of river engineering works on current and past river meander dynamics requires knowing their construction date as well as their exact location. For that purpose, we retrieved data in local, regional, and state archives and systematically identified the current exact location of river engineering works in the field with an RTK-DGPS.

3.3. Influence of bank protections on the longitudinal distribution of lateral erosion between 1950 and 2005

To estimate if bank protections influence the longitudinal distribution of lateral erosion for the 1950-2005 period, we first listed for cross sections spaced one bankfull width apart the presence/absence of bank protection as well as the presence/absence of erosion (whatever its location on concave or convex side). We then used a χ^2 test to determine if exists a significant statistical difference in terms of lateral erosion between banks with protection and banks deprived of protection.

3.4. Determination of critical discharge for lateral erosion

The critical discharge for bank retreat was determined by monitoring the position of the top of active banks between October 2009 and March 2013. All banks presenting signs of recent activity were surveyed. For reaches 1, 2, and 3, it represents respectively 1.7 km (16.2% of the reach length), 2.7 km (32% of the reach length), and 1.4 km (9% of the reach length: Fig. 3). After each event that could cause a bank to retreat, the position of the top of the banks was surveyed with an RTK-DGPS at each main break line, or every 3 m in the absence of any break line. Three types of uncertainty are associated with the location of the bank position: the horizontal measurement with the DGPS (E1, ± 0.03 m), the positioning of the DGPS (E2, ± 0.05 m) and the identification of the limit of the bank (E3, +/- 0.1 m). Considering all these uncertainties as independent, we obtain a total uncertainty of 0.12 m $\left(\sqrt{E1^2 + E2^2 + E3^2}\right)$. All bank evolutions with a retreat rate (computed following the formula of Micheli and Kirchner, 2002) < 0.24 m (2 x 0.12 m) were considered as spurious and were thus excluded from the analysis.

Furthermore, we computed the critical specific stream power for lateral erosion (see Table 1 for the formula). We used the low-flow slope obtained from water-line surveys realized in 2010-2011 with an RTK-DGPS at each inflexion point and at each riffle head and tail. Moreover, two values of critical specific stream power were proposed: the first obtained from the active bed width, the second from the bankfull width. The active bed width was measured from 2005 aerial photos along cross sections roughly spaced one bankfull width from each other. Bankfull width was obtained applying the Navratil et al. (2006) method (see Dépret et al., 2015, for more details). These hydraulic parameters were all computed for river sections where length is between 6 and 12 active bed widths. Because of the relatively large distance between the study sites and hydrological stations, the discharge values were corrected by means of the following formula:

$$Q = q\left(\frac{A}{a}\right)^{0.7} \qquad (2)$$

with Q the discharge at the downstream site in m^3 s^{-1} ; q the discharge at the upstream site in m^3 s^{-1} ; A the catchment area at the downstream site in km²; and a the catchment area at the upstream site in km². Finally, the critical specific stream power was also computed from the mean hydraulic parameters at the reach scale.

Hydrological activity during the study period was moderate. The bankfull discharge was exceeded four times in reach 1, never in reach 2, and only once in reach 3 (Fig. 3). In reach 1, the maximum discharges between two consecutive surveys are between 0.61 x Q_{BF} and 0.92 x Q_{BF} (0.5 x $Q_{1,5}$ - 0.75 x $Q_{1,5}$) for six of the eight monitored events. The other two events experienced flood flows. In reach 2, the maximum discharges between two consecutive surveys were between 0.45 x Q_{BF} and 0.74 x Q_{BF} for all five monitored events (0.61 x $Q_{1,5}$ - 1.01 x $Q_{1,5}$; between 0.53 x Q_{BF} and 1.2 x Q_{BF} before bed incision). In reach 3, the maximum discharges were between 0.54 x Q_{BF} and 0.7 x Q_{BF} (0.64 x $Q_{1,5}$ - 0.82 x $Q_{1,5}$) for four of the five monitored events. The other event exceeded the bankfull level.

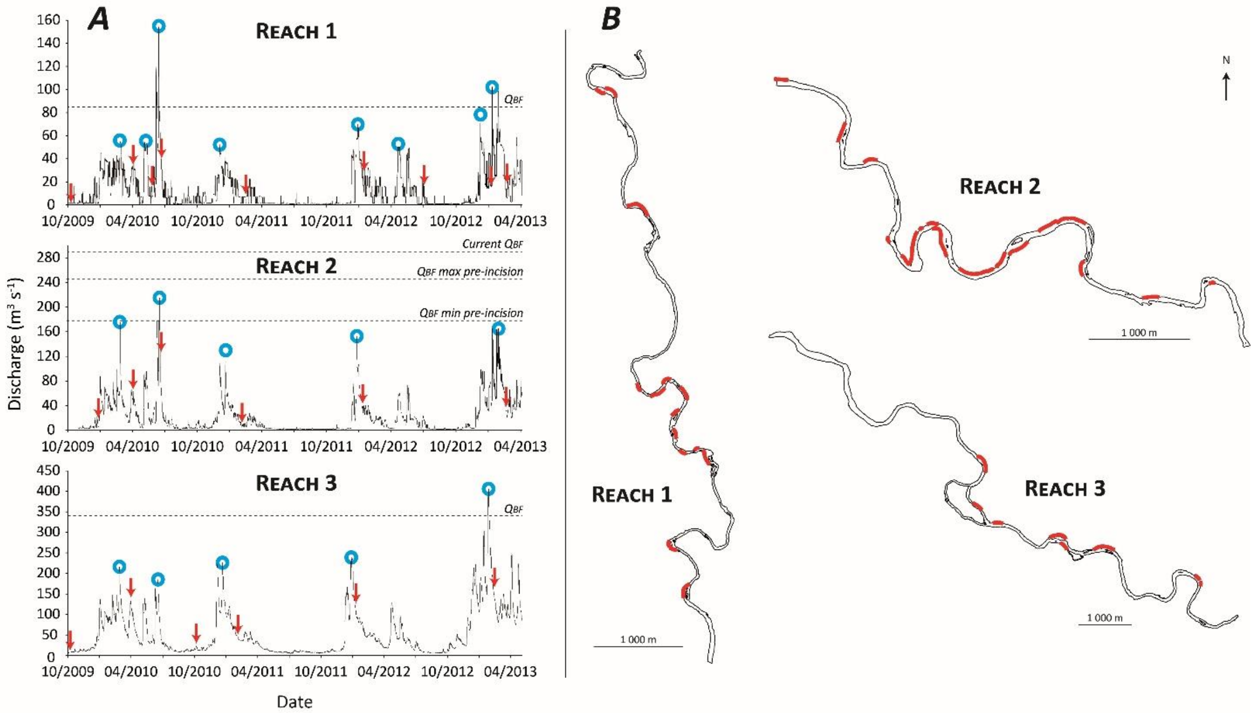


Fig. 3. Monitoring of the top bank position with RTK-DGPS between 2009 and 2013.

(A) Blue circles indicate the monitored events, red arrows the RTK-DGPS surveys. (B) Location of the surveyed banks.

3.5. Determination of critical discharges for bedload mobilization

We are interested in this issue because the degree of mobility of meander loops is closely associated with the sediment supply (Constantine, 2006; Dunne et al., 2010; Rollet and Piégay, 2013; Constantine et al., 2014), which, in turn, is indirectly linked to the ability of streams to mobilize the surface sediments of the riverbed.

Bedload mobility was monitored during two successive hydrological years through the use of passive integrated transponder tags (PIT-Tags) inserted in particles (Nichols, 2004; Lamarre et al., 2005: Fig. 4). Four riffles in reaches 1 and 3 and two riffles in reach 2 were equipped. We chose to equip riffles located in river sections subject to lateral activity since at least 1950. Owing to the size of the PIT-tags (23x4x4 and 16x6x3 mm), only particles whose size roughly exceeded the D_{50} were tagged. The grain-size distribution of tracers was similar to that of the bed truncated at the value corresponding to the smallest particle size equipped with tracers (around 24-27 mm: Fig. 5). The bed grain size was determined by Wolman's surface sampling method with 400 particles measured on each of the riffles (Wolman, 1954).

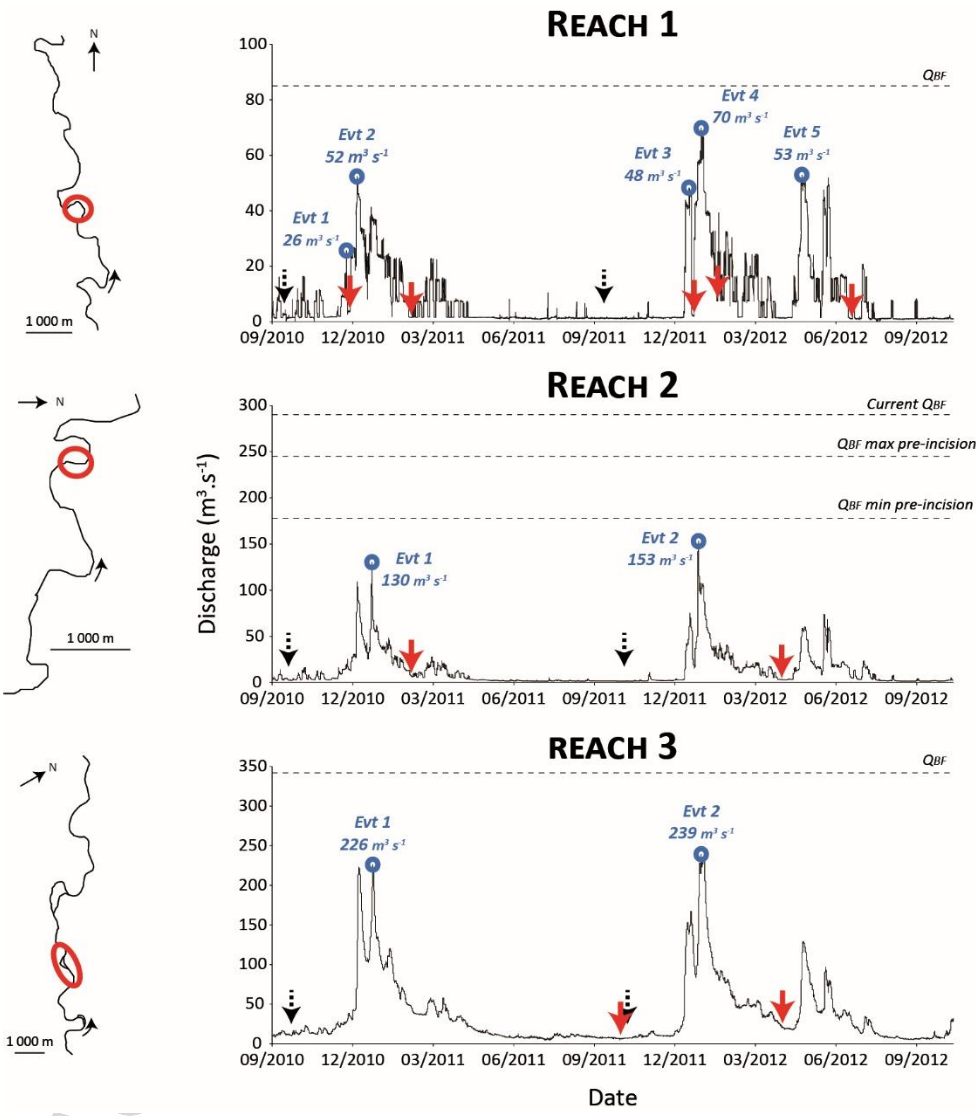


Fig. 4. Location of the surveyed river sections (see red ellipses to the left of the graphs) and hydrological events for the determination of critical discharges for bedload mobilization (black arrows show the date the tracers were introduced; the red arrows show the date the tracers were recovered).

The tagged particles were collected from each of the riffles. They were weighed and their three axes were measured. At their reinjection into the bed, they were inserted in the existing sediment structure, thereby limiting artificial exposure to flows. The tracers were injected individually along cross sections located at riffle heads with a distance between particles ranging from 0.5 to 0.7 m depending on the cross sections. Their position was surveyed with an RTK-DGPS. The total number of tracers for each profile was between 20 and 69. From 2010 to 2012, five separate detection campaigns were conducted in reach 1 and two in reaches 2 and 3 (Fig. 4). During detection campaigns, conducted along each cross section, an absence of detection does not systematically mean a mobilization of the particle. It may also result from a bed aggradation burying the particle. To ensure that a particle has not been buried, a topographic survey was performed at the time of each campaign.

We also computed the critical specific stream power (see Table 1 for the formula). With the exception of the bed width, the data used for this computation was obtained in the same way as for the critical stream power for lateral erosion. The bed width was determined from the topographic surveys of the cross sections and from the water level, registered every 15 min using water-level sensors fixed in the riverbed upstream and downstream of the injection reach.

Hydrological activity between 2010 and 2012 was very moderate. No flooding occurred and the two years were separated by a particularly severe low flow episode (Fig. 4). The maximum discharge during this period was 70 m^3 s^{-1} (0.82 Q_{BF}, 0.66 $Q_{1,5}$) in reach 1, 153 m^3 s^{-1} (0.53 Q_{BF}, 0.72 $Q_{1,5}$) in reach 2, and 239 m^3 s^{-1} (0.7 Q_{BF}, 0.82 $Q_{1,5}$) in reach 3.

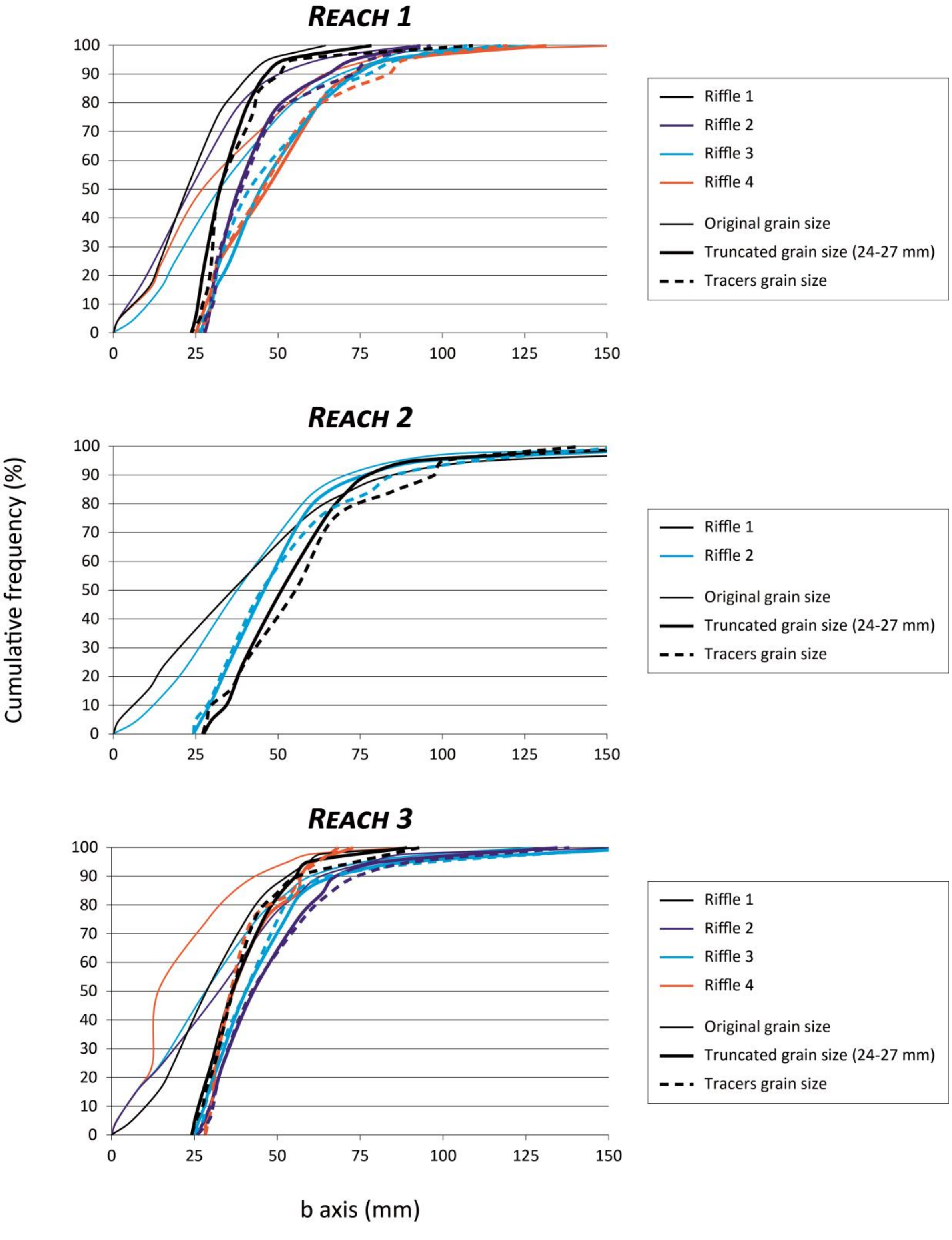


Fig. 5. Grain size of sediments equipped with PIT-Tags and on riffles in which they were injected.

4. Results and discussion

4.1. Main trends in planform evolution in the periods 1830-1950 and 1950-2005

4.1.1. Stability of the river course

The course of the river in 1830, 1950, and 2005 overlap quite noticeably (Fig. 6). The analysis of the planform evolution between 1830 and 2005 thus confirmed the low mobility of meanders. But despite low mobility, substantial morphodynamic activity occurred.

Between 1830 and 1950, the average annual rate of bank retreat along eroded sections was between 0.31 and 0.42 m y^{-1} (Table 4). In each reach, respectively 19.3%, 18.8%, and 12.9% of reach length was affected by lateral erosion on at least one side of the river (Table 4). In the second period, although the 1950 and 2005 river courses superimposed more clearly than those of 1830 and 1950, annual raw erosion was higher than between 1830 and 1950 (Table 5). The same was observed for the annual percentage of eroded bank length (2.9 times higher in 1950-2005 in reach 1, 3.9 times in reach 2, 3 times in reach 3: Table 4) . However, the average annual rates of bank retreat were similar in the two periods (Table 4).

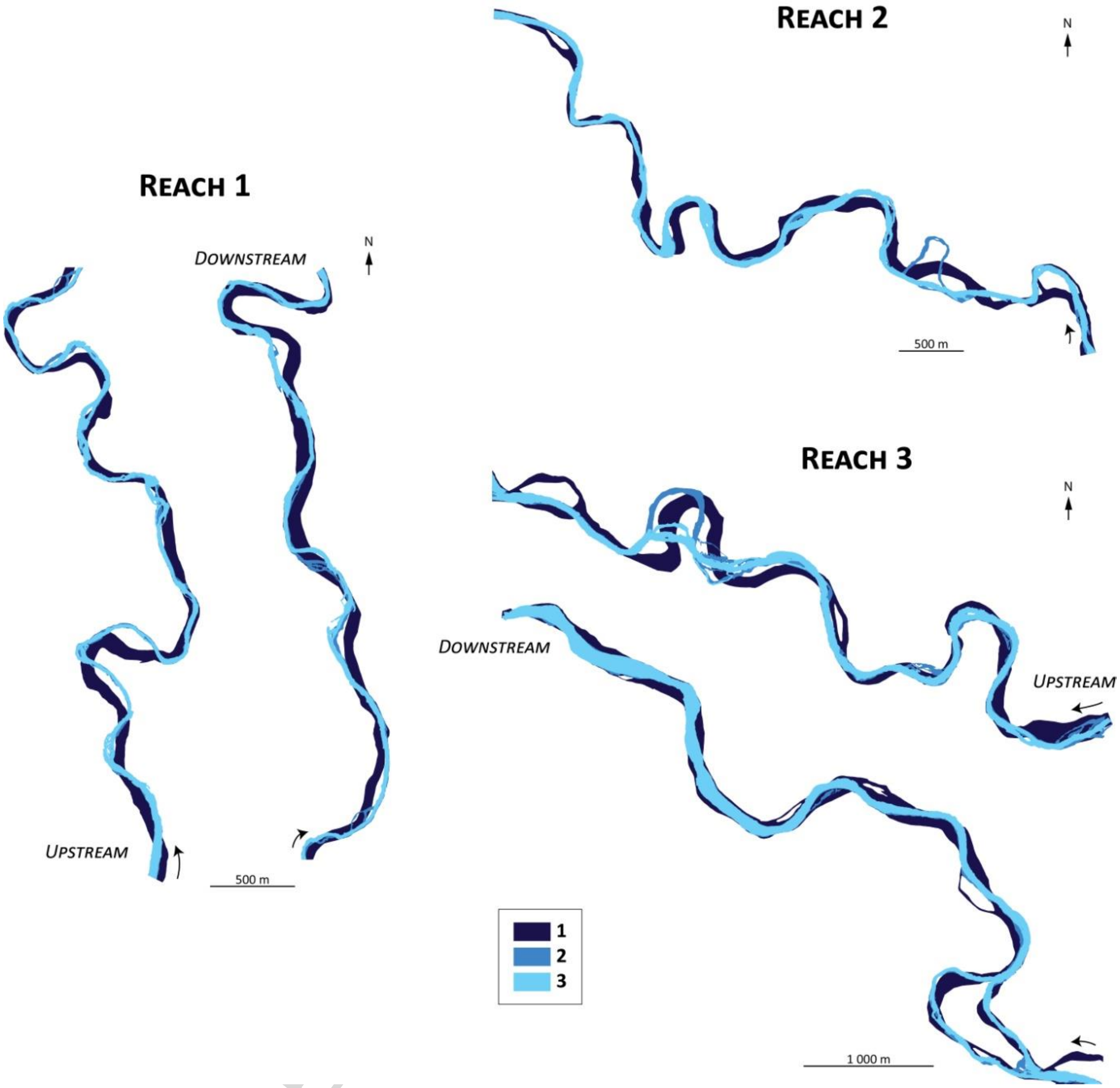


Fig. 6. 1830, 1950 and 2005 river courses. 1: Riverbed in circa 1830 (1833: reach 1; 1827: reach 2; 1825: reach 3); 2: riverbed in 1950; 3: riverbed in 2005.

Table 4

Average annual bank retreat rate, average annual standardized bank retreat rates (average annual bank retreat rate expressed as a % of the original bed width), range of retreat rates, and % of river length affected by lateral erosion (on at least one side of the river) in the periods 1830-1950 and 1950-2005

		Average annual retreat rate ($m\ y^{-1}$)	**Standardized annual retreat rate ($\%\ y^{-1}$)**	**Range of retreat rates ($m\ y^{-1}$)**	**% of eroded bank length**	**% of eroded bank length per year**
Reach 1	1830-1950	0.34	0.50	0.1-0.65	19.3	0.16
	1950-2005	0.31	1.12	0.1-0.77	26.6	0.48
Reach 2	1830-1950	0.31	0.38	0.19-0.75	18.8	0.15
	1950-2005	0.34	0.90	0.09-0.66	32.5	0.59
Reach 3	1830-1950	0.42	0.37	0.15-0.7	12.9	0.1
	1950-2005	0.34	0.54	0.09-0.64	17.1	0.31

Table 5

Annually eroded and vegetated areas in the periods 1830-1950 and 1950-2005 expressed in m² and as a % of the original area of the bed: the balance is the difference between eroded and vegetated areas

		Reach 1		**Reach 2**		**Reach 3**	
		Raw	**%**	**Raw**	**%**	**Raw**	**%**
Eroded areas	1830-1950	1300	0.19	1329	0.21	2289	0.13
	1950-2005	1815	0.63	2340	0.72	3965	0.42
Vegetated areas	1830-1950	4569	0.68	3893	0.62	8262	0.49
	1950-2005	978	0.34	800	0.25	3022	0.32
Balance	1830-1950	-3269	-0.49	-2564	-0.41	-5973	-0.35
	1950-2005	837	0.29	1540	0.47	943	0.1

4.1.2. Some notable morphological modifications

1830-1950: On the three reaches studied here, migration, confined migration, and growth are the most common types of loop evolution (Fig. 7). In addition, eight loops or portions of loops (out of 19) in reach 1, seven loops or portions of loops (out of 11) in reach 2, and five loops or portions of loops (out of 18) in Reach 3 were sufficiently mobile for the total surface occupied by the riverbed in 1830 to be occupied by the alluvial plain in 1950 (Fig. 7). In reach 1, three of the eight loops (numbers 3, 4, and 5 on Fig. 7), migrated and exhibited a relatively important change in morphology. In reach 2, erosive activity was concentrated in the upper two-thirds of the reach. A new loop, which underwent a cutoff in 1950, was formed. The downstream third of the reach remained stable. In this section, the secondary channel of the main island was filled. At the upstream end of the reach, the main channel of the first loop, resembling a chute cutoff channel, was also filled. In reach 3, erosion is almost absent in the downstream third of the reach. Only one small island disappeared after 1825. In contrast, the upstream part was much more active. Four consecutive loops present classic meander loop dynamics with a shift in the bed in the downstream direction. Finally, most of the islands observed in 1825 were incorporated into the floodplain by 1950 by sedimentary filling of side channels, while a new generation of smaller islands appeared.

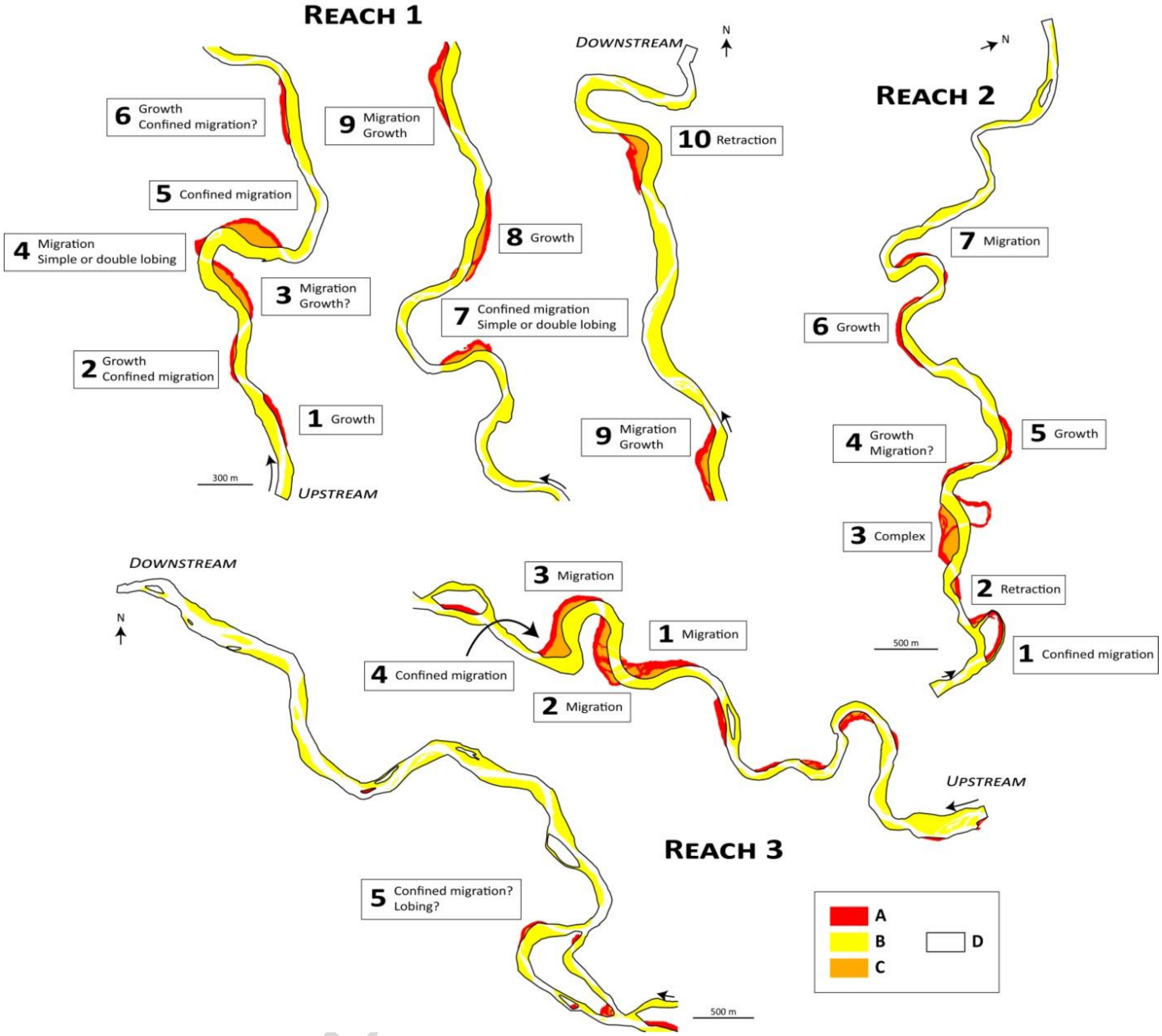


Fig. 7. Planimetric evolution and types of morphological changes on meander loops between 1830 and 1950. A: Eroded areas; B: vegetated areas; C: eroded then vegetated areas; D: riverbed in circa 1830.

1950-2005: The morphological changes between 1950 and 2005 were much smaller than those that occurred in the previous period. Assigning them to a type of change is problematic because of the scarcity of newly vegetated areas during this period. An equivalent process of colonization by vegetation on the opposite bank rarely compensated for bank erosion. For this reason, an increase in bed width was observed in many sections with no change in the position of the river course. With the exception of three short portions of loops in reach 1 (numbers 5, 6, and 7 in Fig. 8), no section of the

1950 bed was sufficiently mobile to be fully occupied by the alluvial plain in 2005. Nevertheless, two major morphological events occurred. In reach 2, a meander loop that was cut off in 1950 was filled in. In reach 3, a loop was cut off (chute) and then filled in (Fig. 8).

The changes in reaches 1 and 3 were spatially discontinuous (Fig. 8). Meanders were characterized by clear alternation of stable and unstable reaches, and most vegetated areas were located in the close vicinity of the erosion areas. In reach 3, erosion activity was more intense upstream (erosion of the large islands in the downstream part resulted from bed maintenance: Fig. 8). Along the downstream section, lateral erosion or stabilization by vegetation was almost nonexistent. reach 2 was somewhat different from the other two (Fig. 8). The activity was less fragmented and almost exclusively the result of erosion. Apart from the oxbow filling, stabilization by vegetation was insignificant.

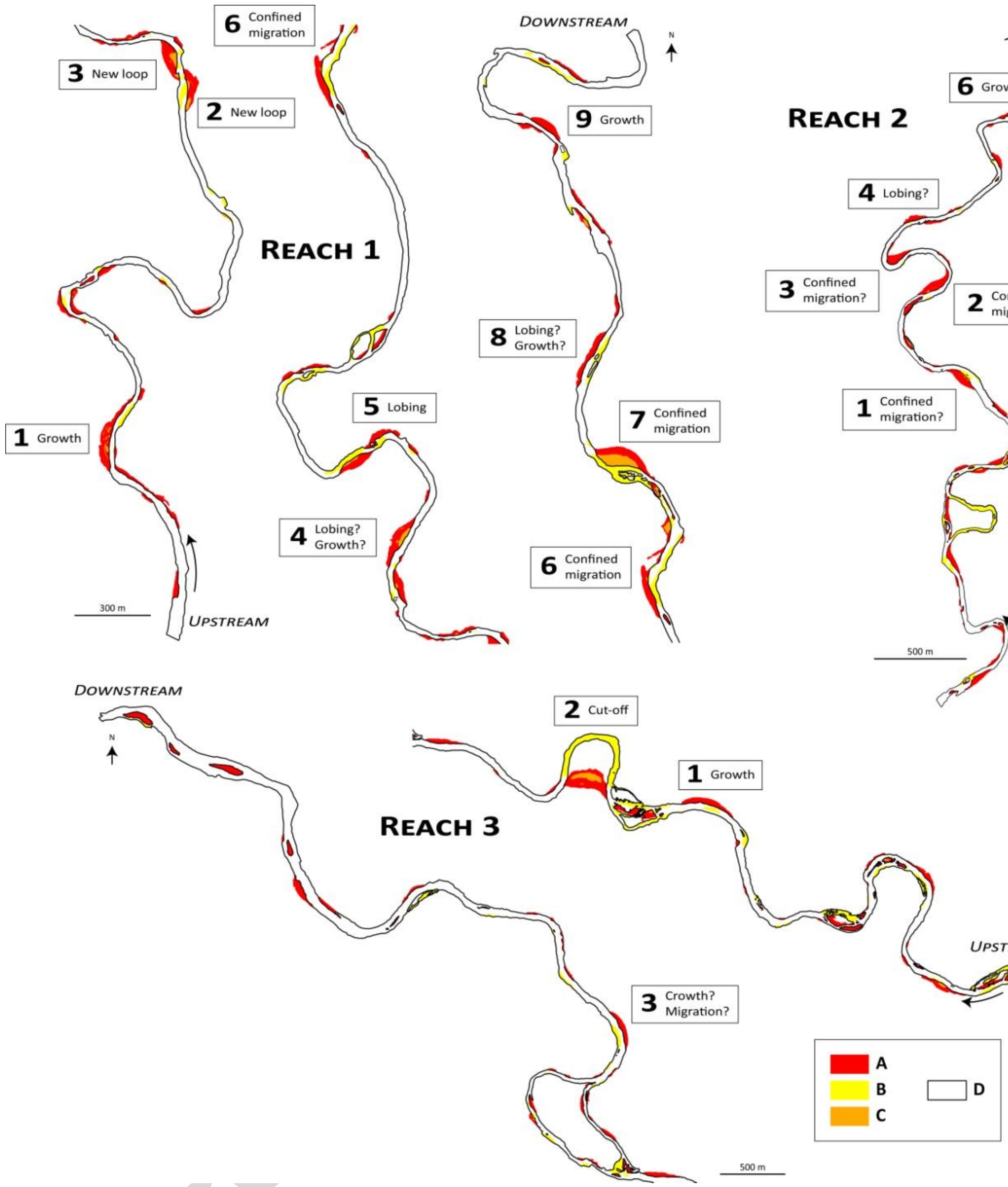


Fig. 8. Planimetric evolution and types of morphological changes on meander loops between 1950 and 2005. A: Eroded areas; B: vegetated areas; C: eroded then vegetated areas; D: 1950 active bed.

4.2. Subperiods between 1950 and 2005: relatively high bank retreat

At the reach scale in the different subperiods from 1950 to 2005, the average annual standardized bank retreat rates (expressed as a % of the original width of the active bed) were between 1.3 and 4.7

(Fig. 9 and Table 6). This equates to a retreat of from 0.7 to 1.3 m y^{-1}. At the loop scale, the maximum retreat rates were between 4 and 5.7 m y^{-1} (Fig. 10).

Considering each reach as a whole, and for the different subperiods, the percent of the length of eroded banks was between 0.4 and 3.1 % y^{-1} (Fig. 9). At the loop scale, the erosion was quite discontinuous as loops were rarely affected over their entire length. Furthermore, with the exception of the last period in reach 1 and of the first period in reach 3, at least half of the total number of loops were subject to erosion for each period (Table 6).

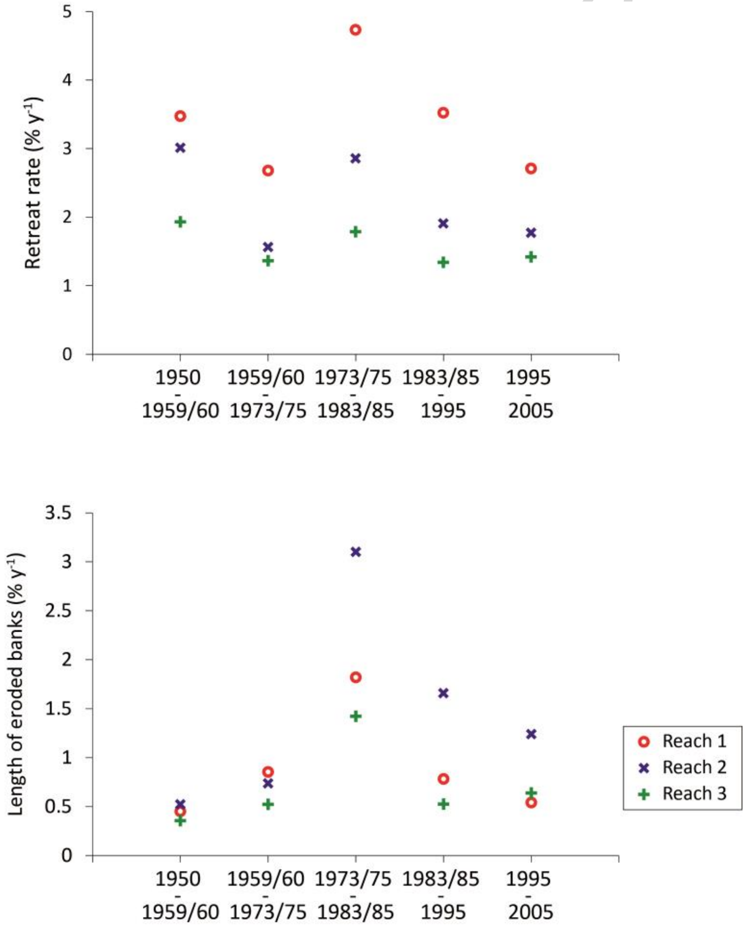


Fig. 9. Standardized annual rates of bank retreat (expressed as % of the original bed width) and annual length of eroded banks (expressed as % of the length of banks) for each reach and each of the subperiods between 1950 and 2005.

Table 6

Bank retreat rates and length of eroded banks for each reach and each subperiod between 1950 and 2005

Reach 1	**1950-1960**	**1960-1975**	**1975-1985**	**1985-1995**	**1995-2005**
Retreat rate (m y^{-1})	0.95	0.75	1.31	1.18	0.96
Lenght of eroded banks (%)	4.5	12.8	18.2	7.8	5.4
Number of loops with lateral erosion	11/19	15/19	19/19	12/21	10/21
Reach 2	**1950-1959**	**1959-1973**	**1973-1983**	**1983-1995**	**1995-2005**
Retreat rate (m y^{-1})	1.13	0.67	1.08	0.86	0.91
Lenght of eroded banks (%)	4.7	10.3	31	19.9	12.4
Number of loops with lateral erosion	9/17	13/17	16/16	15/16	10/16
Reach 3	**1950-1959**	**1959-1973**	**1973-1983**	**1983-1995**	**1995-2005**
Retreat rate (m y^{-1})	1.21	0.82	1.15	0.99	0.99
Lenght of eroded banks (%)	3.2	7.3	14.2	6.3	6.4
Number of loops with lateral erosion	8/24	12/24	14/24	16/24	13/24

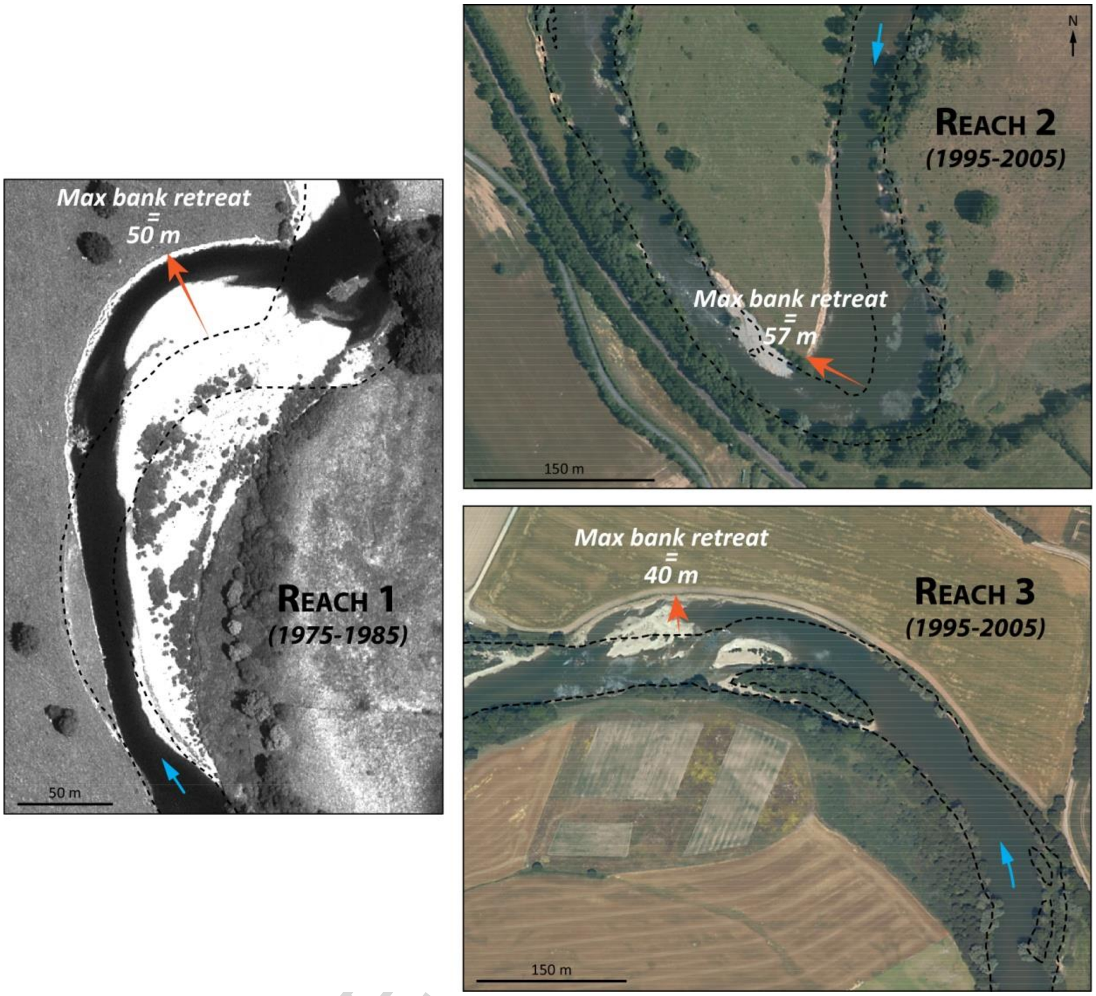


Fig. 10. Maximum bank retreat observed in each study reach for the 1950-2005 period.

4.3. A low critical discharge for lateral erosion

Lateral erosion occurred frequently in all three reaches. Between 2009 and 2013, it began at a maximum instantaneous discharge (at the reference gauging station) of 52 $m^3 s^{-1}$ in reach 1, 130 $m^3 s^{-1}$ in reach 2, and 185 $m^3 s^{-1}$ in reach 3. If one refers to the daily flows, this is equivalent to respectively 24, 14, and 23 days of activity per year. These discharges were between 0.47 and 0.64 $Q_{1.5}$ i.e., well below the bankfull discharge.

For the survey event whose maximum discharge corresponds to the critical discharge, 10 sections of banks were eroded in reach 1, with a mean bank retreat rate of 0.5 m. The specific stream power for these sections is between 5 and 21 W m^{-2} when estimated with the bankfull width. It is between 8 and

34 W m^{-2} when estimated with the active bed width. In reach 2, seven sections of banks were eroded, with a mean bank retreat rate of 0.4 m. The specific stream power is between 5 and 22 W m^{-2} with the bankfull width and between 7 and 27 W m^{-2} with the active bed width. In reach 3, four sections of banks were eroded, with a mean bank retreat rate of 0.45 m. The specific stream power is between 3 and 13 W m^{-2} with the bankfull width and between 4 and 18 W m^{-2} with the active bed width. Computed from these ranges of critical specific stream power values, the percentage of the number of loops that could be subject to lateral erosion with a discharge of 1.5 years return interval is 32-89% in reach 1, 27-93% in reach 2, and 33-87% in reach 3 (in this reach, calculation was made only for loops uninfluenced by the Boutet weir).

If we use the mean hydraulic values at the reach scale, the critical specific stream power is 8-12 W m^{-2} in reach 1, 15-18 W m^{-2} in reach 2, and 6-9 W m^{-2} in reach 3. Finally, for the whole study period (2009-2013), the percentage of river length affected by bank erosion was between 3.9 and 15.3. Bank retreat comprised between 2.2% and 5.4% of the active bed width.

4.4. A quite frequently mobilized bed material load

The critical discharge in the loops of the three study reaches surveyed was low and bedload mobilization thus occurred quite frequently (Table 7). It occurs between 26 and 48 m^3 s^{-1} in reach 1 (discharge value at the reference gauging station), at 130 m^3 s^{-1} in reach 2, and at 226 m^3 s^{-1} in reach 3. The critical specific stream power is between 10 and 21 W m^{-2} in reach 1, 17 and 23 W m^{-2} in reach 2, and 8 and 14 W m^{-2} in reach 3. Computed from these ranges of critical specific stream power values and considering a similar grain size all along each reach, the percentage of the number of loops that could be subject to bedload mobilization with a discharge of 1.5 years return interval is 32-68% in reach 1, 20-40% in reach 2, and 20-60% in reach 3 (in this reach, calculation was made only for loops uninfluenced by the Boutet weir).

The mobilization frequencies were established on short river sections whose geometrical characteristics (mainly slope but also width) differ somewhat from those of the reaches considered in their entirety. To estimate these frequencies at the reach scale, we relied on the critical specific stream power calculated for each of the short sections. We systematically obtained two values: the lowest from a stream power calculated with the active bed width, the highest from a stream power calculated with the bankfull width. When they are computed in this way, the mobilization remains relatively frequent. In reach 1, it is between 8 and 32 d y^{-1} when considering a critical discharge of 26 $m^3 s^{-1}$. It is between 1 and 8 d y^{-1} when considering a critical discharge of 48 $m^3 s^{-1}$. In reaches 2 and 3, it is between 4 and 12 d y^{-1}, and between 2 and 23 d y^{-1}, respectively.

Finally, in the three reaches, the bedload transport was partial because only a portion of the tracers, and thus of the bed, were mobilized each year (Fig. 11). Further, the competence of the river is quite high because, in each reach, almost the entire grain-size distribution was mobilized for discharge below the bankfull level (Fig. 11).

Table 7

Critical discharge for bedload incipient motion and frequency of mobilization of the Cher River.

		Reach 1	**Reach 2**	**Reach 3**
Loop	**Qc**	0.3-0.5 $Q_{1.5}$ 0.3-0.6 Q_{BF}	0.6 $Q_{1.5}$ 0.5 Q_{BF}	0.8 $Q_{1.5}$ 0.7 Q_{BF}
	N° of days y^{-1}	29-85	11	13
Reach	**Qc**	0.4-1.4 $Q_{1.5}$ 0.5-1.7 Q_{BF}	0.6-1 $Q_{1.5}$ 0.4-0.7 Q_{BF}	0.6-1.4 $Q_{1.5}$ 0.5-1.2 Q_{BF}
	N° of days y^{-1}	1-32	4-12	2-23

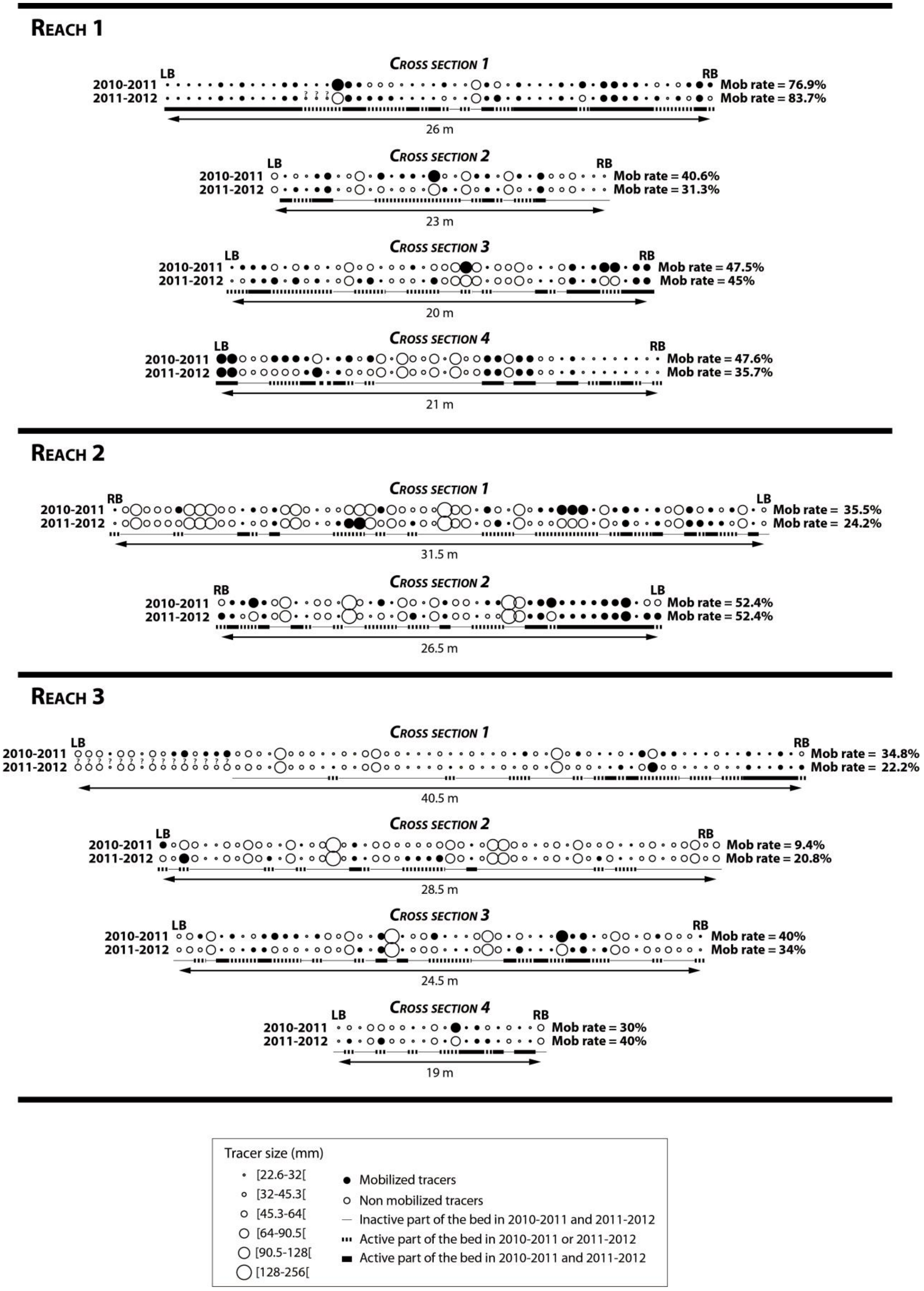

REACH 1
CROSS SECTION 1
LB
RB
2010-2011
2011-2012
Mob rate = 76.9%
Mob rate = 83.7%
26 m
CROSS SECTION 2
LB
RB
2010-2011
2011-2012
Mob rate = 40.6%
Mob rate = 31.3%
23 m
CROSS SECTION 3
LB
RB
2010-2011
2011-2012
Mob rate = 47.5%
Mob rate = 45%
20 m
CROSS SECTION 4
LB
RB
2010-2011
2011-2012
Mob rate = 47.6%
Mob rate = 35.7%
21 m
REACH 2
CROSS SECTION 1
RB
LB
2010-2011
2011-2012
Mob rate = 35.5%
Mob rate = 24.2%
31.5 m
CROSS SECTION 2
RB
LB
2010-2011
2011-2012
Mob rate = 52.4%
Mob rate = 52.4%
26.5 m
REACH 3
CROSS SECTION 1
LB
RB
2010-2011
2011-2012
Mob rate = 34.8%
Mob rate = 22.2%
40.5 m
CROSS SECTION 2
LB
RB
2010-2011
2011-2012
Mob rate = 9.4%
Mob rate = 20.8%
28.5 m
CROSS SECTION 3
LB
RB
2010-2011
2011-2012
Mob rate = 40%
Mob rate = 34%
24.5 m
CROSS SECTION 4
LB
RB
2010-2011
2011-2012
Mob rate = 30%
Mob rate = 40%
19 m
Tracer size (mm)
[22.6-32[
[32-45.3[
[45.3-64[
[64-90.5[
[90.5-128[
[128-256[
Mobilized tracers
Non mobilized tracers
Inactive part of the bed in 2010-2011 and 2011-2012
Active part of the bed in 2010-2011 or 2011-2012
Active part of the bed in 2010-2011 and 2011-2012

Fig. 11. Mobilization rates and localization of mobilized and nonmobilized tracers between 2010 and 2012.

4.5. Strong constraints exerted by river engineering works

4.5.1. Age and extent of bank protections

The bank protections are composed of multi decimeter blocks that are often degraded (Fig. 12). Most have accumulated at the bank toes, frequently below the low-flow water level. Their exact date of construction is unknown because no evidence was found in the archives. However, the archives did reveal that this kind of protection was already present in the river in the first half of the nineteenth century (Fig. 13). Because most of current protection was located along the limits of the active bed in 1950, we can reasonably assume they were installed before that date. This reasoning is difficult to apply to the limits of the 1830 bed owing to the uncertainty associated with their position. However, when current protections are located in areas eroded between 1830 and 1950, they can be assumed to date from after 1830. Furthermore, many of the protections in reach 1, and to a lesser extent in reach 2, are probably at least a hundred years old because trees that are over a century old are now growing on top of them. They could be protections that were provided by the State as part of global planning of the Cher River following the 1856 centennial flood.

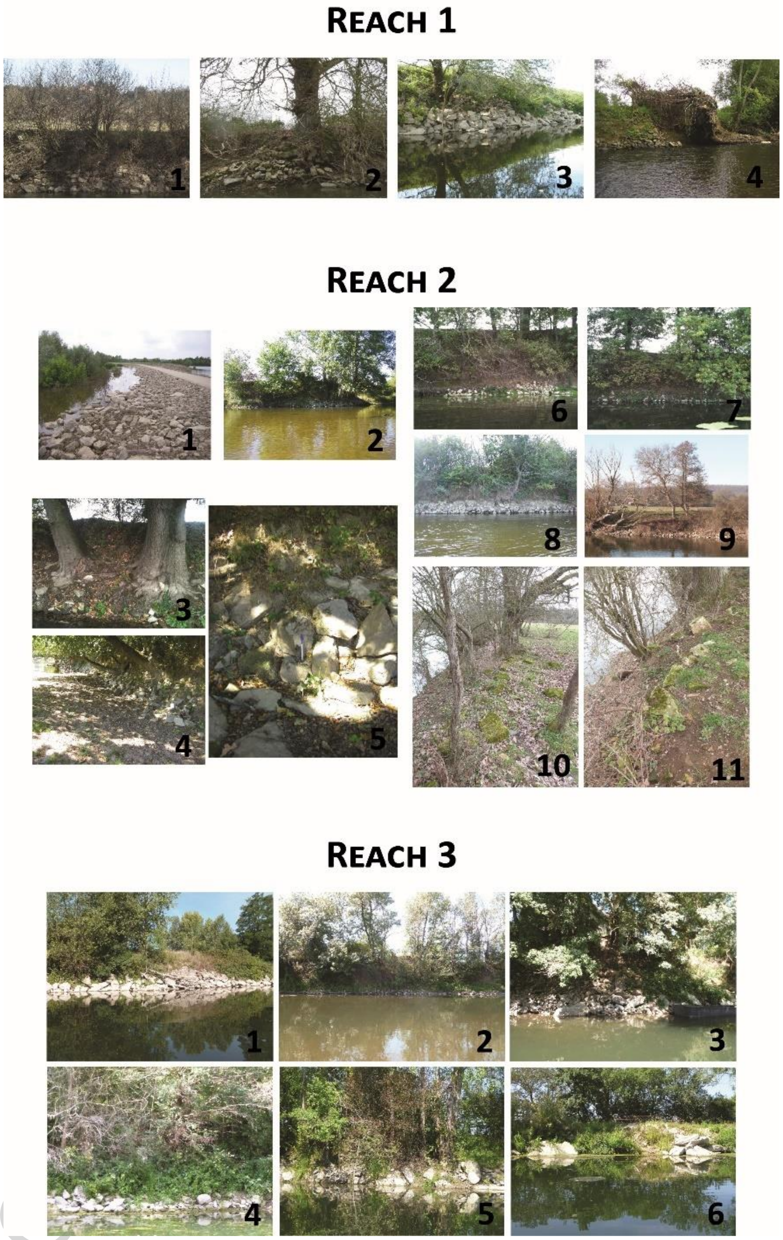


Fig. 12. Overview of bank protections identified in 2010-2011. See Fig. 14 for location.

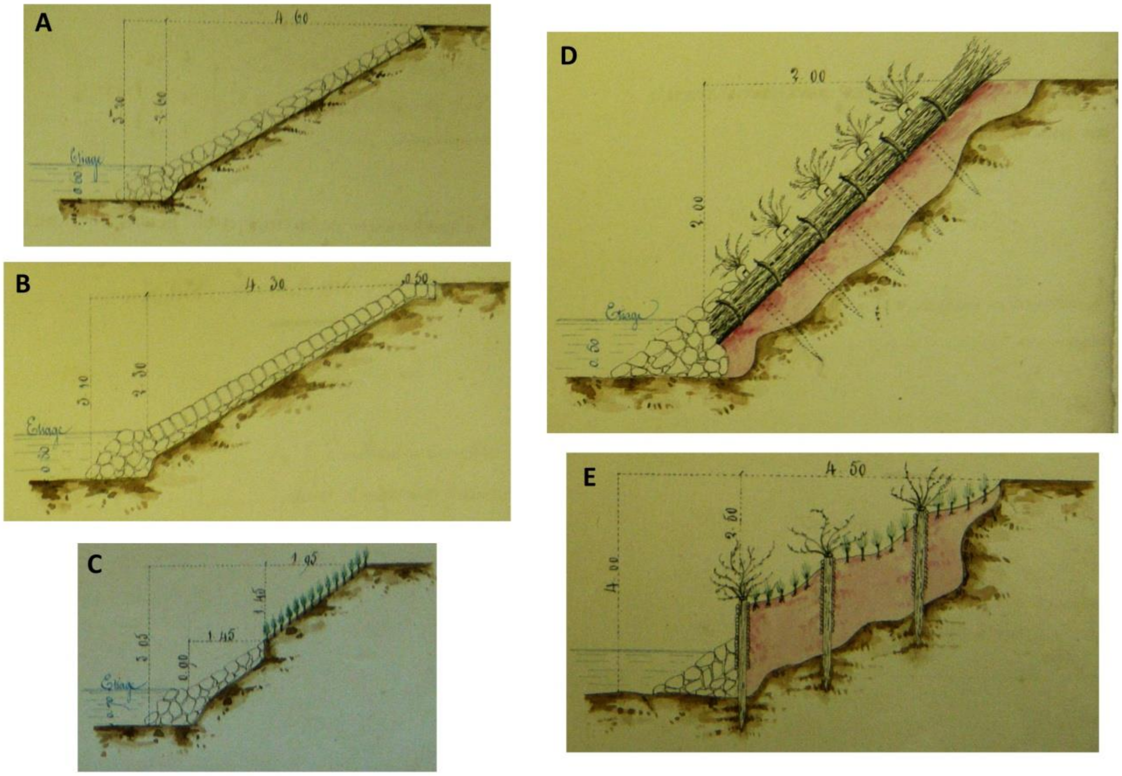


Fig. 13. Examples of types of bank protections built on the Cher River before 1857 (Archives of the Cher Department). (A) and (B) Simple covering with juxtaposed stones. (C) Covering with juxtaposed stones and Salix plantings. (D) Covering with rip-rap at the bank toe and bundles of branches fixed on the bank with stakes. (E) Covering with rip-rap at the bank toe and hurdle of stakes and Salix plantings on the bank.

Finally, field mapping in 2010-2011 revealed that a large proportion of the river banks are protected: 27% to 56% of the length of each reach (Table 8 and Fig. 14). The length of riprapped banks is probably an underestimation because they are immersed or covered by vegetation or fine sediment, particularly in reach 3.

Table 8

Percentage of river length occupied by bank protections; In reach 3, the proportion of bank protection was calculated on the part of the reach that is not affected by the Boutet weir (see below)

		Reach 1	**Reach 2**	**Reach 3**
Current protections	**% of the length of the two banks**	25.5%	30%	14%
	% of the length of the river	51%	56%	27%
Protections constructed before 1950	**% of the length of the two banks**	24.5%	20%	11%
	% of the length of the river	49%	38%	21%

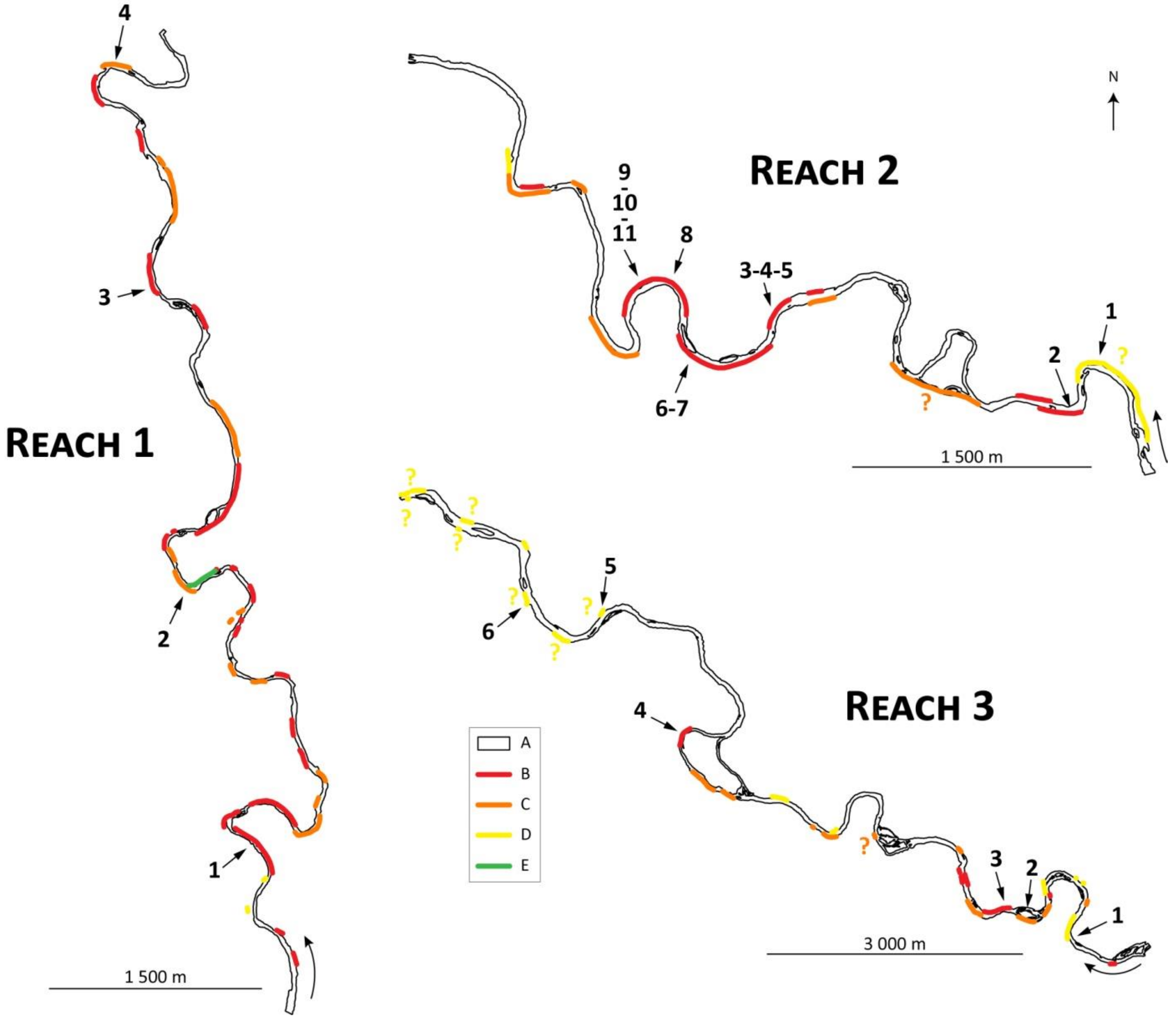


Fig. 14. A: Active bed in 1950; B: bank protections pre-1950 and post-1830; C: bank protections pre-1950; D: bank protections post-1950; E: bank protections pre-1950 and post-1830 integrated in the floodplain between 1950 and 2005. The question marks show the location of bank protections whose date of construction is uncertain. The numbers refer to the photos of bank protections shown in Fig. 12.

4.5.2. Bank protections and longitudinal distribution of lateral erosion from 1950 to 2005

In terms of river length affected by lateral erosion, the difference between banks with protections and banks deprived of protections is statistically significant in reach 1 and in reach 3, but for the latter, only with the bank protections built before 1950 (Table 9). In reach 1, lateral erosion concerned 66% of the cross sections deprived of bank protections and 35% of the cross sections with protections. In reach 2, when considering all the bank protections identified in 2010-2011, lateral erosion concerned 90% of the cross sections deprived of bank protections and 84% of the cross sections with protections. With only the bank protections built before 1950, the values are also very close: 89% and 82% respectively. In reach 3, the analysis was realized for the section not influenced by the Boutet weir (see below). When considering all the bank protections identified in 2010-2011, lateral erosion concerned 68% of the cross sections deprived of bank protections and 56% of the cross sections equipped with protections. With only the bank protections built before 1950, the values are 69% and 47% respectively.

Table 9

Presence/absence of bank protections and of lateral erosion between 1950 and 2005 along cross-sections spaced one bankfull width; the statistical difference is determined through a $\boldsymbol{\chi^2}$ test. $\boldsymbol{\chi_c^2}$ indicates the critical value of the test.

	Erosion	**No erosion**	χ_c^2	χ^2	**p-value**
Reach 1					
Presence of bank protections	62	122	3.84	31.46	< 0.0001
Absence of bank protections	105	58			
Reach 2					
1950 bank protections					
Presence of bank protections	15	121	3.84	1.25	0.26
Absence of bank protections	13	61			
2005 bank protections					
Presence of bank protections	11	91	3.84	0.73	0.39
Absence of bank protections	17	91			
Reach 3					
1950 bank protections					
Presence of bank protections	37	84	3.84	5.03	0.025
Absence of bank protections	19	17			
2005 bank protections					
Presence of bank protections	36	75	3.84	1.28	0.26
Absence of bank protections	20	26			

4.5.3. Weir and other types of engineering structures in reach 3

The downstream 5.5 km of reach 3 (35% of the total length) is under the direct control of the Boutet weir (Fig. 15), constructed in 1418 at the latest (Sogreah, 2011) and with a current low-flow fall height of 2.8 to 3 m. The river length influenced by the weir was estimated by examining and locating evidence of morphological activity: planform eroded surfaces, bars, and riffles. In this portion of the river, planform erosion has been basically absent since 1825. Moreover, almost no bar is observable on the aerial photographs. Finally, no riffles were detected during the field survey in summer 2010. The influence of the weir was further confirmed by the marked difference in slope between the 5.5 km of this section (0.0000273 m m^{-1}) and the remaining reach (0.000307 m m^{-1}), where the slope is 11.2 times steeper. The difference is even more pronounced in terms of bankfull specific stream power (15 times higher: 12.2 W m^{-2} vs. 0.8 W m^{-2}).

On the section unaffected by the weir, other river works were identified along the course of the river (Fig. 15). This is for example the case of the relics of two former mills and their adjoining structures (Fig. 15 and Fig. 16). Rozay’s mill was built in 1495 at the latest (Franquelin, 1998). Its abandonment and the dismantling of some of its facilities date back to 1903 (Franquelin, 1998). Only the weir located at the entrance of the right channel of the Rozay island was preserved. It is now seriously damaged (Fig. 15). Much less information was available about the Perriot mill. Its presence dates back to at least 1694 (Serna, 2013). The role of most of the other types of structures, today in ruins and thus devoid of any functionality, has not been identified (Fig. 15). Like the relics of the mills, they are composed of blocks several dozen centimeters in size that far exceed the competence of the river and sometimes pave the entire width of the bed.

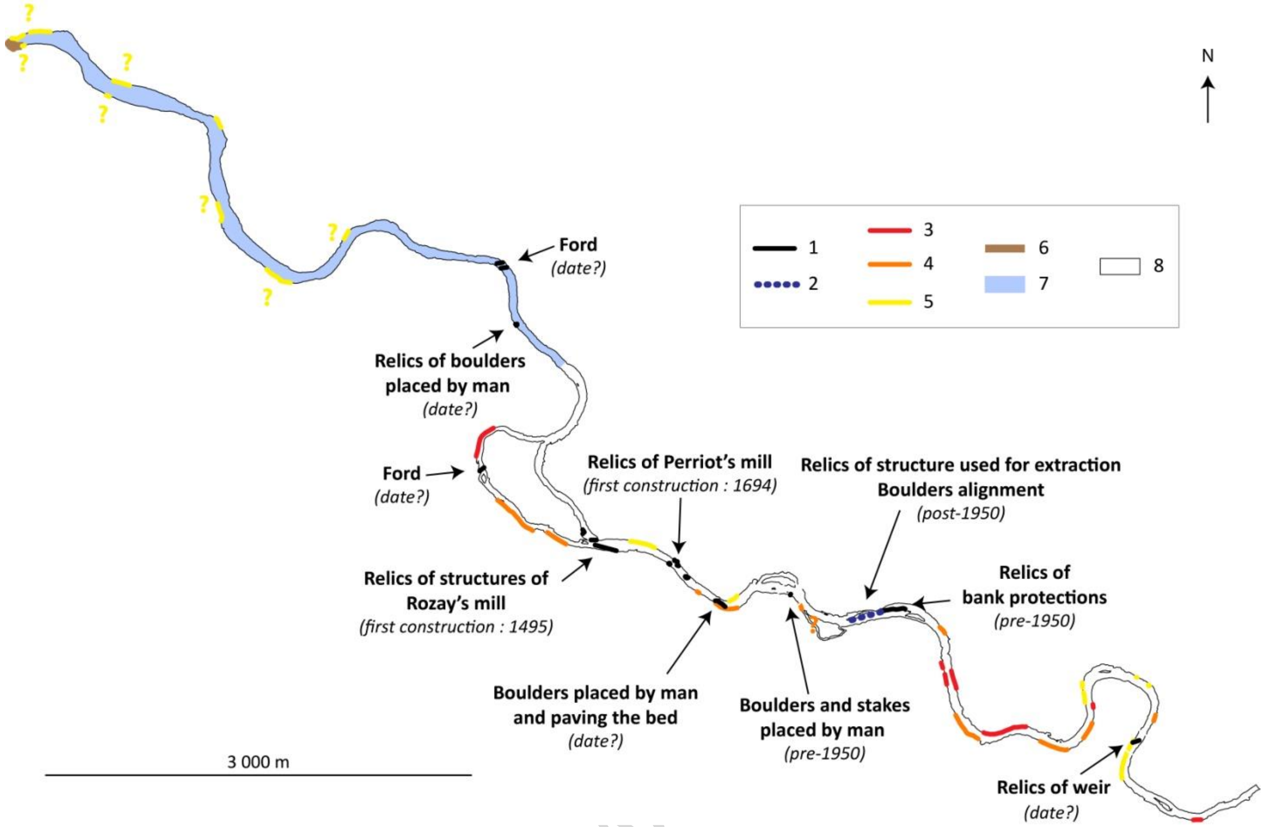


Fig. 15. Engineering structures and remains of structures in reach 3. 1: Remains pre-1950; 2: remains post-1950; 3: bank protections pre-1950 and post-1830; 4: bank protections pre-1950; 5: bank protections post-1950; 6: boutet weir; 7: section influenced by the Boutet weir; 8: 2005 active bed. The question marks show the location of bank protections where date of construction is uncertain.

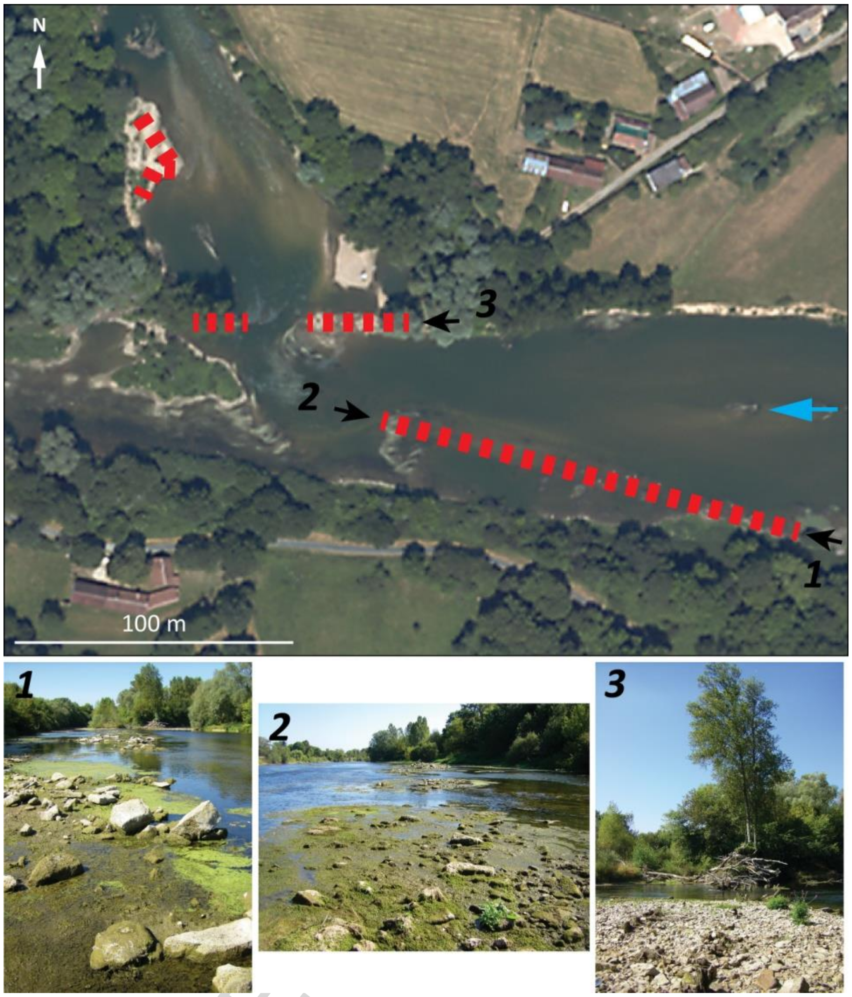


Fig. 16. Current relics of Rozay's mill (first built in 1495 at the latest). The red dotted lines indicate the location of the remains, mainly composed of multidecimeter blocks. On image 3, we can see relics of wooded piles, aligned across the bed at the location of the former weir.

5. Discussion

5.1. Comparisons of channel changes reconstructed from old maps and from aerial photos: biases and methodological limits

Using old maps for the reconstruction of the evolution of river courses raises the question of the reliability of the measured changes (Lawler, 1993; Gurnell et al., 2003). The level of reliability will mainly depend on the spatial accuracy of the representation of the studied objects and our ability to quantitatively take into account this accuracy in the analysis. Gurnell et al. (2003) distinguished three main components defining positional accuracy. The first is related to measurement error, the second to uncertainty in the identification of the boundaries of the studied object, and the third to deformations induced by the representation of the information into a map. Concerning the excerpts from the Napoleonic Cadaster used for the Cher River, these three components were considered (cf. methodological section). Furthermore, to reduce as far as possible the risk of inclusion of spurious channel changes, the uncertainty associated to the positional accuracy was computed fairly conservatively. It thus means that the polygons identified as eroded or stabilized by vegetation between 1830 and 1950 correspond very likely to true evolutions. Conversely, the low amplitude modifications were not detected, inducing a possible underestimation of the channel changes. Nevertheless, one of the main limits of such an analysis is that uncertainty range cannot be associated with the computed evolutions, be they for the bank retreat rates or for the eroded and vegetated areas. In any event, the position of the edge of the river bed in 1830 appears relatively accurate: along sections where the banks were vertical enough, the digitized boundaries of the 1830 river bed quite clearly correspond visually with major break slopes visible on a 2011 LiDAR of the bottom valley and considered as former bank tops (Fig. 17).

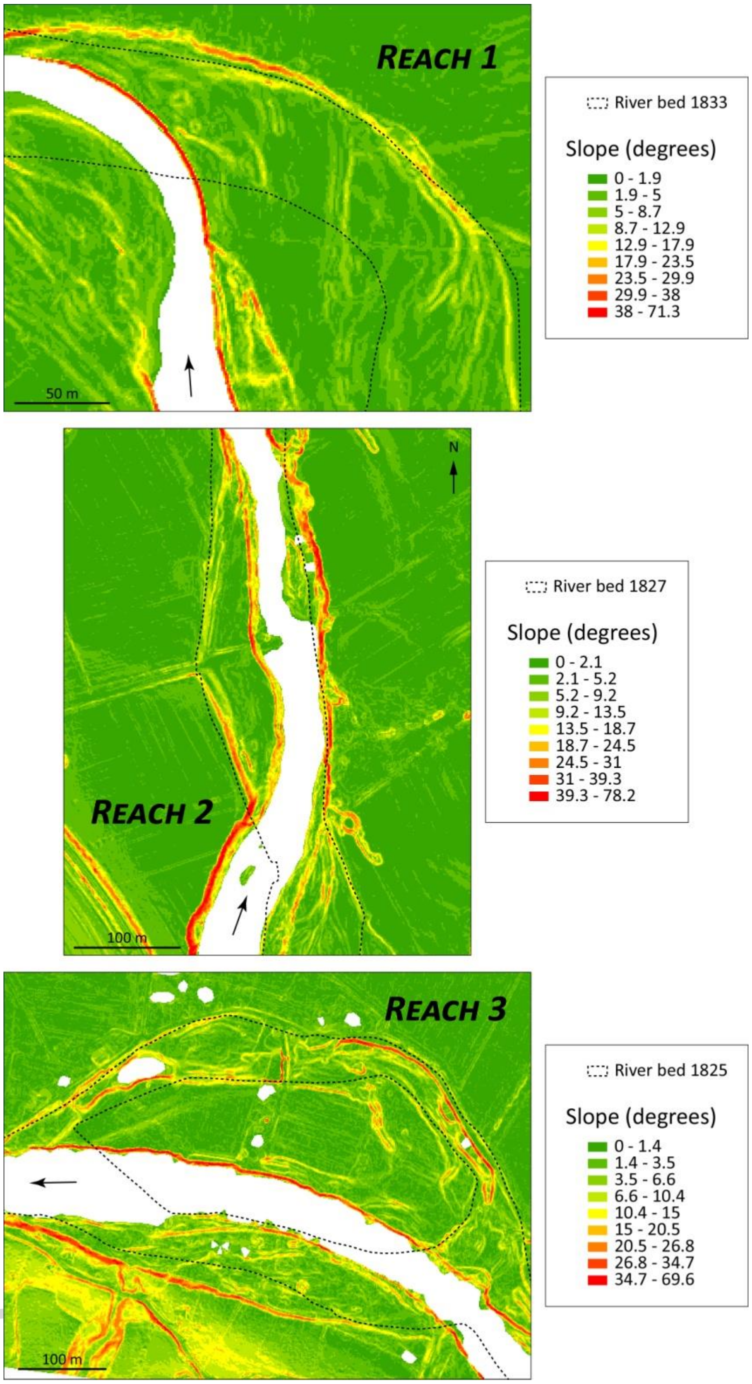


Fig. 17. Slope in sections of the alluvial plain in 2011 (obtained from a LiDAR) and location of the 1830 riverbed.

Moreover, the comparison between the 1830-1950 and 1950-2005 periods must be considered carefully because the digitized channel in 1830 on one hand, and in 1950 and 2005 on the other hand, very likely correspond to different geomorphic units. From 1950 to 2005, it was the active bed. For 1830, the digitized channel was probably more similar to the bankfull bed than to the active bed. The arguments for such affirmation are as follows. First, the Napoleonic Cadaster aimed to determine as precisely as possible the property lines in order to more fairly allocate land taxes and to reduce litigations between owners. Second, the boundaries of rivers belonging to the French State, as the Cher River, are fixed at their maximum level before overflowing. It thus implies that the limits of the surveyed bed for the purpose of the Napoleonic Cadaster correspond probably to that of the bankfull level. In 2005-2010, the bankfull bed width was substantially larger than the active bed width (Dépret, 2014: 1.2-1.6 times larger). If we make the reasonable assumption that such a difference existed in 1830 and 1950, it implies that the eroded and vegetated areas between 1830 and 1950 were probably underestimated and overestimated, respectively. It could signify that the bed narrowing highlighted between 1830 and 1950 is spurious. To verify this, we compared the width of the bankfull bed for the two dates. For this, the width of the digitized bed for 1830 and 1950 was estimated computing the average of cross section length roughly spaced at one bankfull width. Then, the 1950 width (equal to the active bed width) was converted to bankfull width, applying the ratio between active bed width and bankfull width computed for 2005. The comparison of the bankfull width between 1830 and 1950 confirms the narrowing initially stated: the decrease of the bankfull width is 35% in reach 1, 44% in reach 2, and 23% in reach 3.

Finally, discussing the higher erosive activity for the 1950-2005 period in comparison with the 1830-1950 period is necessary. In the three study reaches, the raw erosion rate and the annual percentage of banks that were eroded were respectively 1.4-1.8 and 2.9-3.9 higher during the second period, while the bank retreat rates were similar (0.31-0.42 for 1830-1950, 0.31-0.34 for 1950-2005). This would imply that a potential reduction in the frequency and/or intensity of flood events since the nineteenth century either would have been too low to cause a decrease of the morphogenic activity, or would have been counteracted by the modification of other controlling factors of the erosion, such as the degree of bank resistance for example. This higher activity between 1950 and 2005 nevertheless needs to be put into perspective. First, as we saw above, erosion areas and rates are probably underestimated for the 1830-1950 period. Second, the differences observed with the 1950-2005 period could simply be a result of the significant difference in duration of the two periods (65 years as against 120 years). As already highlighted for example by O'Connor et al. (2003), the intensity of the erosive activity tends to evolve conversely with the studied interval of time. Such a phenomenon can be, for example, observed on the Cher River for the 1950-2005 period. The retreat rates for the subperiods between 1950 and 2005 (1950-1959(60), 1959(60)-1973(75), ..., 1995-2005) are from 2.8 to 4.4 higher than computed using only the 1950 and 2005 aerial photos. The sum of eroded areas for all the subperiods is 1.2-1.4 times higher than the eroded area computed using only the 1950 and 2005 aerial photos. Finally, despite these limitations, a decrease of the erosive activity could have nevertheless occurred between 1830 and 1950, but its detection would have been impossible because of the absence of available intermediate data.

5.2. Geomorphic activity of the meandering Cher River: elements of comparison

The average retreat rates reported in the Cher River for the different subperiods between 1950 and 2005 (Fig. 18), ranging from 1.3% y^{-1} to 4.7% y^{-1}, approach rates reported for mobile meander systems. Fig. 18 shows the retreat rates of 44 mobile meandering rivers — some of them among the most dynamic in the world — as well as the rates measured on the Cher River for each of the subperiods studied. The rates on the other rivers were obtained from old maps and/or aerial photographs using methodologies and periods similar to those used in our study. The highest average annual rates exceeded 5% of the bed width. This was the case of the Dane River (15.5% between 1996 and 2001: Hooke and Yorke, 2010), the Beni River (5-6% from 1967 to 2002 (Gautier et al., 2007)), the Luangwa River (5.8% between 1982 and 1987: Gilvear et al., 2000), and some Canadian rivers (respectively 5.4%, 5.6%, 7.8% for the Muskwa River, Waterton River, and Oldman River over periods of between 21 and 33 years: Nanson and Hickin, 1986).

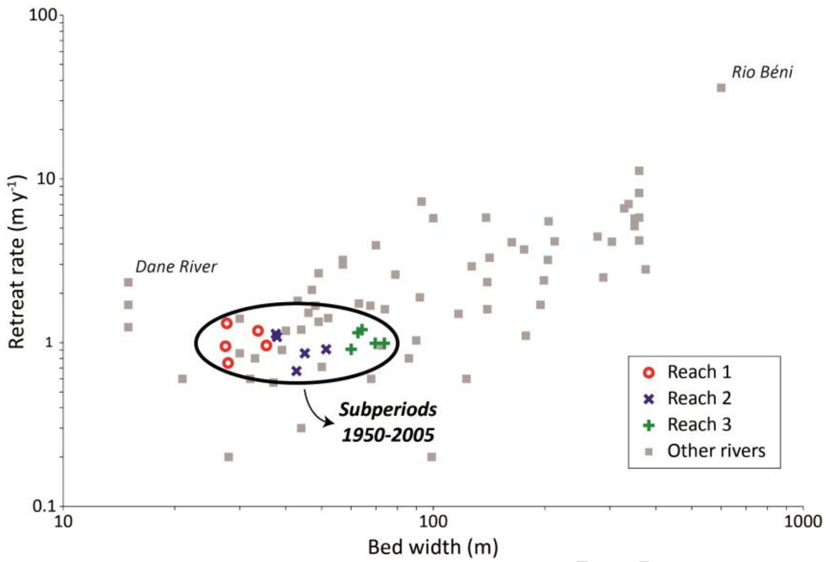


Fig. 18. Annual rates of bank retreat on the Cher River and on mobile meandering rivers expressed as a percentage of the original bed width (source: Nanson and Hickin, 1986; Odgaard, 1987; Gilvear et al., 2000; Shields et al., 2000; Micheli and Kirchner, 2002; Micheli et al., 2004; Wallick, 2004; Pisut, 2006; Gautier et al., 2007; Wallick et al., 2007; Aalto et al., 2008; Nicoll and Hickin, 2009; Hooke and Yorke, 2010; Magdaleno and Fernandez-Yuste, 2011; Michalkova et al., 2011).

In the Cher River, historical analysis and field survey show relatively high bank retreat rates as well as low critical-discharges for lateral erosion. These evidences indicate a substantial potential for lateral mobility, even if the bankfull specific stream (7-34 W m^{-2}) is close to or lower than the threshold range for lateral mobility mostly reported in the literature (25-35 W m^{-2}: Brookes, 1987a, 1987b; Orr et al., 2008; Bizzi and Lerner, 2015). Nevertheless, in a panel of 90 British rivers, Ferguson (1981) identified active free meanders with specific stream power as low as 5 W m^{-2} and inactive free meanders with specific stream power values up to 60 W m^{-2}. Such disparity very probably results from a difference in bank erodibility, which is recognized as a major control of the erosive activity of rivers (Hickin and Nanson, 1984; Baker, 1988; Huang and Nanson, 1998; Millar, 2000). With specific stream power ranging from 1.4 to 5.3 W m^{-2}, Li et al. (2016) reported, for example, a high mobility of the meandering Tarim River (China), which they attributed to fine sediments composing the banks (fine sand and coarse silt), implying their low strength on the one hand and a pulse flow regime on the other. In the three study reaches of the Cher River, banks are schematically composed of two or three main stratigraphic layers, with pebbles, gravels, and sands overlain by overbank sandy silt (Turland et al., 1989a; Lablanche et al., 1994; Larue, 1994; Manivit et al., 1994; Dépret, 2014). The relatively weak cohesiveness of the banks, resulting from their composite structure and the coarseness of their base layer, very likely explains the noticeable lateral activity of the river. Such characteristics make indeed river banks highly erodible (Hooke, 1980; Thorne and Tovey, 1981; Thorne, 1982). This erodibility, combined with the low differential of energy between small and large floods, explains that the planimetric erosion in the meandering Cher River is mainly controlled by low magnitude hydrological events (Dépret et al., 2015).

On the riffles equipped with tracers, bedload mobilization in the Cher River occurs between 11 and 85 d y^{-1} and at 0.3-0.6 x bankfull discharge (Table 7). The equivalency at the reach scale is 1-32 d y^{-1} and 0.4-1.7 x bankfull discharge (Table 7). These latter values are slightly different than those presented by Dépret et al. (2015) because the data used to compute the critical specific stream power are not exactly the same (difference in length of the section considered and use of low-flow slope in one case and of high-flow slope in the other). Regardless of how they were calculated, these values are close, and even sometimes a little higher, than those suggested in the literature. For example, in morphoclimatic conditions similar to those of the Cher River and also using tracers injected in riffles, Houbrechts et al. (2006) reported critical discharge ranging from 29 to 98% of bankfull discharge for many streams of different dimensions in catchment areas ranging from 0.26 to 2904 km². Mobilization frequencies extended from 0.2 to 19 d y^{-1}. For streams whose size is equivalent to that of the Cher River in reach 1 (catchment area >800 km²), the frequency does not exceed 10.5 days. In a study of 45 U.S. streams with a pool-riffle or plane-bed/rapid morphology, with a snow-melt hydrological regime and a wide range of hydraulic and sedimentary characteristics (Q_{BF} = 1-2600 m^3 s^{-1}, slope = 0.0003-

0.05 m m^{-1}; D_{50s} = 27-221 mm), Mueller et al. (2005), using bedload rating curves, reported critical-discharge ranging from 21 to 123% of the bankfull discharge, the average being 67%.

In the Cher River, critical specific stream power for bedload incipient motion ranges from 8 to 23 W m^{-2} for a D_{50} of bed surface between 22 and 38 mm. Compared with the regressions linking specific stream power and the size of mobilized particles obtained in some Belgian gravel-bed rivers (Petit et al., 2005; Houbrechts et al., 2015), the values for the Cher River appear quite coherent (Fig. 19). These relationships were determined for individual rivers (Petit et al., 2005) or for a set of rivers (Houbrechts et al., 2015) whose catchment size is between 12 and 2660 km² and D_{50} of the bed material is between 15 and 230 mm. Concerning this set of rivers, two regressions were proposed. The first corresponds to the best fit equation, the second to the lower envelope curve. Most of the values for the Cher River are contained between these two relationships (or their extension: Fig. 19).

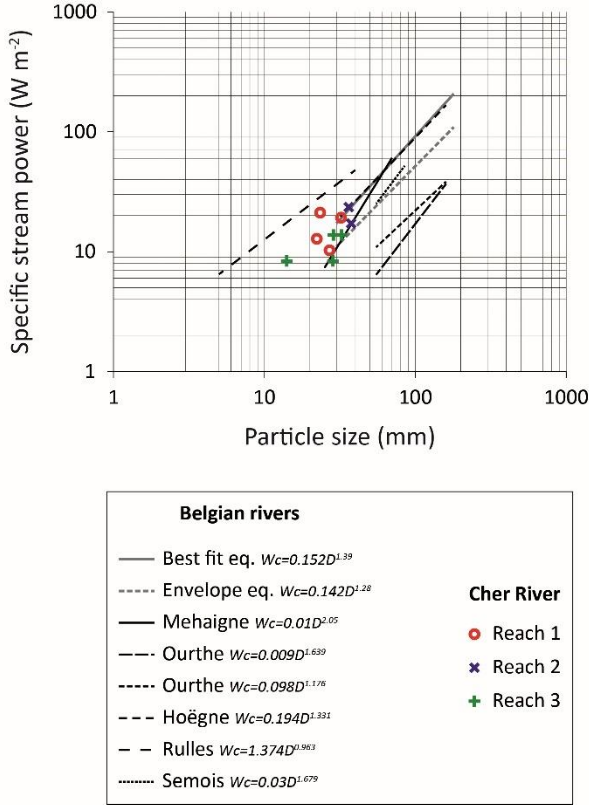
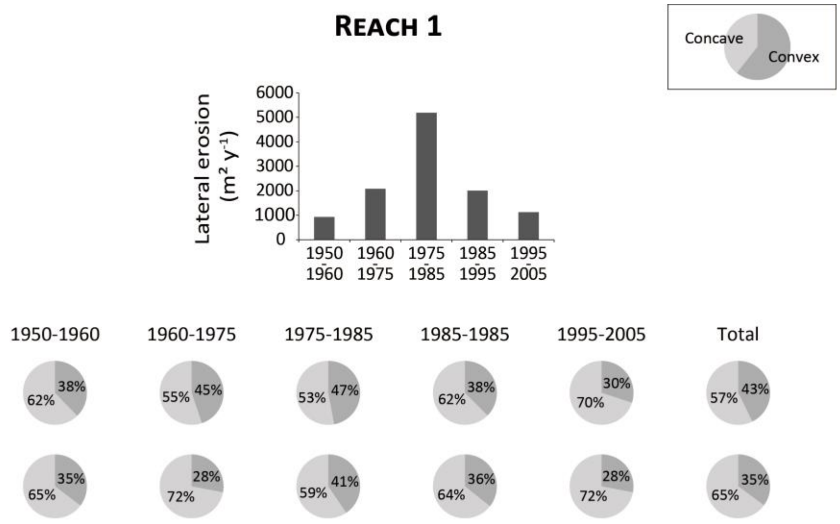


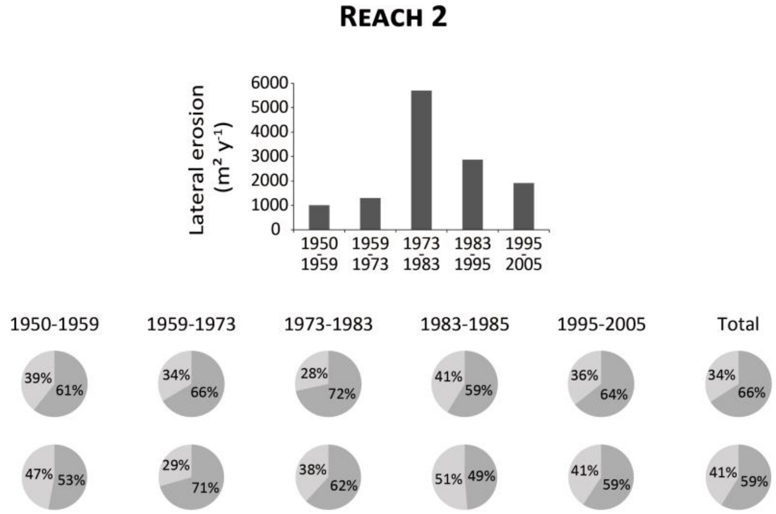
Fig. 19. Relationships between specific stream power and D_{50} of mobilized particles (for Belgian rivers; $W = aD^b$, with Wc the specific stream power, D the size of mobilized particles) or D_{50} of bed material (for the Cher River).

5.3. Causes of low planform mobility of the Cher River meanders

The presence of bank protections along the meander course of the Cher River indicates that the river was subject to lateral displacements at the time of the construction of these engineering structures. Even if they may have not been precisely dated, field evidence and archives indicate that most of them were built before 1950, most probably in fact during the second part of the nineteenth century. If protections attest to river mobility at the time of the construction of bank protections, the question of their current influence remains open. They could have become useless following (i) a pronounced decrease in the frequency/intensity of morphogenic hydrological events, or (ii) a significant reduction in the power of the stream. The planform activity and bank retreat rates reported since the early nineteenth century, as well as the current low critical-discharge for lateral erosion and for bedload mobilization, refute these hypotheses. This suggests that since at least 150 years ago, and still currently, the Cher meanders are perfectly capable of reworking their alluvial plain, demonstrating that the moderate displacements of the river course are not the result of a too weak hydrological activity or of insufficient specific stream power. The planform stability would thus be primarily, if not exclusively, the result of the constraints imposed by the engineering works installed in the bed of the Cher River.

In reaches 1 and 2, owing to their important length (more than 50% of the river course), bank protections can be reasonably considered to be the major cause of the low meander mobility since 1950, and probably even since the second part of the nineteenth. Despite their disrepair, they still represent a major constraint on the initiation and expression of lateral erosion processes. The fact that the blocks fall and accumulate at the bank toes even tends to strengthen these blockages, *overprotecting* the base of the banks, thereby preventing any possibility of undermining. In reach 1, this constraining influence is confirmed by the relation between the longitudinal distribution of the lateral erosion and the location of bank protections: from 1950 to 2005, lateral erosion was significantly higher along sections deprived of protections than along sections equipped with protections (Table 9). Such a relation was not observed in reach 2, where the percentage of river length affected by lateral erosion is similar in sections with and without bank protections. This is very probably because of the influence of the important bed incision that occurred in the reach during the second part of the twentieth century, whose maximum values were 2-2.5 m (Dépret, 2014; Dépret et al., 2015). Bed degradation can indeed promote lateral erosion by destabilization of the banks, resulting from the increase of their height and angle (Schumm et al., 1984; Simon, 1989; Watson et al., 2002; Simon and Rinaldi, 2006). This destabilization would explain the fact that lateral erosion was much less discontinuous in reach 2 than in reaches 1 and 3, with almost the entire length of the reach involved in lateral erosion. Moreover, the consequences of the incision can also be read in the distribution of the erosion according to its location along concave or convex banks. Below, two values are given for each reach. The first presents the distribution obtained from the limits of the loops at the start of the study period. The second presents the distribution obtained from the limits of the loops at the end of the study period. In reaches 1 and 3, respectively 35-43% and 31-34% of the lateral erosion were located along convex banks (Fig. 20). Values in reach 2 were 59-66% (1.3-2.2 higher than in reaches 1 and 3: Fig. 20). While in nondisturbed meandering systems, the majority of lateral erosion occurs along concave banks, in reach 2, the combination of bed incision and of the presence of bank protections, mainly located along concave banks, caused a transfer of a part of the erosion along convex banks.


REACH 1
Concave
Convex
Lateral erosion (m² y⁻¹)
6000
5000
4000
3000
2000
1000
0
1950-1960
1960-1975
1975-1985
1985-1995
1995-2005
1950-1960
1960-1975
1975-1985
1985-1985
1995-2005
Total
62% 38%
55% 45%
53% 47%
62% 38%
70% 30%
57% 43%
65% 35%
72% 28%
59% 41%
64% 36%
72% 28%
65% 35%


REACH 2
Lateral erosion (m² y⁻¹)
6000
5000
4000
3000
2000
1000
0
1950-1959
1959-1973
1973-1983
1983-1995
1995-2005
1950-1959
1959-1973
1973-1983
1983-1985
1995-2005
Total
39% 61%
34% 66%
28% 72%
41% 59%
36% 64%
34% 66%
47% 53%
29% 71%
38% 62%
51% 49%
41% 59%
41% 59%

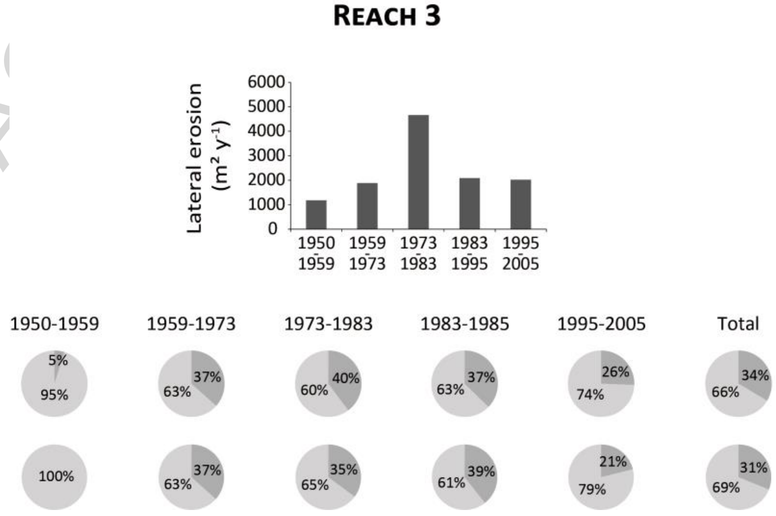

REACH 3
Lateral erosion (m² y⁻¹)
6000
5000
4000
3000
2000
1000
0
1950-1959
1959-1973
1973-1983
1983-1995
1995-2005
1950-1959
1959-1973
1973-1983
1983-1985
1995-2005
Total
5% 95%
63% 37%
60% 40%
63% 37%
74% 26%
66% 34%
100%
63% 37%
65% 35%
61% 39%
79% 21%
69% 31%

Fig. 20. Percentage of lateral erosion located along convex and concave banks between 1950 and 2005.

In reach 3, the downstream 5.5 km (35% of the total length) is under the direct control of the Boutet weir (Fig. 15). In this section, the bankfull specific stream power of 0.8 W m^{-2} (against 12.2 W m^{-2} in the section upstream) appears to be too low to sustain erosive activity (Ferguson, 1981; Rhoads and Miller, 1991). For this reason, the section can be considered to have been *frozen* for at least two centuries. In the rest of the reach, bank protections are less present than in reaches 1 and 2 (20-25% of the river length against more than 50%). Despite this fact, bank protections could have controlled at least partially the longitudinal distribution of the erosion, as, when considering the protections built before 1950, the lateral erosion between 1950 and 2005 was significantly higher along sections deprived of protections than along sections equipped with protections (Table 9). Nevertheless, because of their limited presence, bank protections appear to be possibly insufficient as a sole explanation for the low mobility of this reach. Other types of engineering structures have certainly contributed directly to stabilizing the river course. We observed that the riverbed is occupied by remains of such structures, composed of blocks several dozen centimeters in size that far exceed the competence of the river, and sometimes pave the entire width of the bed (Fig. 15 and Fig. 16). Even in their current state of disrepair, they likely still function as major constraints to the mobility of the river. One of the most striking examples is that of the two former mills and of their associated structures, particularly the spillways and the weirs, that are generally recognized as hard spots that prevent or severely restrict river bed mobility (Malavoi, 2003: Fig. 15 andFig. 16). Finally, the combined actions of bank protection and of the other types of structures identified in reach 3 would more satisfactorily explain the overall stability of the meander course since 1830. Moreover, compared to reaches 1 and 2, bank protections in reach 3 may have been incomplete because of the greater width and depth of the channel.

Overall, estimating the influence of bank protections or other structures on the location of planform erosion is a difficult task because of the multiplicity of other potential drivers and their possible interactions. The longitudinal distribution of the lateral erosion may indeed result from a combination of numerous causes, including mainly (i) the bank resistance (Huang and Nanson, 1998; Millar, 2000; Michalkova et al., 2011; Motta et al., 2012), whose variability in gravelly meandering systems is mainly controlled by riverside vegetation and the fine sediments deposited in abandoned channels (Fisk, 1944, 1947; Thorne, 1992; Hooke, 1995; Gilvear et al., 2000; Hudson and Kessel, 2000; Micheli and Kirchner, 2002; Micheli et al., 2004; Güneralp and Rhoads, 2011; Motta et al., 2012); (ii) the local, upstream and downstream curvature (Hickin and Nanson, 1984; Nanson and Hickin, 1986; Furbish, 1988, 1991; Hooke, 1997, 2003b; Zolezzi and Seminara, 2001); (iii) the complexity of the planform geometry (Güneralp and Rhoads, 2009b); (iv) the stream power (Hickin and Nanson, 1984; Nanson and Hickin, 1986; Richard et al., 2005; Larsen et al., 2006a, 2006b; Nicoll and Hickin, 2009); (v) the local sediment supply (Constantine, 2006; Dunne et al., 2010); and (vi) the presence of bedrock outcrops or the close proximity of the channel to valley wall or terrace (Hooke, 2007). On the Cher River, the link between the location of bank protections and the spatial distribution of lateral erosion can also be complicated by the fact that the river can locally circumvent the protections, as it happened for example for a loop in reach 3.

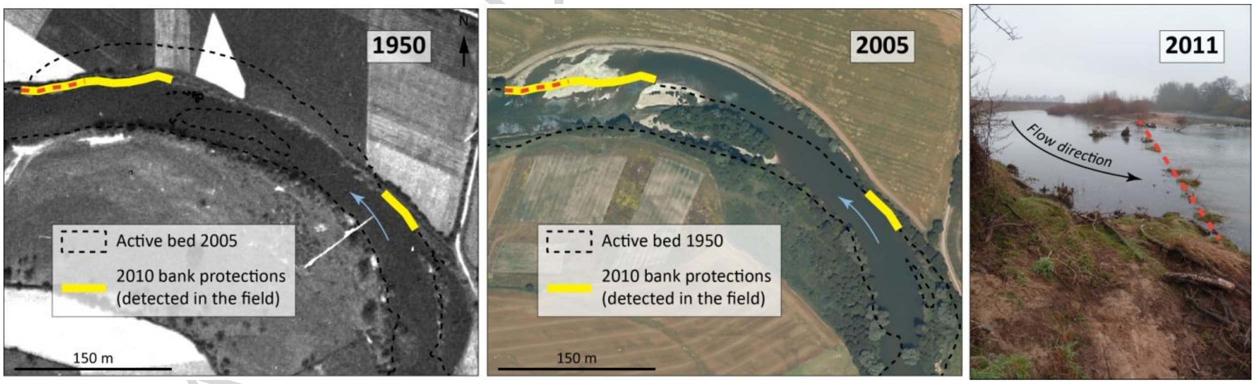


Fig. 21. Example of circumvention of bank protections (reach 3). The dotted red line shows the alignment of blocks visible on the right image. The yellow line indicates the bank protections visible in the field in 2010 and surveyed with an RTK-DGPS. Originally, the whole length of the concave bank was probably protected.

Finally, our conclusion concerning the significant potential for lateral mobility on the Cher River partly contradicts the findings of Urban and Rhoads (2003) or Güneralp and Rhoads (2009a) who demonstrated, in a different context of human modification, the absence of planform recovery of meandering rivers in Illinois (USA). The lack of readjustment of these rivers following their straightening is mainly explained by a too low specific stream power. The effects of the channelization are considered to be long-lasting and not readily changed by subsequent fluvial action within the modified systems. Nevertheless, in the Embarras River Basin (Urban and Rhoads, 2003), the limited capacity for recovery appears logical insofar as even unmodified reaches are not mobile, suggesting — for the totality of the river network — either excessively high bank resistance or a size of inherited parent material that exceeds river competence. In the Kishwaukee River watershed (Güneralp and Rhoads, 2009a), the main studied channelized reach also remained immobile after human intervention; but its bankfull stream power, with a maximum of 7 W m^{-2}, is clearly lower than along the Cher River meanders (from 12 to 34 W m^{-2} at the reach scale, excluding the section influenced by the Boutet weir). Moreover, the unmodified reaches in the Kishwaukee River watershed, with a bankfull stream power (7-20 W m^{-2}) similar to that of the Cher River, are subject to significant displacements. The short channelized sections located along these unmodified reaches showed signs of readjustment, but their activity was less intense than along the *natural* sections. Nonetheless, from our point of view, this does not necessarily signify a low capacity of the entire river length for recovery of mobility. Indeed, even on rivers with lateral activity, stable sections are not rare. On the Dane River, Hooke (2003a, 2007, 2008) for example reported a spatial alternation of unstable and less mobile sections over a period of 140 years. This was explained by the combined influence of at least two of the following parameters: low gradient, low sinuosity, the presence of bedrock outcrops, the proximity of valley sides, or terraces (Hooke, 2007). On the Cher River, the probability of recovery for lateral mobility in case of suppression of bank protections appears greater than for the channelized rivers of the Illinois because the protections are mainly located along sections with relatively high sinuosity and stream power.

6. Conclusion

This article focuses on the characterization of the planimetric evolution of low mobility meandering systems and on the identification of the causes of their reduced morphodynamic activity. Two nonmutually exclusive hypotheses were proposed to explain this relative stability. The first is the possible existence of bank protections that might have inhibited the natural migration of loops. The second is related to a possible decrease in the frequency and/or intensity of morphogenic hydrological events since the nineteenth century, which might have reduced the capacity of the river to mobilize its bedload and/or erode its banks.

First, our investigations have demonstrated the intrinsic capacity of the meanders to erode their alluvial deposits and the frequent mobilization of the entire particle-size distribution of the surface of the bed. Second, they have highlighted a high density of engineering structures in the riverbed. For these reasons, the limited mobility of the meanders, confirmed by the diachronic analysis of planform of the river between 1830 and 2005, would be explained primarily by the constraints exerted by these structures.

From an operational point of view, these results are of direct relevance for managers as they show that the Cher River has substantial potential for self-restoration. This is important because the riverbed, which was severely degraded during the second half of the twentieth century, is now in a situation of sediment deficit. Our results also imply that the *natural* lateral dynamics of the Cher River are very probably able to support a diversity of riverine habitats. Finally, the reaches we studied are probably representative of many low-energy European rivers. Densely equipped in past centuries, their beds are now occupied by many engineering structures in varying stages of decay. Most are currently disconnected from their original function and are now considered as hydraulic wasteland (Lecoeur and Gautier, 2005). Nevertheless, as a heritage, they are difficult to circumvent, as they structure the hydrosystem. In the current context of good ecological status required by the Water Framework Directive, it is essential to locate and identify them to determine their potential ability to constrain the morphogenesis of rivers. The example of the Cher River demonstrates that the existence of these structures, and hence their influence on river dynamics, can be all too easily underestimated or overlooked. Such a knowledge gap tends to seriously limit our understanding of dysfunctions affecting the hydrosystems and, as a result, masks their real potential for restoration.

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