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Morphological evolution of a rural headwater stream after channelisation

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ABSTRACT

In recent decades, stream valleys have been profoundly modified by the construction of weirs and dams and by channelisation. Channelisation modifies the morphology of streams and induces changes in their energy regime and sediment transport capacity. These types of changes in the channel morphology have to be quantified to allow the implementation of management strategies to regulate sediment transfer. However, studies over an entire stream using historical comparisons remain scarce, and the associated uncertainties have not yet been resolved.

In this study, the sedimentary response to channelisation on a medium time scale (42 years) of a French river known as the Ligoire is investigated. This river is the main channel of a small rural headwater catchment that has been channelised over 21 km. We have used the historical cross sections before and after channelisation and the current ones, and the objectives of this study were as follows: (1) to develop a methodology of cross section superposition and the associated uncertainties; (2) to quantify the erosion and aggradation processes in the bed and on the banks along the bed profile; and (3) to calculate a sediment budget for the entire stream and determine the relative contributions of the banks and the streambed to this budget.

A comparison of the cross sections before and after the channelisation shows that the morphology of the stream has been completely altered: the main channel length was reduced by 10%, the bankfull width was increased on average by 63%, and the slopes were smoothed. A total of 60,000 m^3 of sediments was excavated during the channelisation works.

Our results indicate that erosion is the dominant process: over 63% of its length, the streambed was incised by 0.41 m on average; and over 60% of its length, the banks were eroded by 0.20 m on average. The successive patterns of erosion and deposition along the stream are the result of the cumulative effects of channelisation and of the presence of weirs and artificial knickpoints in the Ligoire channel.

The vertical uncertainty of the elevation of the historical cross section is an important parameter for controlling the areas and sediment budget values. Using Monte Carlo methods, we found that 1000 sediment budgets from different profile shiftings are necessary to obtain a variation coefficient below 0.1%. The overall mean stream sediment budget for the period 1970–2012 is -9358 $\pm$ 412 m^3, with 66% originating from the banks and 34% from the streambed. Relative to the Ligoire watershed surface, the stream sediment yield is 2.71 $\pm$ 0.12 $m^3.km^{-2}.y^{-1}$. The approach developed in this study is easily replicable and relatively cheap and provides an integrated quantified, overview of the morphological adjustments after channelisation works on a stream.

1. Introduction

To allow for the transformation of extensive agriculture into intensive agriculture, most rural watersheds in lowland areas of Europe have been completely remodelled since the early twentieth century (Stoate et al., 2001). Changes generally included reparcelling of the land, modification of the drainage, and elimination of landscape elements (such as hedges and wetlands) that had dampened liquid and solid fluxes (De Groot et al., 2002; Van der Zanden et al., 2013). Stream valleys have been profoundly modified through the construction of weirs and dams and by channelisation. The latter process modifies the morphology of a stream to reduce the frequency and magnitude of floods, drain new agricultural land, favour navigation, and reduce erosion in the channel (Brookes et al., 1983). The different methods of channelisation include the recalibration, realignment, or rectification of meanders, damming, or levee construction, bank protection, and bed cleaning (Brookes, 1985).

In the 1980s, certain studies (Brookes, 1985; Simon and Hupp, 1987) mentioned that channelisation operations can cause serious and almost systematic morphosedimentary dysfunctions. Indeed, increasing the slope gradient and associated transport capacity of a stream (Wilcock, 1991) leads to bed scouring and bank erosion in the high-energy sections (Surian and Rinaldi, 2003; Simon and Rinaldi, 2006), resulting in

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the transport of eroded sediment downstream and its accumulation in low-energy reaches (Nakamura et al., 1997; Kroes and Hupp, 2010). This aggradation primarily involves fine sediment, which may clog the streambed (Landwehr and Rhoads, 2003), deteriorate the physicochemical water quality (Shields et al., 2010), and degrade aquatic habitats (Steiger et al., 2005). In addition, changes in land use can result in an increasing supply of fine sediment and, thus, accentuate the aggradation phenomenon (Walling and Amos, 1999; Collins and Walling, 2007). Moreover, the suspended sediment deteriorates water quality though pollutants adsorbed on the fine fractions, such as heavy metals, nutrients, organic contaminants, or pesticides (Kronvang et al., 2003; Walling et al., 2003; Ballantine et al., 2009).

These environmental problems have led to the development of different approaches to quantifying the production, transport, and deposition rates in each of the geomorphological units of a watershed. One of the most frequent approaches is the sediment budget, which has been widely employed as a sediment management tool (Dietrich et al., 1982). These budgets help establish sustainable management strategies for sediment transfer (Walling and Collins, 2008). Furthermore, these budgets show that the sediment contribution from the banks of a channel on a decadal time scale in temperate rural catchments is ~10% in the case of streams slightly impacted by human influence (Walling et al., 2002) but can reach more than 50% in channelised streams (Wilson et al., 2008; Day et al., 2013; Palmer et al., 2014). Thus, the sediment emanating from a channelised river can represent a large proportion of the total sediment yield from a landscape (Simon and Rinaldi, 2006). This contribution varies with the size and extension of the modifications to the fluvial corridor (Malavoi and Adam, 2007), but it also varies based on changes to the watershed (Schilling et al., 2011).

This type of dysfunction has been observed over almost 300,000 linear kilometres in the USA (Schoof, 1980), 40,000 km of streams in Great Britain (Brookes et al., 1983), and tens of thousands of kilometres of streams in France (Malavoi and Adam, 2007). Nevertheless, the quantification of the morphosedimentary impact of channelisation on such streams and the contribution of the channels to the sediment budget commonly remain underdocumented (Heitmuller, 2014). Moreover, although most qualitative studies dealing with the impact of channelisation only focus on the channelised reach, channelisation also causes morphological readjustments in upstream and downstream adjacent reaches.

In fact, regular and comprehensive monitoring of the morphology of a stream is difficult (Sear and Newson, 2003), as it requires the deployment of high-spatial-resolution instrumentation over several decades, which limits the number of available studies (Gomez et al., 2007; Heitmuller, 2014). To overcome this lack of monitoring, the impact of channelisation on the stream banks and bed morphology is commonly quantified by retrospective studies. The pre-works morphology is generally extracted from aerial photographs (or occasionally from historical cross sections) and then compared to the current morphology by means of recent aerial photographs (Kesel and Yodis, 1992; Sipos et al., 2007; Segura-Beltrán and Sanchis-Ibor, 2013), newly measured cross sections (Terrio and Nazimek, 1997; Rinaldi and Simon, 1998; Kiss et al., 2008; Heitmuller, 2014), or airborne LiDAR topographic surveys (Rhoades et al., 2009; De Rose and Basher, 2011; Day et al., 2013; Kessler et al., 2013). Still, retrospective studies based on airborne methods are mostly restricted to evaluating morphological changes in stream banks and do not provide the three-dimensional morphology of the channel. Therefore, Gregory (2006) recommends the use of cross sectional surveys at different time steps for the quantification of changes affecting the river bed and banks. However, in many cases, the uncertainties of the measurements are not clearly defined, and furthermore, the use of historical cross sections over a medium time scale remains scarce.

In this context, the objective of this study is to investigate the morphosedimentary response to channelisation on a medium time scale (42 years) of a stream in a small headwater within a lowland catchment that has been strongly impacted by agricultural practices. The main objectives of the investigation consist of (i) developing a methodology for comparing cross sections and assessing the associated uncertainties; (ii) quantifying erosion and aggradation processes in the bed and on the banks along the channel profile; and (iii) calculating the sediment budget for the entire stream and determining the relative contribution of the banks and the streambed to this budget.

2. Study area

The Ligoire drainage basin is an 82-km^2 watershed located in the southwestern part of the Paris sedimentary basin; its length is 19 km from southwest to northeast, and its elongation ratio is 0.52 (Fig. 1). The area is hilly, but it has a moderate relief. The slopes have an average gradient of 5%, and elevations range from 60 m asl at the catchment outlet to 143 m asl, which is the highest point of the divide at the northeastern edge of the basin.

The geology of the Ligoire basin is characterised by an east–west trending anticline. The incision of the anticline during the Quaternary period led to the outcropping of Cretaceous rocks. In the Ligoire valley, these geological formations are represented in the stratigraphic order by micaceous chalks including flintstones (middle Turonian, C3b), by early Turonian argillaceous chalk with flints (C3a), and by late Cenomanian marlstone (C2). These formations are overlaid by sandy micaceous limestone with flints (late Turonian), Senonian clays and flints, Tertiary sandy-clay deposits, and Quaternary aeolian loess. Land use consists mainly of intensive agriculture, and 75% of the basin surface is covered by crops (corn, wheat, and rapeseed).

The drainage network comprises 107 km of streams. The two main streams are the Ligoire trunk channel and its main tributary: the Riolle. The Ligoire is 21 km long, issues from a spring in the northeast of the basin at an elevation of 131 m asl and joins the Esves River at an elevation of 58 m. In 1970, to enable the transformation from extensive agriculture into intensive agriculture, the main channel of the Ligoire was entirely straightened and resectioned over 21 km, and artificial knickpoints have been implemented along the stream. The longitudinal profile of the channel bed is punctuated by several artificial knickpoints, such as masonry weirs, riprap infill of fords, and bridge pillars (Fig. 2). The most remarkable is found at the Verger mill, where a dam impedes sediment transfer to the downstream reach and enhances sediment deposition along a 1200-m reach upstream. Except for this 2-m-high dam, the drops over most of the obstacles do not exceed a few tens of centimetres.

Many of the morphological, sedimentary, biological and chemical dysfunctions described in the introduction are observed in the Ligoire River.

3. Material and methods

In France, many stream channelisation projects were carried out in the first half of the twentieth century (Bravard et al., 1999). Usually, the stream morphology was surveyed by means of cross sections, longitudinal profiles, and linear drawings on the cadastral maps of the period. These morphological data were used as a basis for designing the new morphology of the channelised stream. Information of this type shows strong potential to provide accurate data, and these data were used in the present study to quantify the hydraulic, morphologic, and sedimentary impact of the realignment and resectioning of the main stream. In this study, we analysed the changes in the stream morphology for two periods: (i) before and after the channelisation and (ii) after the channelisation and currently.

3.1. Stream morphology before and after the channelisation

Topographical data before and after the channelisation were extracted from surveys of the stream cross section carried out by the Public Works Department of the Indre-et-Loire province. A total of 135 cross sections were measured along the main channel. These data were

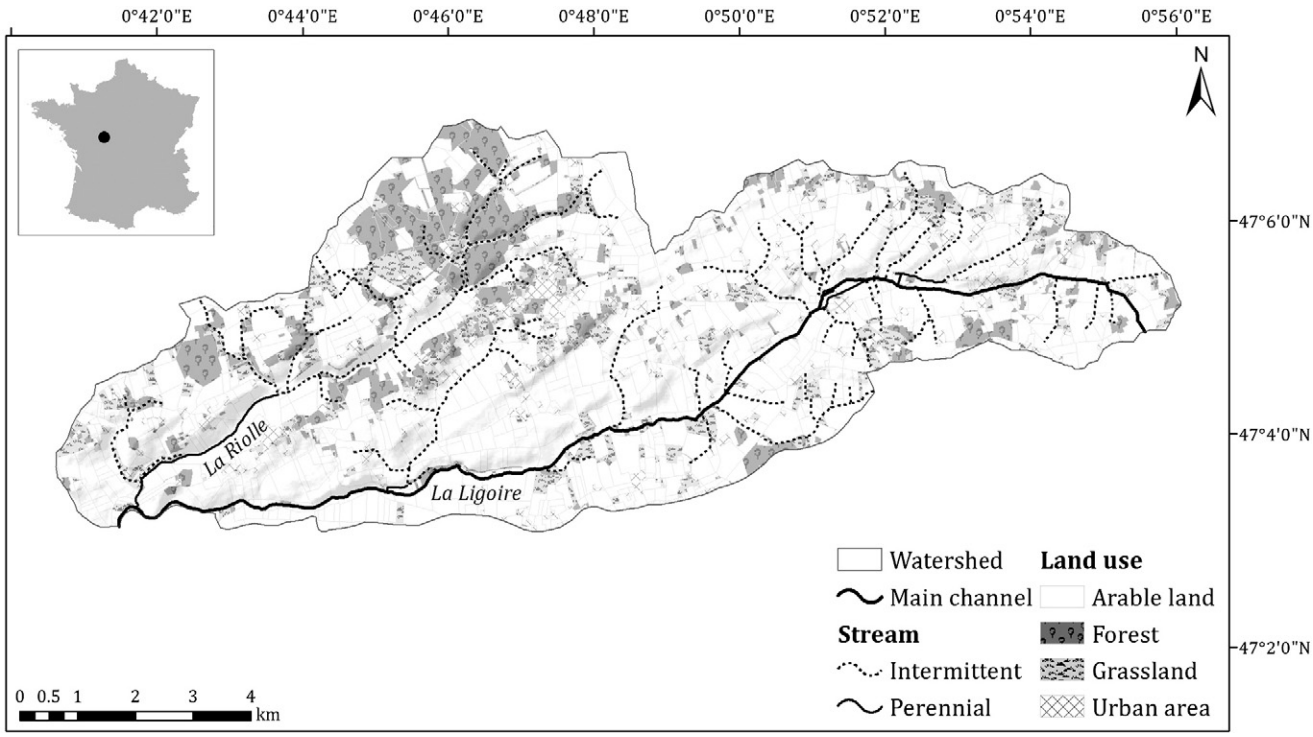

Fig. 1. Maps of the Ligoire watershed showing the land use and the drainage network.

used to design the new trapezoidal profiles. The distances between the cross sections are known, and each cross section was plotted on cadastral maps. Thus, the location of the historical cross sections was not referred to using a coordinate system. To allow comparisons of the topographic data, we georeferenced the historical cadastre in the Lambert-93 coordinate system, and then we extracted the centroid of all the historical cross sections.

3.2. Current stream morphology

A cross section was measured for each of the 135 georeferenced stations. The sections were measured using a DGPS (Differential Global Positioning System) Magellan Proflex 500, which has a post-processing accuracy of 1 cm in the *Z* direction and 0.5 cm in the *X* and *Y* directions. To identify relations between the stream morphology and the sediment deposition, we measured the sediment thickness and grain size within the streambed at each station.

The sediment thickness was obtained in two steps. First, we measured the bed-surface elevation. Second, the DGPS rod was driven into the streambed until it became blocked for a second elevation measurement (Lisle and Hilton, 1999). Then, the thickness was obtained by subtracting both values.

Finally, a visual estimate was made of the grain size at each topographic measuring point in the streambed using Wentworth's grain size classification as well as the sediment thickness.

3.3. Superposition of stream morphologies and associated uncertainties

To compare the morphology of the channel for the two periods, the cross sections are superposed. The cross sections from before

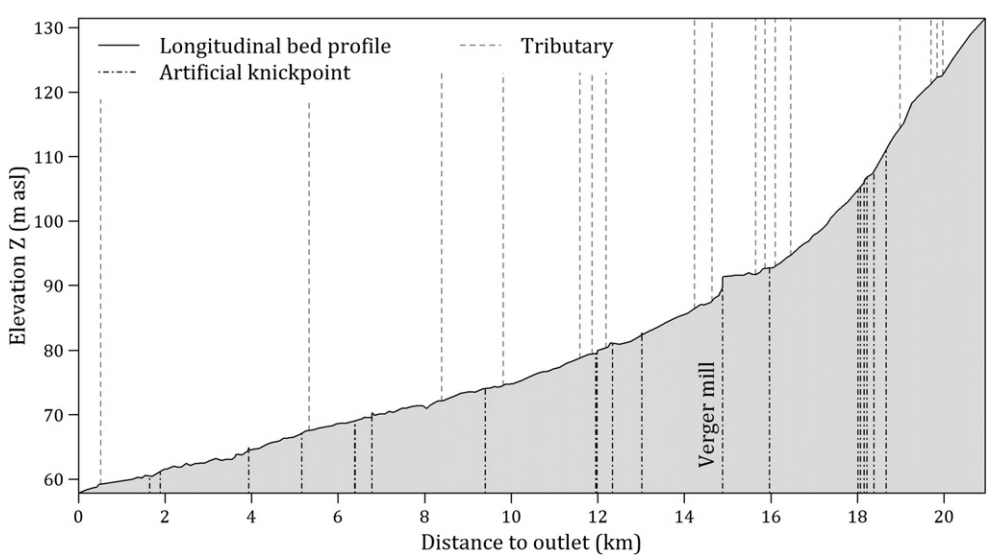

Fig. 2. Current longitudinal bed profile of the main channel of the Ligoire with its tributaries and artificial knickpoints.

and after the channelisation were directly superposed because the cross sections after the channelisation were based on the ones that had existed before it (Fig. 3). In this case, the uncertainties can be considered negligible.

Because the superposition of the current cross sections and the cross sections after channelisation is more complex, a specific method was developed. In our process, the superposition is realised based on the topographic data available for the current cross sections and the centroid of the cross sections after the channelisation. At first, the most adequate superposition is to centre both data. More precisely, (i) the historical bed-surface elevation and the current bed-surface elevation are superposed on the elevation axis, and (ii) both axes of symmetry are superposed on the station axis (Fig. 4A).

Furthermore, vertical and lateral potential uncertainties caused by the superposition of both cross sections were considered. First, with respect to the vertical uncertainties, we consider the uncertainty in the elevation measurements using the DGPS to be negligible, but this error is not negligible for the historical elevation data. Given the instrument used in the past, namely, a levelling rod, the uncertainty in the elevation Z can be estimated as $\sigma = \pm 5$ cm. Therefore, we shift each after-channelisation cross section vertically according to the established uncertainty in the Z direction (Fig. 4A). Second, for the lateral uncertainties, each cross section after channelisation is shifted laterally to the left bank (Fig. 4B) and to the right bank (Fig. 4C) of the current cross section. For both shifts, the uncertainty σ is also considered.

Therefore, nine positions of the historical cross sections after channelisation are considered according to different combinations of lateral and vertical shifting.

3.4. Quantification of changes in the stream morphology

The calculation of the net surface difference (m^2) between the superposed cross sections allows us to quantify the changes in the channel morphology for the two periods.

For the first period (before and after the channelisation), the areas between the cross sections are calculated for the entire channel (the banks and the streambed). The values of the channel areas are negative, and these areas correspond to the sediment areas extracted during the channelisation works. As stated in Section 3.3, the lateral and vertical uncertainties are considered negligible. A channel area is calculated per station, giving a total of 135 channel areas.

For the second period (after channelisation to today), which corresponds to the adjustment period of the Ligoire River, the values of the areas can be either positive or negative based on the type of processes involved: deposition and erosion, respectively. To provide more spatial insight into those processes, the channel was separated into the streambed (dark grey in Fig. 4) and the banks (light grey in Fig. 4). We calculated the areas for the streambed and the entire channel. The difference between the two areas gives the area for the banks according to Eq. (1):

$$Area_{channel} = Area_{streambed} + Area_{banks} \tag{1}$$

To take into account the lateral and vertical uncertainties, nine shifts were considered in the calculations of the areas. For each station, this process resulted in nine areas for the channel, nine for the streambed, and nine for the banks. Thus, for the 135 stations, $135 \times 9 = 1215$ areas were computed for the channel, 1215 were computed for the streambed and 1215 were computed for the banks.

Moreover, the sensitivity of lateral and vertical shifting in the calculation of the nine channel areas per station is studied. Initially, we calculated the mean area and its variation coefficient for each of the 135 nine-value series. Then, each of the series was reclassified into three sets of three values. The first set comprises the centred area values of the cross sections after the channelisation, the second set comprises the right-bank-shifted cross sections, and the third set comprises the corresponding cross sections of the left bank. For each three-value set, the variation coefficient and the mean were calculated.

The erosion and deposition processes in the streambed and along the banks can also be quantified by distance measurements. The maximum distance D_{bed} separating the minimum elevation of the cross section after channelisation and the minimum elevation of the current bed gives a numerical value for the incision of the bed or the sediment deposition. The uncertainty of $\sigma = \pm 5$ cm is utilised in the calculation of this distance.

With respect to the banks, the ratio between the area of the banks and their current developed length (the wetted perimeter minus the width of the minor bed) gives the eroded or deposited distance D_{banks} (Eq. (2)):

$$D_{banks} = \frac{Area_{banks}}{Wetted\ \ perimeter - Streambed\ \ width} \tag{2}$$

For each station, this distance is calculated nine times, or once from each of the nine areas identified as the bank positions, and we use these distances to calculate the mean values and their uncertainties. Finally, we deduce the erosion or deposition rates for the bed or the banks by dividing by 42 years (which is time elapsed since channelisation, 1970–2012).

3.5. Sediment budget

We recognised that each cross section is representative of half of the distance to the previous cross section and to the next cross section. The volume of the channel reach (in m^3) that is represented by a given cross section is determined by Eq. (3). The sum of the volumes of each station gives the overall sediment budget of the Ligoire channel (Eq. (4)):

$$Volume\left(m^3\right) = Area\left(m^2\right) \times \left(\frac{1}{2}\ upstream\ \ distance + \frac{1}{2}\ downsteam\ \ distance\right) \tag{3}$$

$$Sediment\ \ budget\left(m^3\right) = \sum_{i=1}^{135} Volume\ \ (Site\ \ i) \tag{4}$$

For the first period, the sediment budget is negative and corresponds to the extraction of sediment during the works. During the adjustment period of the stream (1970–2012), whereas a negative budget indicates that the dominant process was erosion of the channel sediment, a positive budget indicates that the dominant process

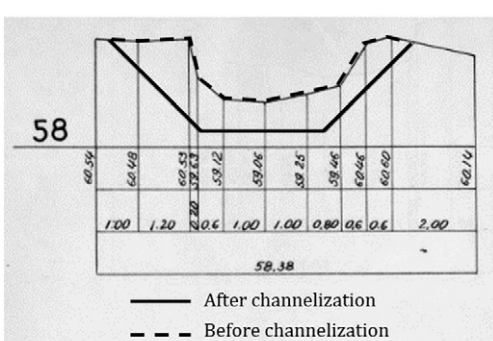

Fig. 3. Example of a cross section before and after channelisation. The cross section after the channelisation was designed based on the cross sections found before the channelisation.

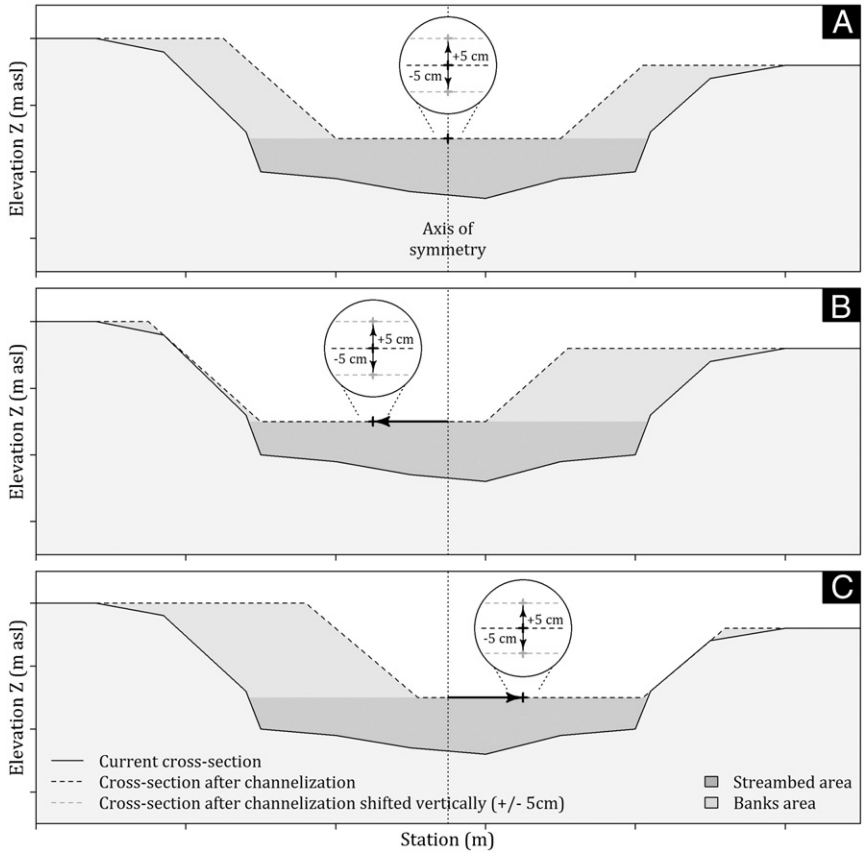

Fig. 4. Schematic representation of the adequate superposition of the cross sections after the channelisation and the current cross sections with the associated uncertainty $\sigma = \pm 5$ cm on the elevation *Z*. The superposition is carried out by considering the coincidence of (A) the axis of symmetry, (B) the left bank, and (C) the right bank. For each shift, the area between the cross sections after the channelisation and the current cross sections is calculated for the channel, the streambed, and the banks.

was sediment deposition. Moreover, the value of the sediment budget compared to the Ligoire watershed surface and to the study period gives the specific rate of erosion or deposition (in $m^3.km^{-2}.y^{-1}$).

However, as nine channel areas are available for each of the 135 stations, 9^{135} sediment budget values are possible. As a result, Monte Carlo methods were used to examine these possibilities. At each station, we randomly selected one of the nine channel areas, and then the sediment budget of the channel was calculated as described previously (Eq. (4)). Based on the results from employing 2, 5, 10, 20, 50, 100, 200, 500, 1000, 2000, 5000, 10,000, 20,000, and 50,000 budgets, we calculated a mean sediment budget. Subsequently, the associated uncertainty (standard deviation) was calculated from each set of selections, which ranged from 2 to 50,000. The convergence of the sediment budget values from this method was studied to determine the optimum number of selections needed to calculate a mean reliable and stable sediment budget and its value.

3.6. Hydraulic variables

The measured erosion and deposition processes indicated the morphosedimentary response of the energetic disequilibrium imposed by channelisation of the Ligoire River. To study this relationship, hydraulic variables (Table 1) were calculated for each cross section and for each time step (i.e., before the channelisation, after the channelization, and currently), and these variables were linked with D_{bed}, D_{banks}, the channel areas, the streambed areas, the banks area, the streambed grain size, and the sediment thickness. The longitudinal slope was calculated at each cross section by performing a linear regression between the minimal elevation values for the cross section and the upstream and downstream cross sections.

4. Results and discussion

4.1. Channelisation of the Ligoire: the creation of a disequilibrium

The different hydraulic variables measured before and after the channelisation show a drastic modification in the morphology of the Ligoire channel:

- Horizontally: the cutting of meanders and displacement of the stream reduced the main channel length by 10%: it shrank from 20,843 to 18,903 m.
- Transversally: the bankfull width grew on average by 63% (from 5.0 to 8.2 m), and the bankfull height grew by 57% on average (from 1.0 to 1.61 m).
- Longitudinally: the slope distribution before and after the channelisation (Fig. 5B) clearly shows that the variability of the

Table 1
The different morphologic and hydraulic variables measured for each cross section before and after channelisation and currently.

Variables	Name	Unit
i	*Longitudinal slope*	$m.km^{-1}$
L	*Top width*	*m*
l	*Water surface*	*m*
H	*Full channel depth*	*m*
β	*Aspect ratio*	-
C	*Conveyance*	$m^3.s^{-1}$
Wp	*Wetted perimeter*	*m*
Wa	*Wetted area*	m^2
Rh	*Hydraulic radius*	-
P	*Specific stream power*	$W.m^{-2}$

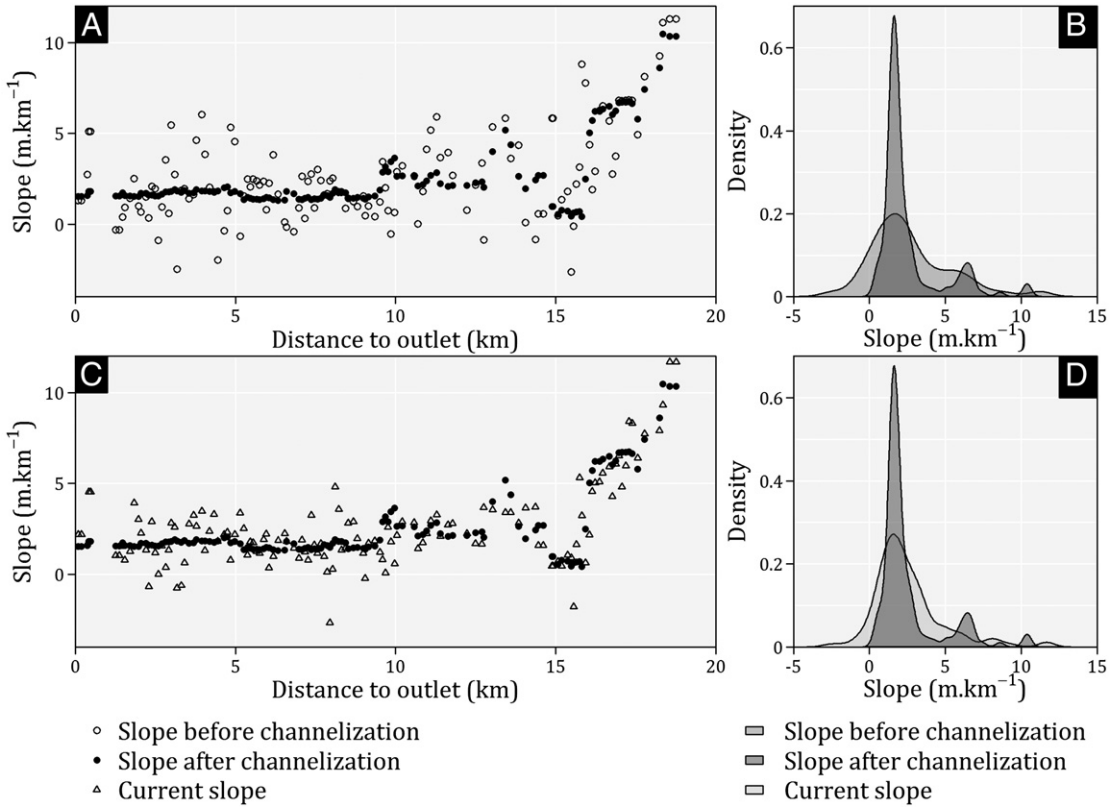

Fig. 5. Evolution of the longitudinal slopes of the streambed for period 1 (before and after the channelisation) (A) and period 2 (after the channelisation to the present) (B). Corresponding evolution of the probability density function of longitudinal slopes for period 1 (C) and period 2 (D).

longitudinal slopes (Fig. 5A) strongly decreased, resulting in an almost continuous longitudinal cross section.

Thus, our results show how the channelisation completely altered the morphology of the stream. A total of 60,000 m^3 of sediments was excavated during the works. The conveyance increased on average by 316% (from 3.8 to 15.9 m^3.s^{-1}), and the specific stream power increased by 80% (from 28.0 to 50.4 W.m^{-2}).

4.2. Morphological adjustments over the study period (1970–2012)

Currently, the slopes have greater variability (Fig. 5C and D) than they did just after the channelisation, which is caused by morphological readjustments during the period from 1970 to 2012.

The distance measurements D_{bed} and D_{banks} show that the channelisation mostly led to erosion of the main Ligoire channel. In fact, the streambed was incised by 0.41 m and the banks eroded by 0.20 m on average over 63% and 60% of the length of the entire channel, respectively (Table 2). Still, the sediment deposition was not negligible, as it occurred in 37% of the streambed and 40% of the banks.

The distribution of channel areas is very close to the distribution of the bed and the banks. In over 61% of the channel length, the net erosion is on average −1.05 m^2. Conversely, in over 39%, the net deposition is on average +1.40 m^2 (Fig. 6). This result is explained by the fact that for a given cross section, the processes affecting the bed and the banks act similarly. Indeed, for 46% of the stations, the bed and the banks have been affected by net erosion; and for 30% of the stations, they are both subject to deposition (Table 3).

Table 2
Stream lengths affected by erosion and deposition processes in the streambed and on the banks.

	Mean erosion (−) or deposition (+) (m)	Mean rate of erosion or deposition (m.y^{-1})	Affected length of the Ligoire River (%)
Streambed	−0.41 ± 0.06	−0.010	63
	+0.28 ± 0.06	+0.007	37
Banks	−0.20 ± 0.04	−0.050	60
	+0.90 ± 0.04	+0.020	40

From a longitudinal viewpoint, these erosion and deposition processes occurred successively along the stream. Therefore, five reaches can be identified, where three are dominated by erosion and two are dominated by aggradation (Fig. 6). Understanding these processes requires an upstream-downstream analysis of their hydraulic and morphologic characteristics (Table 3).

Reach 5, which is very upstream from the Ligoire channel, has the highest energy; and this fact has remained true even after the channelisation when the slope became 7.25 m.km^{-1}. Increasing the slope, width, and bankfull height (1.5%, 102%, and 66%, respectively) caused an increase in the specific power of the reach by 423%: it increased from 25 to 131 W.m^{-2}. As a consequence, the channel was subsequently strongly eroded (Fig. 7A), with an average incision in the bed of 0.38 m and a mean bank erosion of 0.15 m, creating a narrow and deep section with an aspect ratio of 3.62. In the upper part of this reach, the incision reaches 0.86 m and is locally blocked by micaceous chalk including flintstone (middle Turonian, C3b) outcrops (Fig. 7C). Therefore, the erosion power of the water is transferred laterally, which induces the undercutting of the banks over a height of more than 2 m (Simon and Hupp, 1987). This pattern has led locally to major bank failures that created reaches with streambed incision and accretion on the banks. Nevertheless, the influence of five weirs (Fig. 7A) of heights of a few tens of centimetres around the village of Mouzay (kilometre 18.0) is not negligible. In spite of strong longitudinal slopes, these weirs limit the incision of the stream in this area.

Reach 4, in contrast, has the lowest energy because of a gentle slope after channelization of 1.28 m.km^{-1} and a specific power of 13 W.m^{-2}. This area corresponds to the sediment deposition zone caused by the

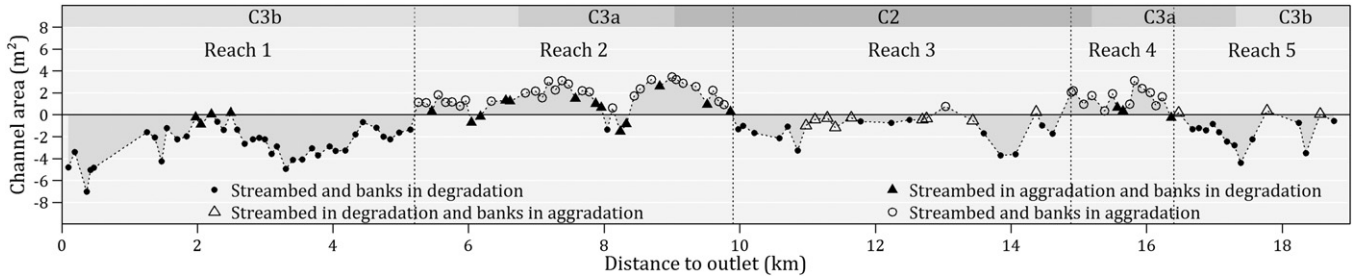

Fig. 6. Estimated channel area along the longitudinal profile of the river: (+) is aggradation and (−) is erosion. (C3b): Micaceous chalks including flintstones; (C3a): argillaceous chalk with flints; (C2): marlstone.

Verger mill (kilometre 14.9) (Fig. 7A). In this reach, the initial stream section was wide and shallow, but during the channelisation, it was further widened by 52% (from 4.99 to 7.58 m) (Fig. 7B). Currently, the channel is in a state of net aggradation (with a channel area of 1.71 m^2), and it has a mean deposit thickness in the bed of 0.20 m and a bank accretion of 0.05 m. The configuration of this reach is ideal for this aggradation phenomenon, as the erosion in reach 5 supplies a large quantity of sediment downstream. In reach 4, the drop in slope of 82% (from 7.36 to 1.28 $m.km^{-1}$) and the widening of the bankfull width by 33% have caused a drastic reduction in the carrying capacity of the water flow, with the consequent deposition of sediments. The formation of a deposit with a thickness of over 1 m at the beginning of this reach clearly shows this phenomenon (Fig. 7A).

Reach 3, which is downstream from the Verger mill, was historically a high-energy section with a slope of 2.86 $m.km^{-1}$ (Fig. 8A). Following channelisation, its specific power increased by 39% from 26 to 36 $W.m^{-2}$. Moreover, the retention of a solid load upstream from the mill further modifies the solid-transport capacity of the Ligoire waters downstream of this knickpoint. Thus, we observe an average bed incision of 0.42 m and strong erosion of the channel (the mean channel area is -0.97 m^2). As a result, the reach has been mostly deepened, with an average increase in the bankfull height of 41% and narrow and deep sections with an aspect ratio of 4.50. Downstream of the dam, in the area of energy dissipation, the bed was deepened by a maximum of 1 m, but incision is now blocked by the outcrop of nonerodible clay (late Cenomanian, C2) (Fig. 8C). The erosion products are transferred downstream where they accumulate upstream from the Roche mill (kilometre 13.0). Downstream from this knickpoint, the presence of three weirs at the Montfouet ford (kilometres 12.3–11.9) further limits bed incision, and sediment deposits exist for ~10 m behind each weir. In this area, many of the stations exhibit accreting banks caused by bank failures. Finally, downstream from this stretch, the absence of natural or artificial knickpoints is conducive to the resumption of complete erosion of the channel.

Reach 2 was the most extensively modified section during the channelisation process: the bankfull width and the height increased on average by 96% and 95%, respectively (Fig. 8B). Notwithstanding gentle slopes (1.56 $m.km^{-1}$ after the channelisation), the oversizing of the section caused a 306% increase in its specific power from 8 to 32 $W.m^{-2}$. Currently, this reach is in net aggradation, with a mean thickness of bed deposits of 0.34 m and a bank accretion of 0.04 m. This reach has the same functioning as reach 4. In fact, the passage from reach 3 to reach 2 is shown by an abrupt drop in slope angles of 43% (from 2.75 to 1.56 $m.km^{-1}$) and an increase in the bankfull width of 36%. Although the specific power of the reach increased, the widening of the water surface has led to a decreased sediment transport capacity and an aggradation of the bed surface of 0.67 m on average (Fig. 8A). The presence of weirs at the Arche ford (kilometre 9.4), at Joubardes (kilometre 6.4), and at the Gruteau mill (kilometre 5.1) locally amplifies the aggradation phenomenon.

Table 3
Average morphologic, hydraulic and sedimentary characteristics of the five identified reaches.

		Reach 1		Reach 2		Reach 3		Reach 4		Reach 5	
Length (m)		5.14		4.11		4.63		1.35		2.39	
Streambed area (m^2)		−0.92		1.22		−0.94		0.93		−0.54	
D_{bed} (m)		−0.31		0.26		−0.42		0.20		−0.38	
Banks area (m^2)		−1.04		0.34		−0.05		0.25		−0.62	
D_{banks} (m)		−0.22		0.04		0.00		0.05		−0.15	
Channel area (m^2)		−2.23		1.32		−0.97		1.71		−1.26	
Number of cross sections		39		42		24		14		16	
Streambed and banks in erosion		35		1		14		0		12	
Streambed in erosion and banks in aggradation		0		0		9		0		3	
Streambed in aggradation and banks in erosion		4		13		0		2		1	
Streambed and banks in aggradation		0		28		1		12		0	
Top width (m)	before	5.10		4.72		5.94		4.99		2.82	
	after	7.49	47%	9.23	96%	6.78	14%	7.58	52%	5.69	102%
	current	7.80	4%	7.64	−17%	6.86	1%	7.62	0%	5.80	2%
Top depth (m)	before	1.09		0.99		1.35		1.16		0.69	
	after	1.39	27%	1.93	95%	1.17	−13%	1.26	9%	1.14	66%
	current	1.56	12%	1.66	−14%	1.64	41%	1.31	4%	1.72	51%
Aspect ratio (−)	before	4.79		5.51		4.66		4.57		4.57	
	after	5.41	13%	4.80	−13%	5.78	24%	6.44	41%	5.00	9%
	current	5.15	−5%	4.50	−6%	4.50	−22%	5.95	−8%	3.62	−28%
Longitudinal slope ($m.km^{-1}$)	before	1.63		1.52		2.86		2.59		7.25	
	after	1.70	4%	1.56	3%	2.75	−4%	1.28	−51%	7.36	2%
	current	1.65	−3%	1.58	1%	2.76	0%	1.46	14%	7.29	−1%
Specific stream power ($W.m^{-2}$)	before	11.4		7.90		25.8		27.7		25.7	
	after	22.2	95%	32.2	306%	35.8	39%	13.3	−52%	134.4	423%
	current	23.9	7%	18.7	−42%	25.0	−30%	5.80	−56%	150.6	12%

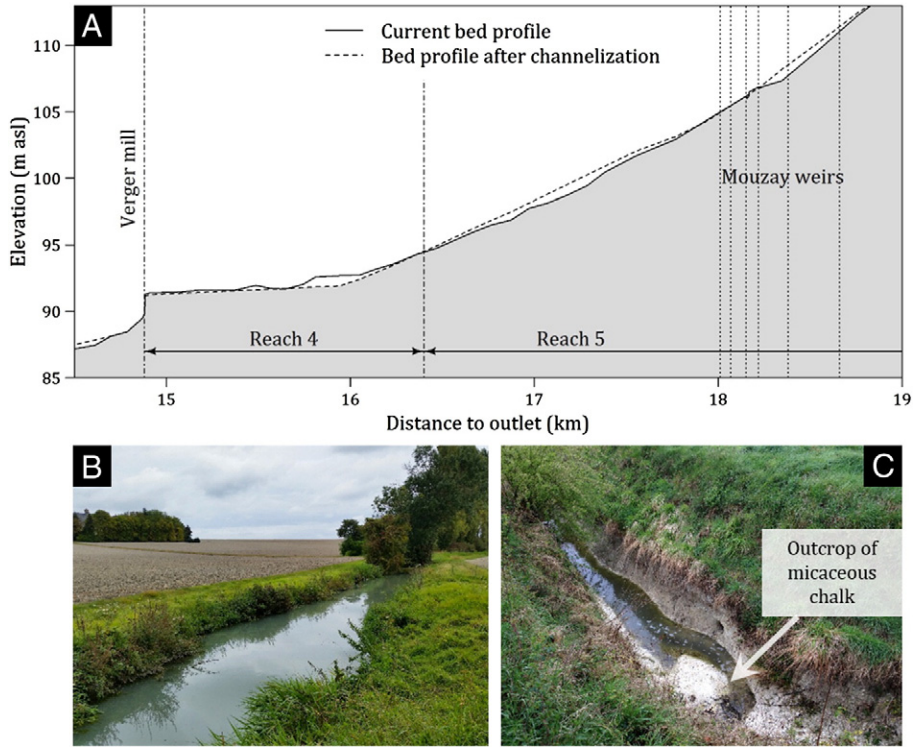

Fig. 7. (A) Longitudinal profile after channelisation and today. (B) In reach 4, the energy within the channel was not sufficient to transport all sediments coming from reach 5 and caused aggradation. (C) In reach 5, the steep slopes caused an erosion of the main channel and the incision reached micaceous chalks.

Reach 1 begins downstream from the Gruteau mill and ends at the Ligoire watershed outlet. During the channelisation, the bankfull slope, width, and height were increased by 4.3%, 47%, and 27%, respectively. This change in morphology led to an increase in the specific power of 95%: the power increased from 11 to 22 W.m^{-2}. Currently, the channel is strongly eroded, with a channel area of -2.23 m^2. This erosion affects both the streambed and the banks, as the mean bed incision is -0.31 m and the average erosion of the banks is −0.22 m. The sedimentary functioning of reach 1 is similar to the functioning of reach 3. A massive sediment deposition upstream from reach 1 modifies the

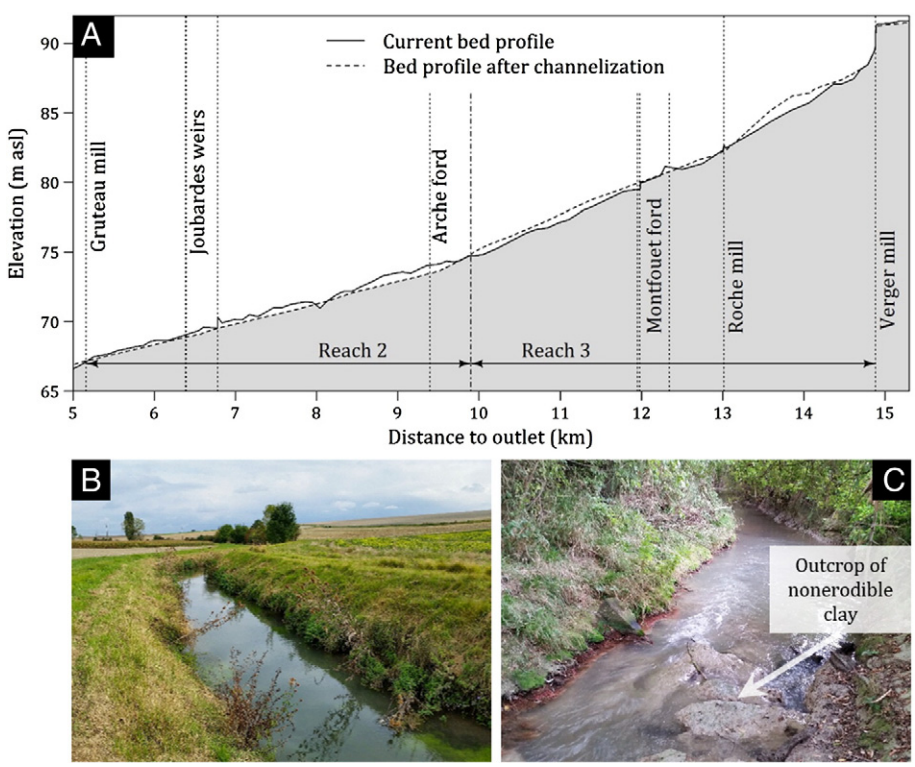

Fig. 8. (A) Current and after-channelisation bed profiles. (B) The low energy, combined with sediments supplied from reach 3, resulted in aggradation in reach 2. (C) The steep slopes in reach 3 and the modification of the solid-transport capacity of the stream by the Verger mill involved the incision of the channel and the outcropping of nonerodible clay.

transport capacity of the waters and, thus, provokes sediment removal from the streambed and the banks of the reach. The intensity of this uptake increases from the Gruteau mill until kilometre 3.3, where the incision can reach 1.16 m and the bank erosion is 0.50 m. Beyond this maximum, sediment removal decreases until the Saint-Paul mill (kilometre 2.6) and the RD 101 road (kilometre 1.9). These two knickpoints again prevent further deepening of the bed and favour sediment deposition in this section. Finally, below this reach, the channel is completely eroded and incision is mostly blocked by paving of the streambed.

This detailed descriptive analysis of the different channelised reaches helps us understand the active processes, as it clearly shows that the morphologic adjustments measured in a reach are governed not only by the human modifications in this reach (channelisation and artificial knickpoints) but also by the human modifications that have been made upstream and downstream from this reach. Moreover, this analysis illustrates the common patterns observed in channelised streams, i.e., erosion of the high-energy reaches and aggradation of the low-energy ones (Simon and Hupp, 1987).

Still, the generalisation of the intensity of morphologic readjustments with respect to the channel geometry is not possible. Additionally, no significant correlation could be established between the morphologic, hydraulic, and sedimentary variables regardless of the study period considered (before and after the channelisation and today). The relationships between the channel areas and the longitudinal slopes after the channelisation illustrate this complexity (Fig. 9). For a same-slope value after the channelisation, the section today may be erosional or depositional. Other parameters — such as bed roughness (Simon and Thorne, 1996), bank-sediment grain size distributions (Couper, 2003), aquatic and terrestrial vegetation (Rodrigues et al., 2006; Heppell et al., 2009), or the activity of vermin such as coypus (Ford and Grace, 1998) — locally complicate the reaction of a section to an energy disequilibrium.

Only an exact description of the channel allows an overall interpretation of the morphologic evolution of the channelised stream. In this case, erosion is observed not only in a reach with steep slopes (reach 5) but also in reaches with gentler slopes (reaches 1 and 3). In the first case, the high transport capacity of the stream causes erosion of the channel. In the second case, the retaining effect of the weir(s) upstream creates a lack of suspended sediment load and erosion. Conversely, aggradation is commonly observed in reaches with gentle slopes, which can be either natural (reach 2) or man-made through the sediment deposition zone behind a dam (reach 4). Aggradation is also observed in reaches with strong longitudinal slope, but this phenomenon is very localised. Thus, from our study, the distribution of erosion and deposition processes following the channelization clearly corresponds to the cumulative effects of such modifications and the presence of knickpoints along the Ligoire channel.

The important rate of fine sediment observed in certain reaches is influenced by the current geometry of the channel. In fact, certain trends become clear when comparing the current longitudinal slope, the current surface-water width, and the sediment thickness (Fig. 10A) and grain size for each station (Fig. 10B). Fine sediment will preferentially be deposited in sections with a longitudinal slope <4 m.km^{-1} and a surface width >2 m. The widening of the surface width observed in reaches 2 and 4 reduces the stream velocity, decreases the transportation capacity, and causes deposition of the sediment load. Conversely, the erosional power of the water in sections with a strong slope and a narrow channel (reaches 1, 3, and 5) will only allow the deposition of thin beds and coarse-grained sediments.

4.3. Sensitivity of the channel area calculation method

We studied the influence of the vertical and lateral shifting on the dispersion of the 135 sets of nine values of the channel area. The dispersion within each set is moderate, as the mean variation is 33.5% (Fig. 11A). Still, the median of 16.6% indicates that this mean is strongly influenced by high dispersion values, with a variation coefficient of up to 675%. This dispersion increases when the unit-area value approaches zero, and *vice versa*.

When a distinction is made between lateral and vertical shifting, the dispersion is mainly caused by vertical shifting. The reason is that although the mean value of the dispersion is 38.6%, it is only 2.7% for the lateral shifting (Fig. 11B). Thus, the uncertainties of the areas are mainly associated with the vertical shifting of the historical cross sections compared to the corresponding shifting of the current cross sections.

Consequently, the validity of the uncertainty on Z of $\sigma = \pm 5$ cm can be questioned. However, this figure can be verified by quantifying the longitudinal variability of the bed elevations Z of the cross sections after the channelisation based on the distances and slopes between these cross sections. More precisely, the uncertainty σ was applied to the bed-elevation value Z of each cross section to calculate the longitudinal distance by integrating over the interval [Z-σ; $Z + \sigma$]. For 81% of the cross sections, the interval [Z-σ; $Z + \sigma$] incorporates a distance of at least 25 m. Hence, within a radius of 12.5 m around a given cross section, the average bed elevation of the cross sections falls between Z-5 cm and $Z + 5$ cm.

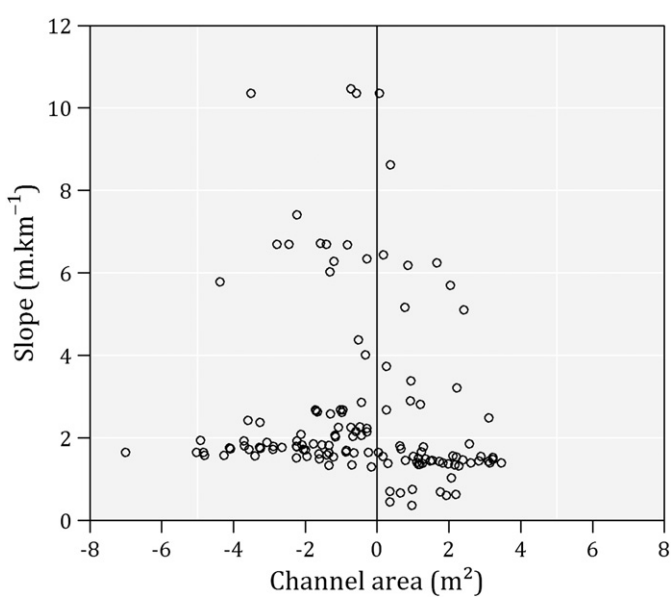

Fig. 9. Relationship between the longitudinal slopes after the channelisation and the channel areas. For a given slope value, the area can be positive (an erosional cross section) or negative (a depositional cross section).

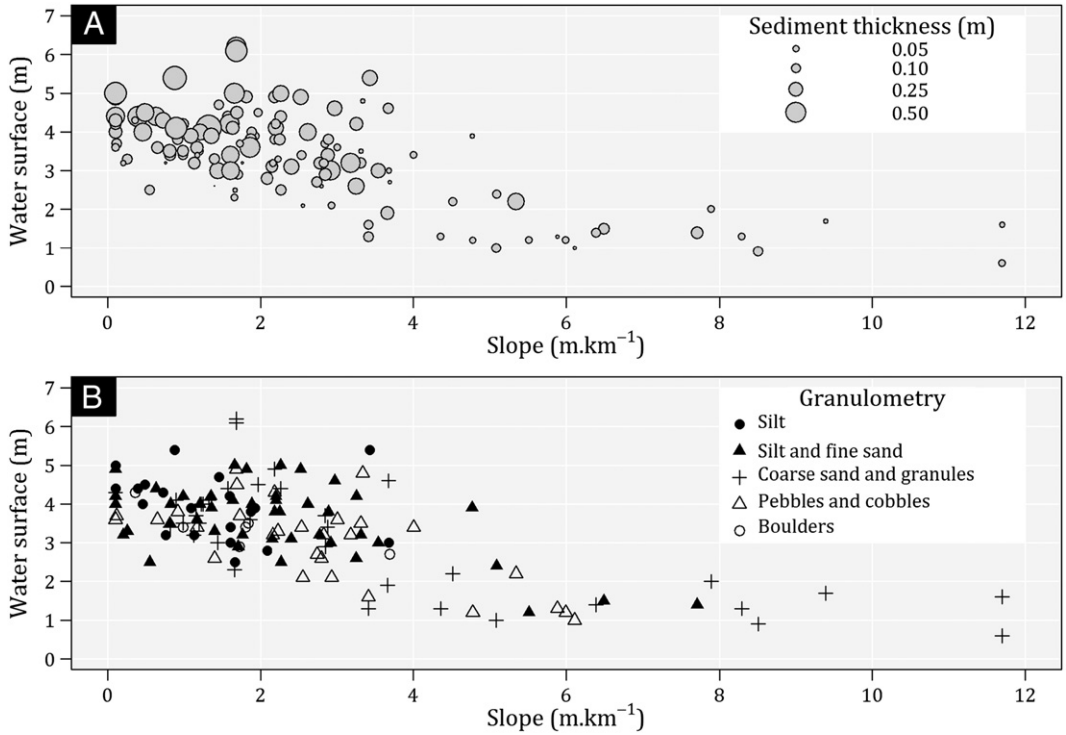

Fig. 10. Relationships between the current water surface, the current longitudinal slope, (A) the sediment thickness, and (B) the dominant sediment grain size.

4.4. Sediment budget of the Ligoire channel

4.4.1. Sensitivity of the sediment-budget calculation method

We used Monte Carlo methods to determine the optimal number of sediment budgets for calculating an overall sediment budget. The mean sediment budget progressively converges with the increase in the number of budgets used (Fig. 12A) from −9302 m^3 for two budgets to −9359 m^3 for 50,000 budgets. This stabilisation can be observed, as (if we use 1000 sediment budgets) the mean volume is −9358 m^3.

The larger the number of overall sediment budgets is, the smaller the variation coefficient of the iterations will be. For example, this coefficient is 5.3% when two sediment budgets are used and 0.02% for

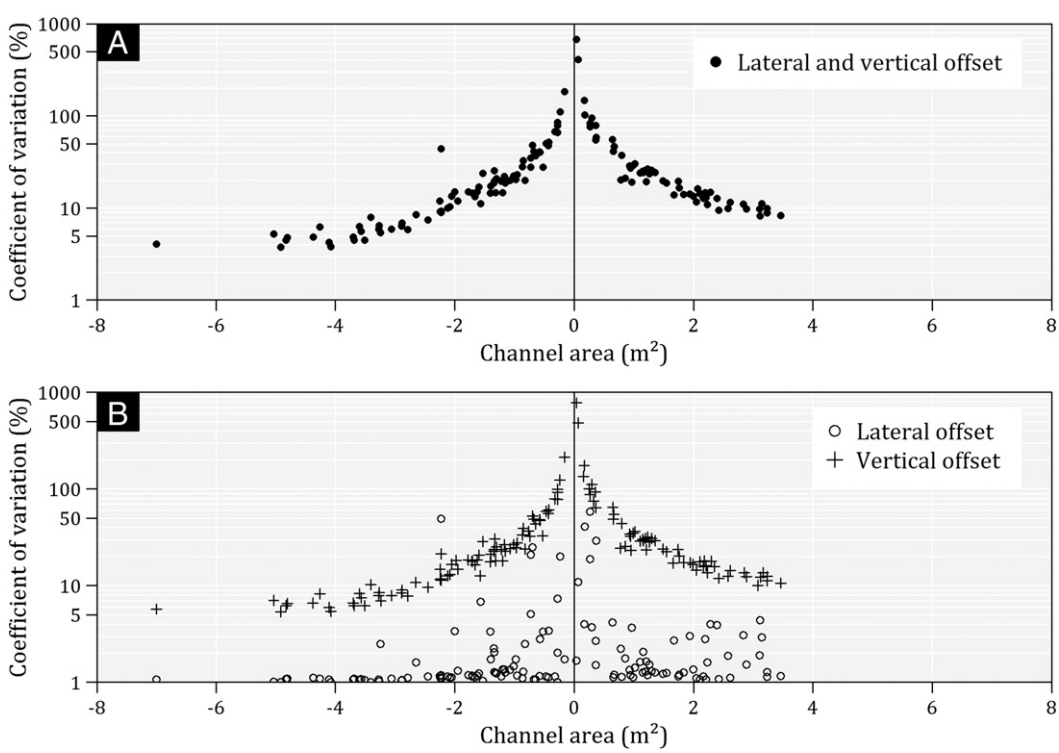

Fig. 11. The variation coefficient in terms of the mean channel area of each set: (A) of each of the 135 nine-value sets of channel areas (with no distinction between lateral and vertical shifting); (B) of each of the 135 × 3 value sets of three channel areas (which make a distinction between lateral and vertical shifting).

50,000 budgets. Similarly, this stabilisation appears when 1000 budgets are used, and the variation coefficient of the iterations is only 0.1%.

The same descriptive approach is valid for the mean standard deviation (Fig. 12B). Similar to the mean sediment budget, the mean standard deviation converges to 412 m^3 when 1000 standard deviations are used. The iteration variation coefficient associated with this value is low at 2.3%, and it decreases from 61.8% when two standard deviations are used to 0.3% for 50,000 standard deviations. Therefore, we utilised 1000 sediment budgets to calculate the mean sediment budget and the mean standard deviation.

4.4.2. Mean sediment budget of the Ligoire channel

The sediment budget of the main Ligoire channel can be calculated with the method developed in our study. The results are a sediment volume eroded from the channel of 19,358 ± 329 m^3 and a sediment deposition of 10,178 ± 243 m^3. Thus, the mean sediment budget is −9358 ± 412 m^3 (Fig. 13), of which 3121 ± 228 m^3 came from the bed and 6237 ± 412 m^3 came from the banks. These figures imply that during the period from 1970 to 2012, ~9400 m^3 of sediment was removed from the Ligoire basin; and whereas 66% came from the banks, 34% came from the streambed.

Relative to the Ligoire watershed surface of 82 km^2 and the study period of 42 years, the specific erosion rate (or the contribution of the main channel to the sediment budget) is $Y^* = 2.71 \pm 0.12\ m^3.km^{-2}.y^{-1}$. We use a bulk density to provide a value for sediment export (Lick and McNeil, 2001), and it represents between 3.4 and 5.7 $t.km^2.y^{-1}$.

Finally, after adding this overall sediment budget of the channel to the volume of sediment excavated during channelisation, the main channel in 2012 clearly had a sediment deficit of almost 70,000 m^3, illustrating the profound sedimentary impact of channelisation on a stream.

5. Conclusion

The morphologic, hydraulic, and sedimentary impact of channelisation in the Ligoire River (France) was recorded over 42 years. The aim of this work was to develop a method for quantifying such changes and to assess the associated uncertainties and their influence on the calculated values of the erosion, aggradation, and sediment budget.

To this end, we compared cross sections of the stream before and after the channelisation based on historical documents, and we measured new cross sections during recent fieldwork. This study required the development of methods for superposing historical and current cross sections and for integrating the uncertainties related to errors in the measurements used in our calculation. The vertical uncertainty of the elevation of historical cross sections is an important parameter for controlling the area and sediment budget values. In addition, the use of Monte Carlo methods indicates that 1000 overall sediment budgets must be calculated to obtain a variation coefficient below 0.1% for the mean channel sediment budget.

During the channelisation work, the trace of the main channel was straightened and 60,000 m^3 of sediment were excavated. This alteration caused a serious energy disequilibrium and morphologic readjustments of the stream through erosion and aggradation processes. After the work, the Ligoire was affected by net erosion processes in 61% of its length. This erosion mostly occurred in the high-energy stretches of the channel. Thickness and grain size measurements of the sediments show that general widening of the channel caused deposition of fine-grained sediments in the low-energy stretches where the water surface was widest. The present study clearly shows that the distribution of erosion/aggradation phenomena is the result of the cumulative effects of the channelisation and of the presence of natural and artificial knickpoints in the Ligoire channel. However, in view of the imposed disturbance, such readjustments were insufficient to allow for a return to the initial state of the streambed as it was before the 1970s. An important implication is that the present hydromorphological functioning of the stream is still under the influence of the channelisation, and therefore it cannot be explained by topographical or hydrologic parameters. Thus, the use of historical information is crucial for understanding the likely evolution of these types of altered streams. Overall, between 1970 and 2010, ~9400 m^3 of sediment was removed from the main

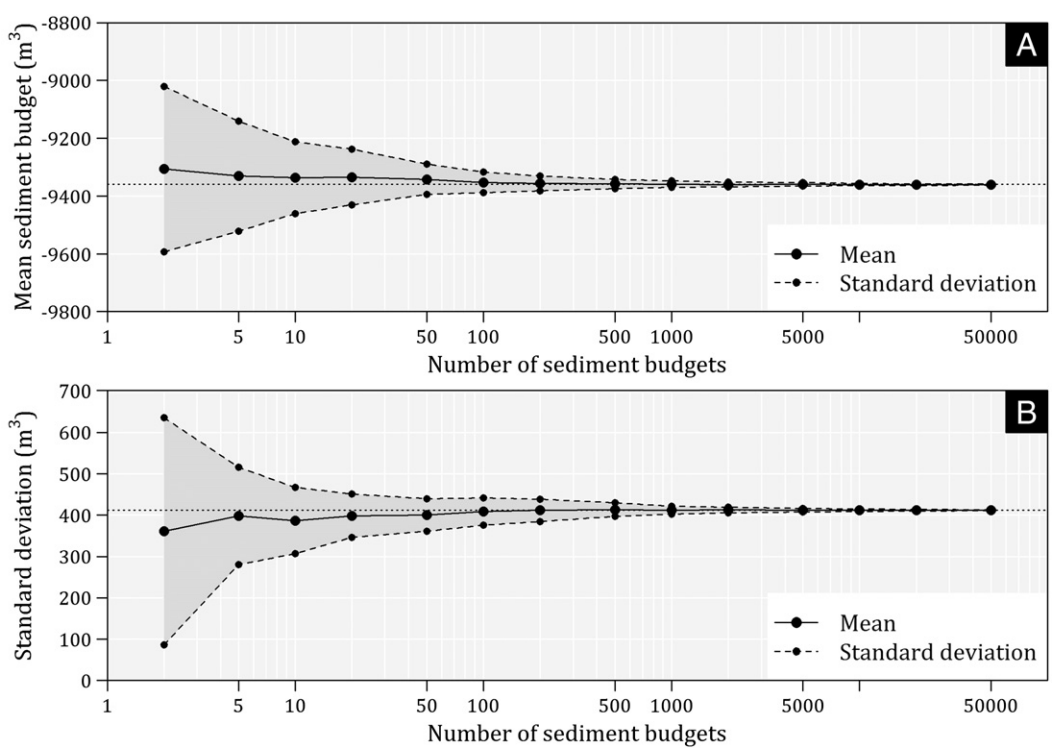

Fig. 12. From 2 to 50,000 sediment budgets are considered for the calculation of (A) a mean sediment budget, and (B) the associated standard deviation. For each number of sediment budgets, the mean sediment budget and the standard deviation are iterated 50 times, and the mean and the standard deviation from these calculations are extracted.

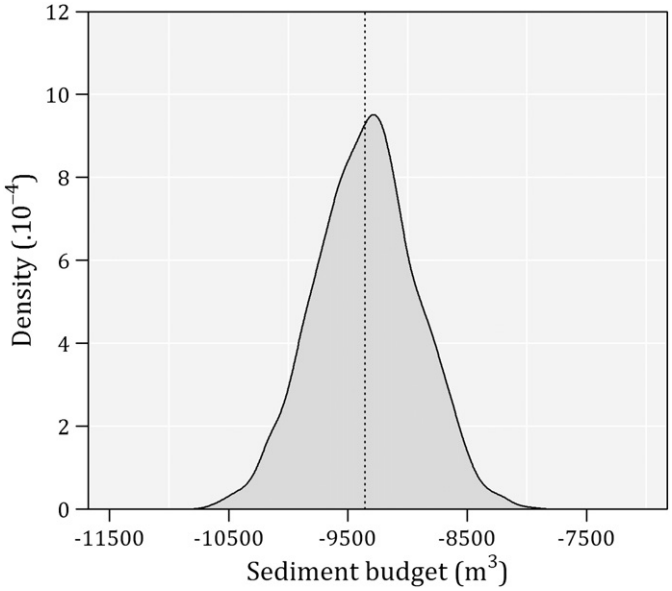

Fig. 13. Probability density function of the case of 1000 sediment budgets of the Ligoire channel. The mean sediment budget and its associated uncertainty are derived from this distribution.

channel by stream action. This figure represents an annual yield of 2.71 ± 0.12 m^3.km^{-2}.y^{-1} (between 3.4 and 5.7 t.km^2.y^{-1}), including 66% of the bank sediments and 34% of the sediments that come from the streambed. Compared to the total sediment flux exported from watersheds of a similar size in the Loire Basin (Gay et al., 2014), the Ligoire may contribute a significant part of the sediment budget of the catchment area drained by the stream (the minimum figure is 20%).

Finally, our approach of comparing historical documents with modern high-resolution field data is easily replicable and relatively cheap to implement, and it provides a quantified overview of the re-equilibration phenomena after modification work is performed on a stream. Monitoring and sampling of so-called natural streams can take place yearly or every few years, and such work is promising for drawing up sediment budgets of rivers on a regional scale.

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