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RESEARCH ARTICLE

Quantification of bank erosion in a drained agricultural lowland catchment

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Abstract

The long-term and current volumes of sediment exported from stream banks were calculated as potential sources of sediment in a large pond located at the catchment outlet of a small agricultural lowland basin strongly affected by anthropogenic pressure in France. Bank erosion was measured over a short period using a network of erosion pins along a small stream (1400 m long) to quantify the material exported during a single winter (2012–2013). The material exported by this same stream over the last 69 years was quantified using an original approach involving the comparison of a compilation of three-dimensional historical stream redesign plans that date back to 1944 with the state of the banks in 2013 (differential global positioning system and LiDAR data). The results suggest that a global trend of material loss along the stream banks monitored by erosion pins, with an average erosion rate of 17.7 mm $year^{-1}$ and an average volume of exported material of 75 t km^{-1}. Over 69 years, this same stream exported an average of 36 t km^{-1} $year^{-1}$, and the average loss of material from the banks throughout the whole catchment was estimated to be 14 t km^{-1} $year^{-1}$. The contribution of bank material to the filling of the pond over the last 10 years is between 46% and 52% based on an extrapolation of erosion pin dynamics or between 27% and 30% based on the comparison of LiDAR data to the average historical profile extrapolated for the catchment. These results suggest that bank erosion represents a major source of sediment in degraded waters in traditionally understudied agricultural lowland catchments, where anthropogenic pressures are high.

KEYWORDS

agricultural lowland catchment, bank erosion, channelisation, erosion pins, historical cross sections, long-term erosion

1 | INTRODUCTION

Western European agricultural plains have been subjected to major land use changes and a global modernization of agricultural practices since the middle of the 20th century (Antrop, 2005). Gradually, the landscapes have opened, the fields have been enlarged, and areas formerly occupied by grasslands have been converted to more productive agricultural lands (Meneau, 2000). Large streams and drainage networks have been designed to drain the water in the hydromorphic lowlands of Western Europe (e.g., Ciszewski & Czajka, 2015), as well as other areas around the world (Lenhart, Verry, Brooks, & Magner, 2012). These rectilinear and recalibrated stream networks are currently deeply incised and feature steep and actively eroding banks (e.g., Landemaine, Gay, Cerdan, Salvador-Blanes, & Rodrigues, 2014; Malavoi & Adam, 2007; Prosser, Hughes, & Rutherfurd, 2000). They can therefore significantly contribute to the increase in suspended sediment load in water bodies and to the global degradation of water quality (e.g., Bull, 1997; Mizugaki, Nakamura, & Araya, 2006; Zaimes, Schultz, & Isenhart, 2006). Two major approaches have been developed to quantify the input of sediment into streams due to bank erosion. The first one, using fingerprinting techniques, allows quantification of the contribution of bank erosion versus that of other sediment sources to the delivery of sediment to streams (e.g., Caitcheon, Olley, Pantus, Hancock, & Leslie, 2012; Collins et al., 2012; Foucher et al., 2015; Olley, Burton, Smolders, Pantus, & Pietsch, 2013; Peart & Walling, 1988). The second approach aims to quantify the volume of sediment originating from bank erosion over a given time (e.g., Kronvang, Andersen, Larsen, & Audet, 2013; Lawler, 1991; O'Neal & Pizzuto, 2011).

Previous fingerprinting studies compiled by Walling and Collins (2005) indicate that bank erosion can contribute between 1% and 55% of sediment exported by British rivers. However, several studies have shown that this contribution can be much higher, exceeding 40% in a significant number of catchments (Collins, Zhang, Walling, Grenfell, & Smith, 2010; Owens, Walling, & Leeks, 2000) and reaching more than 80% in specific conditions (e.g., Kronvang et al., 2013; Laceby, 2012; Olley et al., 2013).

Bank erosion has been studied in mostly natural environments or in large streams (e.g., Kessler, Gupta, & Brown, 2013; Ta, Jia, & Wang, 2013). Less attention has been paid to stream banks located in intensively cultivated agricultural plains with narrow streams (<5 m width).

Bank erosion is a natural process controlled by various causal and driving processes (Henshaw, Thorne, & Clifford, 2013). One of the most important factors controlling bank retreat is fluvial erosion (Darby, Rinaldi, & Dapporto, 2007), which tends to increase during flood events and can therefore exhibit seasonal patterns. Other processes are also likely to promote bank erosion, such as the freeze–thaw process (Thorne, 1990; Wynn, Henderson, & Vaughan, 2008; Yumoto, Ogata, Matsuoka, & Matsumoto, 2006) and subaerial processes, such as desiccation (Prosser et al., 2000). These factors result in the breakup and loss of material from the bank face via mass failure, in which gravitational forces overcome the resisting forces of friction, interlocking, and cohesion (Lawler, Thorne, & Hooke, 1997). These factors are more or less efficient depending on the state of the vegetation cover (Laubel, Kronvang, Hald, & Jensen, 2003b; Wynn & Mostaghimi, 2006), the presence or absence of wood and roots in the channel (Watson & Marden, 2004), and the physical state of the bank in terms of moisture (Green, Beavis, Dietrich, Jakeman, & Jakeman, 1999; Simon, Curini, Darby, & Langendoen, 1999), texture (e.g., Couper, 2003; O'Neill & Kuhns, 1994; Thorne, 1982), and presence of animal trampling and/or burrows (Kauffman, Krueger, & Vavra, 1983; Trimble, 1994). The last factor that can induce bank erosion is anthropogenic pressure exerted by past and present stream management practices and by agricultural practices (e.g., Lefrançois, 2007; Zaimes & Schultz, 2015; Zaimes et al., 2006).

Various methodologies have been developed to quantify sediment loads originating from bank erosion with the aim of establishing appropriate management practices to reduce the export of sediments. Most of these applications are based on survey techniques that are limited in scale temporally and/or spatially (Heritage & Hetherington, 2007). Most of these studies have focused on the short-term monitoring (day, month, or year [Lawler, 1993]) using various methodologies, such as erosion pins (e.g., Couper, Stott, & Maddock, 2002; Palmer, Schilling, Isenhart, Schultz, & Tomer, 2014; Veihe, Jensen, Schiøtz, & Nielsen, 2010), photo-electronic erosion pins (Lawler, 1991; Lawler, West, Couperthwaite, & Mitchell, 2001), airborne laser scanning (Milan, Heritage, & Hetherington, 2007; Thoma, Gupta, Bauer, & Kirchoff, 2005), and aerial photography (Bartley et al., 2008; Grove, Croke, & Thompson, 2013). These approaches can be used to record bank activities and dynamics at short- to medium-time scales. The major drawbacks of some of these methods are that they are highly dependent on the climatic conditions during the period of measurement, they cannot be implemented over long-time periods, and they do not give information on past bank erosion dynamics. The erosion pins technique has, however, been considered to be the most appropriate for the study of short- to medium-term (seasonal) bank erosion dynamics. Moreover, its relatively low-implementation cost permits a wide spatial coverage (Laubel et al., 2003; Lawler, Grove, Couperthwaite, & Leeks, 1999). Many other bank erosion measurement techniques exist, but they present some limitations, as highlighted in the review of Lawler (1993). For example, historical aerial pictures (De Rose & Basher, 2011), tree root denudation (Malik & Matyja, 2008), and maps (Yao, Ta, Jia, & Xiao, 2011) can be used to measure two-dimensional lateral channel changes, but the third dimension represented by bank height is often unavailable (Rhoades, O'Neal, & Pizzuto, 2009). To estimate the long-term erosive dynamics, we employed an original approach combining three-dimensional historical cross sections and high-resolution aerial light detection and ranging (LiDAR) data in this study to compare the reference state of banks during their design in 1944 to their state in 2013.

This paper, therefore, aims to quantify spatial and temporal variations in sediment delivery from bank erosion in an intensively cultivated lowland catchment that has been heavily affected by anthropogenic activity since the Second World War (i.e., because the implementation of artificial ditches and a dense drainage network during the period 1945–1970—Foucher et al., 2014). Globally, streams are commonly being recognized as primary sources of sediment to streams and rivers (e.g., Laceby, 2012). Recent studies in an intensively farmed watershed have found that human-altered stream channels are a minor component of net sediment delivery to a 52 ha pond (Foucher et al., 2015 Le Gall et al., 2016). Based on historic channel cross section surveys, the volume of material eroded from stream banks is quantified at different spatial and time scales:

- The annual volume of material eroded from stream banks along a small headwater stream (1,400-m long) during one hydrological year has been estimated using erosion pin data.
- Long-term bank erosion has been estimated by comparing elevation data obtained in 2013 from differential global positioning system (DGPS) acquisition combined with aerial LiDAR survey to three-dimensional historical plans dating back to the stream redesign in 1944. This approach is applied at the stream and subcatchment and catchment scale.

Finally, this study will allow the comparison of the current and past proportions of eroded bank material against the total volume of sediment delivered to the catchment outlet. More generally, these results will give us a better understanding of the contribution of bank erosion to the suspended sediment production in a drained lowland agricultural context.

2 | MATERIAL AND METHODS

2.1 | Study site

The experimental Louroux pond catchment is a small agricultural headwater basin (24 km^2), representative of intensively cultivated lowland regions in Western Europe. This study site is located in the southwestern part of the Parisian basin of France (Figure 1). It has been monitored since the beginning of the year 2013 to continuously record sediment dynamics at a high temporal resolution (every 15 min) and to fingerprint the origin of sediments transported by the streams (Foucher et al., 2015; Le Gall et al., 2015).

This area features an Atlantic climate with an average annual rainfall of 684 mm. The basin is characterized by a very flat topography (mean slope of 0.44%) with an elevation ranging from 94 to 129 m. The geology of this catchment is mainly dominated by four geological units: Senonian clayey formations, lacustrine limestone, Miocene shelly sands ("Faluns de Touraine"), and Quaternary aeolian silts (Rasplus, Macaire, & Alcaydé, 1982). The land use is mostly arable land, occupying 78% of the total area, followed by pasture (18%) and forest (4%; CorineLandCover, 2002).

One of the most important water bodies of the area is located at the catchment outlet: the Louroux pond (52 ha). This reservoir has been used to record the evolution of sediment deposits since the mid-20th century (Foucher et al., 2014; Figure 1).

Over the last 70 years, this basin, similar to the majority of agricultural lowland areas in Western Europe, has been extensively affected by changes in land use and agricultural practices in the context of intensive crop farming (e.g., Antrop, 2005). The study of reservoir deposits has established a link between this land use change and the acceleration in sediment produced in this catchment (Foucher et al., 2014), with

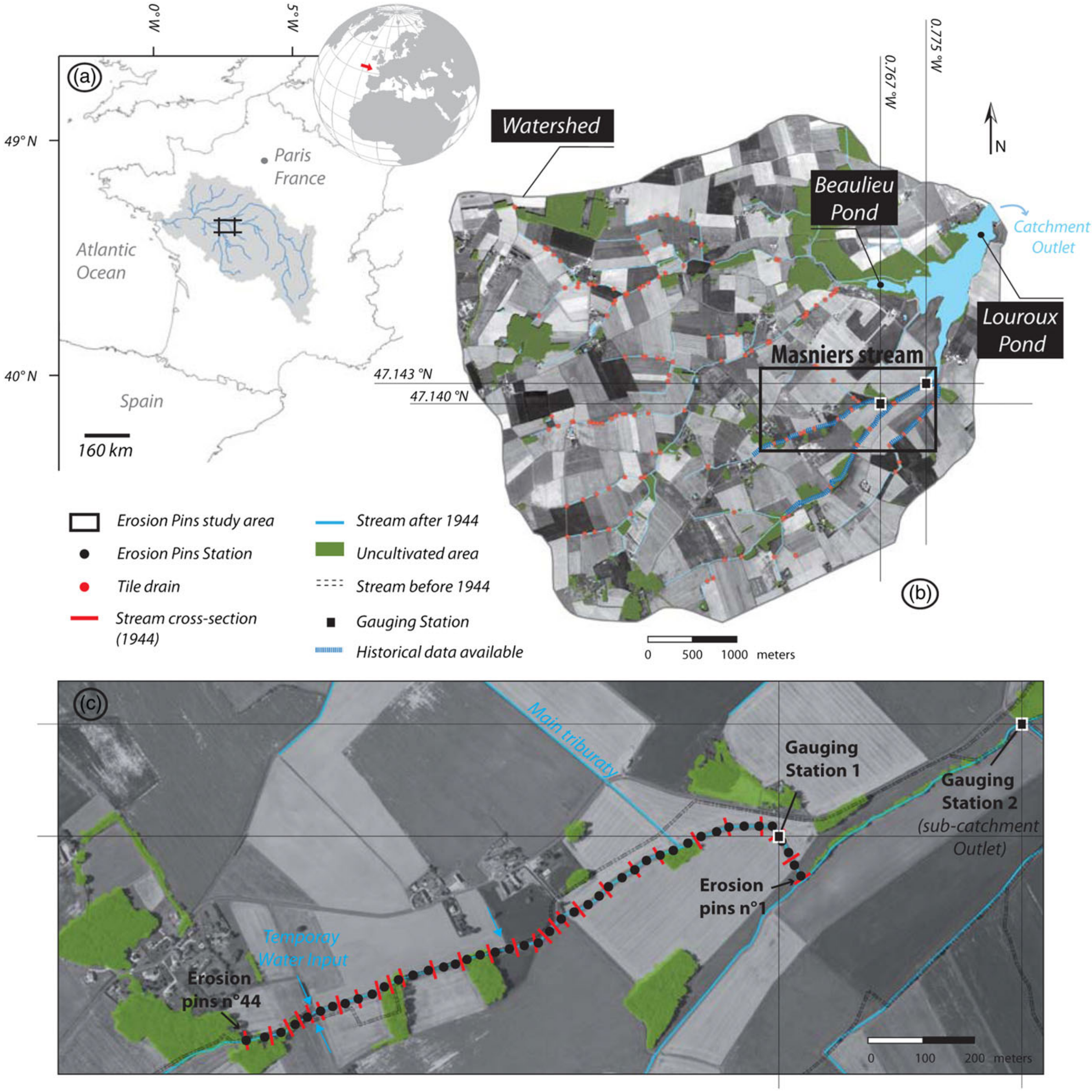

FIGURE 1 (a) Localization of the experimental Louroux pond catchment in France. (b) Presentation of the study area and locations of the gauging stations, tile drain outlets and streams. (c) Locations of erosion pin sites and historical profiles

current erosion rates that are approximately 60 times higher than before the agricultural changes.

On this catchment, three land consolidations have been implemented (in 1935, 1952, and 1992) and more than 30 km of stream channels have been created or redesigned since the Second World War. Today, the catchment comprises approximately 45.5 km of streams, of which only 25% are surrounded by grass strips because most of the streams are actually legally defined as ditches. We estimate that the majority of the basin is drained, and at least 210 tile drain outlets were identified during a field survey performed in 2012 (Figure 1; Foucher, 2015).

As a result of these intensive modifications, the water quality in the streams and the pond has degraded due to the increase in agricultural inputs, which have induced growing eutrophication in the water bodies (Foucher et al., 2014; Water Agency Loire-Brittany, unpublished data). The input of sediment (between 2,152 and 2,445 t year^{-1}) into the 52 ha pond at the outlet of the catchment has become problematic over the last 10 years, and this input corresponds to an average erosion rate from the catchment of between 90 and 102 t km^{-2} year^{-1} (Foucher et al., 2014).

Many sources of sediments described in previous studies, such as surface soil erosion, drainage network transfer, and bank erosion, may have contributed to the filling of this pond (e.g., Walling, Russell, Hodgkinson, & Zhang, 2002). In this study, the morphological variations of the banks over a hydrological year and over the last 69 years have been measured in a small part of the catchment represented by a 1,400-m-long stream section (Masniers stream, Figure 1) and then extrapolated over the entire catchment.

2.2 | Material and methods

Two distinct methodological approaches with the following aims have been used

- to reconstruct the short-term dynamics of bank erosion and channel change to quantify the current volume of exported material and
- to quantify the material mobilized through bank erosion over the last 69 years.

2.2.1 | Short-term morphological changes of banks

Spatial and temporal variations in sediment removal and accumulation at the bank sites have been measured during the winter discharge (November 2012–July 2013) using erosion pins and DGPS surveys.

The erosion pin technique consists of inserting metal rods into the bank at right angles to the bank face. The erosion and accretion dynamics can be assessed by repeated measurements. Two hundred fifty-eight pins, each 45-cm long and 0.8 cm in diameter, were deployed in November 2012 across 44 measurement sites along a 1400-m-long section of the Masniers stream (Figure 1c). The sites have been positioned arbitrarily along the stream, with an interval between each station of approximately 32 m. Each of the stations features six pins inserted at different levels into the bank. These metal rods have been established at the top, at the base, and at the middle of the stream bank. Washers have been placed around each pin to define the initial stream bank surface. The morphological evolution of the bank has been quantified using a measuring stick and has been performed by the same operator in January, April, and July 2013, with an average measurement interval of 92 days. During each of these measuring periods, the change in exposure has been measured once for each pin. No replication has been conducted for this study.

Every station and every pin have been georeferenced. Stream cross sections have been measured at the same location as profiles dating back to 1944. These measurements have been performed using a DGPS Magellan Pro Flex 500 with a centimetric resolution (Figure 1). The first DGPS survey was conducted during the pin installation, shortly before the beginning of the hydrological year.

These erosion pin measurements have been used for quantifying the volume of material exported from each bank face during the studied period by multiplying the mean activity of each bank side by the average height of the stream (calculated by the DGPS data) and the stream length (1,400 m).

To compare active erosion or accretion and stream dynamics through time, we installed two continuous monitoring stations located within and downstream of the Masniers stream and one weather station at the catchment outlet (Figure 1). Continuous records of water level and turbidity are available from each of the monitoring stations using V-notch and turbidity sensors. However, these monitoring stations were installed in early 2013 and do not cover the entire year of measurement (Figure 2).

2.2.2 | Estimation of long-term bank erosion

The introduction of intensive agriculture in the Louroux catchment has led to the creation of a dense stream network within only a few years. The streams have been created by following predefined plans. Some of these plans have been recovered from local archives. Historical records correspond mainly to stream designs performed in the southern part of the watershed, particularly within the Masniers stream and further south (Figure 1). These maps provide precious information about the dimensions and the morphology of the streams before and after recalibration in 1944. Unlike other studies that have been limited to two-dimensional data (e.g., De Rose & Basher, 2011), these plans provide accurate data in three dimensions and limit the errors in long-term bank erosion estimates, as highlighted by the previous studies (e.g., Landemaine et al., 2014; Rhoades et al., 2009). These historical data are composed of accurately positioned transverse profiles collected on average every 51 m, which provide data on the width at the bottom and at the top of the banks and the slope of the banks after recalibration. These lateral and longitudinal data from 44 cross sections have been used to reconstruct the 1944 morphology of the section of the Masniers stream documented by the DGPS profiles. The 1944 stream morphology has then been compared to the current morphology of the stream.

Historical cross sections could not be retrieved for the northern part of the catchment. The hypothesis was made that the northern and southern parts presented similar stream morphology after stream redesign. The 109 historical cross sections available in the southern part of the catchment have therefore been used to estimate an

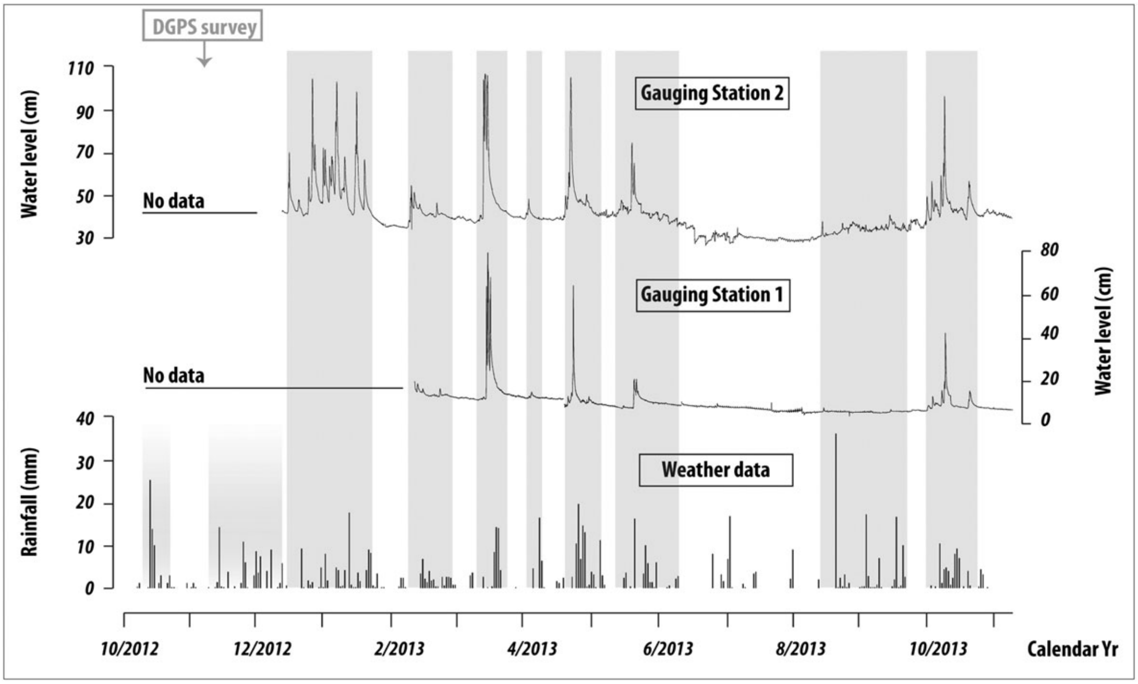

FIGURE 2 Temporal changes in discharge at gauging stations 1 and 2 and rainfall during the study year. DGPS = differential global positioning system

average profile after the stream redesign in 1944. This average section has been extrapolated over the entire hydrographic network to obtain an estimate of the stream volume in 1944 for the whole Louroux catchment.

To assess the error associated with the use of an average section, we made a comparison with the volume of the streams based on historical data punctually collected in other parts of the catchment at various scales, including the stream scale documented by historical plans and the poorly documented catchment scale. At the stream scale, the volume calculated using the average cross sections has been compared with the volume estimated with the 44 historical cross sections collected along the 1400-m-long Masnier stream. The same operation has been performed at the subcatchment scale by comparing the volume estimated with the average profile to the volume calculated with the 65 historical cross sections available along the 4,700 m of streams present in this subcatchment (Figure 1).

The results obtained have been used to estimate the error associated with the use of an average profile at several scales before using the past stream volume estimation at the catchment scale.

In addition to the volume comparison at several spatial scales, the Bland–Altman comparison has been employed to compare the morphological differences between the average historical profile, the profile available at the stream scale and the historical profile available at the subcatchment scale. The Bland–Altman method allows the graphical comparison of two measurements methods (in our case, the morphology of the average profile versus the real profiles). In this comparison, the two techniques are plotted against the average of the two techniques (Altman & Bland, 1983). This analysis is based on the quantification of the agreement between two quantitative measurements by studying their mean difference and constructing the limits of agreement. The Bland–Altman plot analysis is a simple way to evaluate the bias between the mean differences and to estimate an agreement interval.

In parallel to this approach based on archive data, an airborne LiDAR campaign was conducted throughout the Louroux catchment during a low-water period in the spring of 2013 to calculate the current volume occupied by the streams. The major strength of this approach is that it overcomes the point-based nature of the DGPS survey by obtaining a continuous Digital Elevation Model (DEM) after processing. Therefore, the method may more accurately define the current volume of the streams network with the possible application over large areas. This aerial survey produced a high-resolution airborne LiDAR record with a density of 7 points/m^2 before processing and 4.5 points/m^2 after processing. The LiDAR point clouds have been calibrated by measuring points and homologous segments. Calibration residuals show an accuracy of approximately 5 cm in the XY plane and 12 cm in the Z direction. The points have been classified with the Terrasolid Suite® to distinguish ground points, vegetation points, overlapping points, and inconsistent points. The classification methodology is organized around several steps. The first step consists of the manual detection of outliers and false point measurements. The second step involves the automatic determination of the soil surface by deleting the vegetation cover. Additional treatment steps have been described in Vandromme, Foucher, Cerdan, and Salvador-Blanes (submitted). The study of Vandromme et al. (submitted) has indicated that the main limitations of this method are the underestimation of the bottom ditch morphology and local issues related to the presence of vegetation. According to the authors of that study, the volume of the streams in the Louroux catchment is underestimated by approximately 11% (Vandromme et al., submitted). The aerial LiDAR data and the associated error have been used in this study to estimate the current stream morphology at the catchment scale to quantity the material exported since 1944.

3 | RESULTS AND DISCUSSION

3.1 | Erosion pin activity

Of the 258 erosion pins installed along the stream, 83% have recorded at least one erosive or depositional event over the study period (Figure 3). Within this period of measurements, erosion dominated, resulting in the average removal of 17.7 mm along the stream.

In the first measurement survey, 32% of the pins exhibited erosion (25% exhibited accretion); in the second survey, 37% exhibited erosion (27% exhibited accretion); and in the last survey, 26% exhibited erosion (21% exhibited accretion). A large proportion of the erosion pins did not record a change from a measurement period to the next. Unchanged pins accounted for 41% of the pins at the end of the first period, 35% at the end of the second period, and 52% at the end of the third period.

The maximum erosion rate has been recorded during the third phase between April and July 2013, corresponding to an estimated loss of material of 3,136 mm year^{-1} at pin station n°6 on the lower part of the bank. The most significant accretion has been measured during the second phase of measurements between January and April 2013, corresponding to an average deposition of material on the left bank of 1,693 mm year^{-1} at station n°29.

3.1.1 | Current spatial and temporal evolution of bank dynamics

The three measurements periods present distinct dynamics that are the consequence of numerous parameters, such as the bank state, the vegetation cover, or the stream hydrodynamics (Figure 2). Throughout the stream, during the first period (November 2012–January 2013), the sediment activity has been dominated mainly by material deposition with a net mean accumulation rate of 19.8 mm year^{-1}. This accumulation trend has reversed in the second phase of measurement, with a net mean erosion rate of 30 mm year^{-1} along the stream. This erosional trend has accelerated during the last period, with a net mean erosion rate of 41 mm year^{-1}. Figure 3 shows that the last period of measurement features more localized pin activity, but this activity represents the greatest loss of material.

The first survey period does not exhibit a clear spatial pattern of erosion or accretion activities along the stream. Still, Figure 3 shows that the majority of active pins are located in the lower part of the

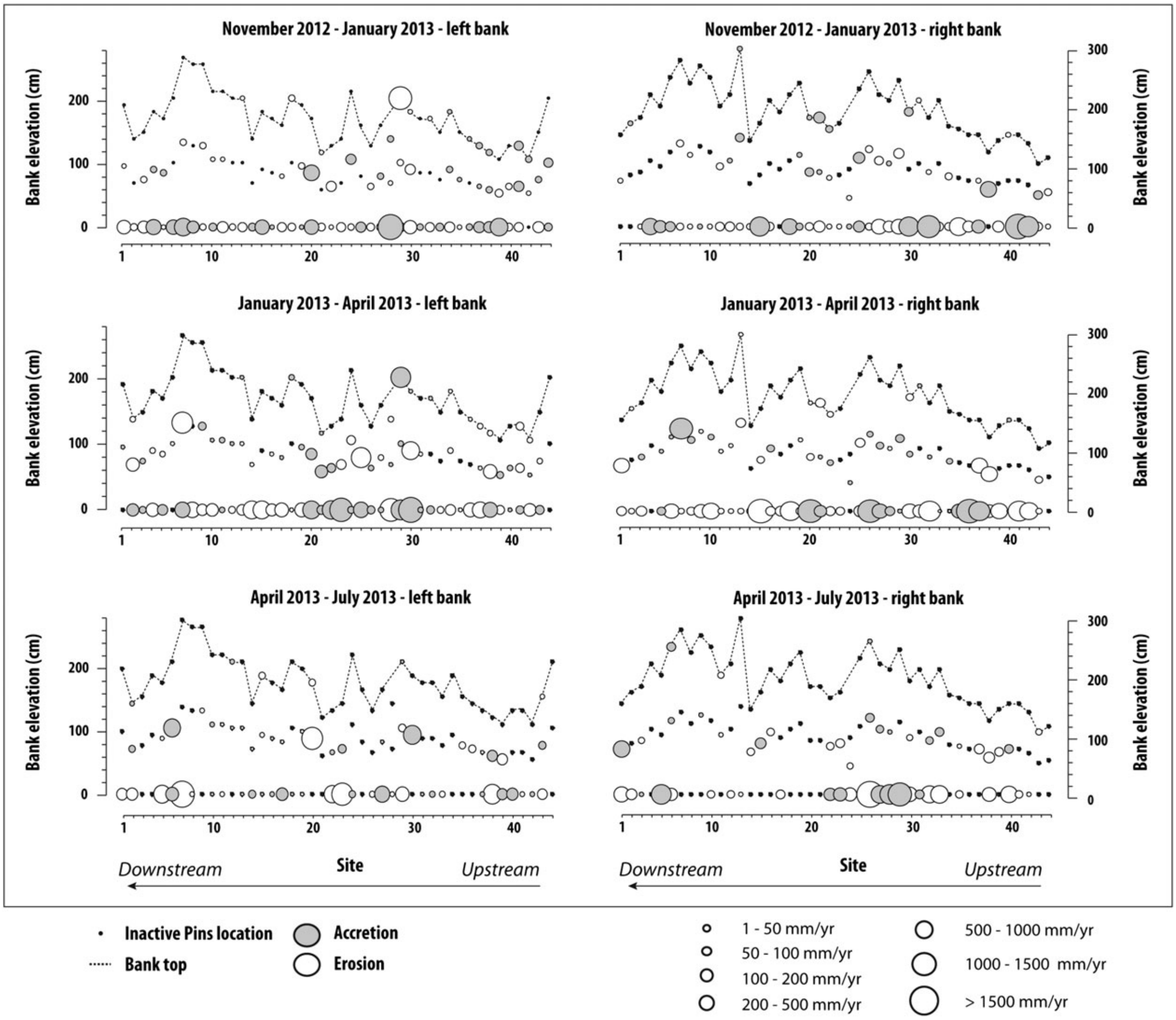

FIGURE 3 Spatial and temporal evolution of pin activity during the hydrological year 2012–2013

bank, where nearly all pins (94%) have been active. The redistribution of material at the base of the bank can in part be explained by the nature of the substrate present in the streambed of the Masniers stream (Figure 1). This river is located on a noncohesive sandy substratum (Rasplus et al., 1982), which is sensitive to excavation phenomena along the lower part of the bank and plays a significant role in bank destabilization during the rewetting period. This noncohesive sandy substratum is present in 32% of the catchment area. During the second survey period (January to April 2013), a spatial structure has been observed, with two preferential accretion areas between the pin stations 20 and 30 and around pin station 35 surrounded by a global erosive trend. This pattern is particularly evident in the lower part of the banks (Figure 3). Longitudinal zoning also seems to be present during the last measurement phase, with pin groups with similar behavior between stations 1 and 8, 20 and 30, and 37 and 41.

The accretion or erosion spatial structure in the last two periods may, to some extent, be related to human management: A bridge is located between pin stations 20 and 21, and the Venturi channel of the monitoring station is located between pin stations 4 and 5.

3.1.2 | Morphodynamic evolution along the stream

A hierarchical cluster analysis has been performed to define the similarity and dissimilarity between the pin station activities along the stream and to interpret the bank dynamics. To perform this classification, we compiled all the pin stations and seasonal measurements. Based on this classification, three mains areas corresponding to two classes are clearly distinguished and are shown in Figure 4. The downstream part of the river (area C) between pin stations 1 and 20 and the upstream part (area A) between pin stations 35 and 43 exhibit similar behaviors, while area B in between exhibits clearly different dynamics.

Figure 4 illustrates the bank position-related accretion or erosion dynamics of the three defined areas. This longitudinal and vertical segmentation highlights some trends in the bank dynamics.

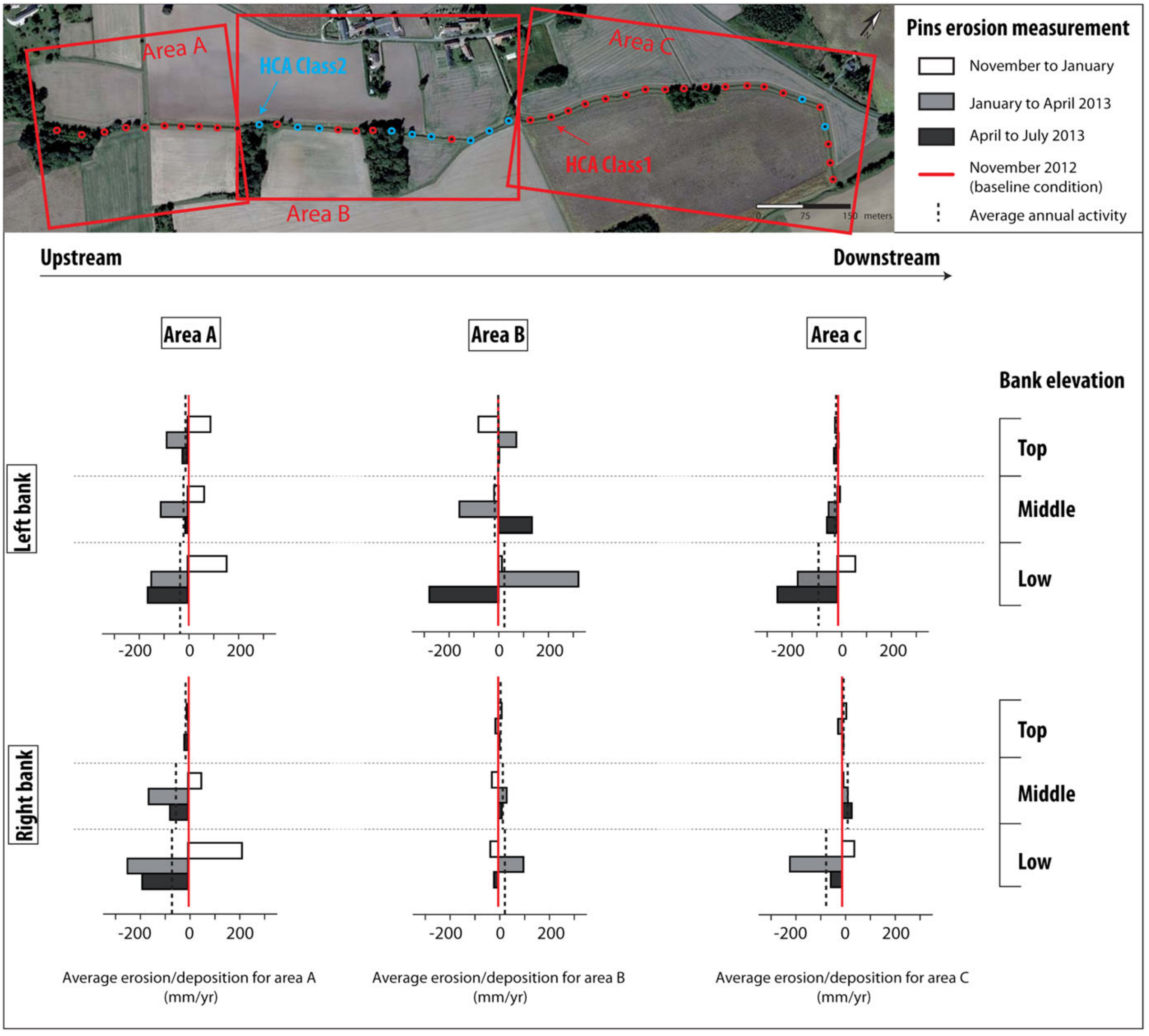

FIGURE 4 Vertical and spatial evolution patterns of the stream bank dynamics during the winter discharge and the locations of the three main area and the two classes extracted from the hierarchical cluster analysis (HCA) classification

From November to January, the stream was entirely covered by dense vegetation (reeds and thorn bushes), which protects the bank surface from the discharge at the beginning of the hydrological year (Figure 3). This period, therefore, promotes material accumulation in the downstream and upstream parts of the river (reaching values of +50 and +200 mm year^{-1}), especially on the lower part of the bank. The majority of the pins within areas A and C present positive activity (Figure 4). This accretion can be explained by the higher water level and the first flood, which tends to destabilize the banks due to gravitational effects. During this period, the bank migration is hampered by the vegetation. The central part of the stream section features considerable vegetation development and stable banks, and the water level was high in this area, even for very low water flows.

At the beginning of January, the vegetation had been crushed throughout area A (Figure 4). The banks, which were previously protected by decaying vegetation, became more prone to erosion. During January to April, flood events were frequent, especially at the beginning of January (Figure 2). This period is characterized by a generalized loss of material in the A and C areas, with a mean export of −225 mm year^{-1} for the lower part of the right bank in area A and −200 mm year^{-1} for area C. Figure 4 shows a systematic increase in erosion towards the base of the banks. In area B, an accretion trend dominated, especially in the lower part of the left bank with an average calculated accretion of +300 mm year^{-1}.

This accumulation trend is not generalized at the middle part of the bank and at the pins indicate a net erosion of −150 mm year^{-1}. This accumulation at the base and erosion in the middle of the bank seems to indicate a predominance of gravitational events associated with the bank destabilization that began during the first period.

During the last survey period, floods events are scarce (Figure 2). The pin data in the three areas indicate global erosion (Figure 4). For area A, all the pins on both sides of the bank experienced erosion, especially in the lower parts of the bank. In area B, the lower parts of the left bank also experienced a loss of material, with an export of −275 mm year^{-1}, whereas the middle part of the same bank experienced an accretion of +100 mm year^{-1}. The downstream area shows the greatest erosion dynamics between April and July, with an average erosion of −220 mm year^{-1} on the lower part of left bank.

The average measurements during the study period shown by the dotted lines on Figure 4 indicate a global trend of material loss in the upstream and downstream parts of the river. This is especially the case for the lower left and right parts of the banks in areas A (−45 and −75 mm year^{-1}) and C (−90 and −75 mm year^{-1}). On the other hand, the accretion of material was observed for the lower parts of the banks in area B (+25 mm year^{-1}; Figure 4).

The stream bank activity in area A is characterized by an alternation of marked accretion and erosion events. In areas A and C, the banks were destabilized during the first month of the hydrological year, and the accumulated material was evacuated by subsequent flood events. It is also possible that towards the end of the hydrological year, another gravitational event provided fresh material. The dynamics of area B changed at the same times as those of the other areas, but the trends are reversed. In this area, the lower part of the bank was eroding during the first survey period, accumulating during the second, and eroding towards the end of the hydrological year.

3.1.3 | Quantifying bank erosion over one hydrological year

Based on morphological data obtained during the DGPS survey and the sediment activities estimated with the erosion pin approach, an average volume of material exported during the 2012–2013 hydrological year has been calculated.

One of the limitations of this estimation is that the pins were not measured between July and October 2013. However, due to the presence of dense vegetation and the low rainfall and water level recorded by the stream monitoring stations (Figure 2), the sedimentary dynamics during this period were likely low.

DGPS acquisition along the streambed showed that the average heights of the right and left banks were 200 and 158 cm, respectively. The measurements of pins previously described during the hydrological year enabled the calculation of an average loss across the full-bank height of 13.77 mm year^{-1} (σ 36 mm year^{-1}) on the right bank and an average of 21.6 mm year^{-1} (σ 39 mm year^{-1}) on the left bank. These data correspond to a mean annual loss of material of 17.7 mm year^{-1} over the entire riverbank of the channel.

From these figures, we estimate that 35 and 44.6 m^3 of material have been exported from the right and left banks, respectively. These results suggest that an annual volume of 80.1 m^3 has been exported from the banks along the studied part of the Masniers stream (Figure 1). This value corresponds to an annual removal of 61.5 m^3 km^{-1}. With a mean dry bulk density in the stream banks of 1317 kg m^{-3} (σ 75.8 kg m^{-3}, calculated from n = 5 composite samples), 105 t (σ 6 t, according to variations in dry bulk density) of material has been exported from this 1400-m-long stream section during one hydrological year, corresponding to 75 t km^{-1} (σ 4.5 t km^{-1}).

The results obtained in this study for the Masniers stream are of the same order of magnitude as previous studies conducted in Europe. In British rivers, Couper et al. (2002) estimated an erosion rate ranging between 8.6 and 11.7 mm year^{-1}. In Danish rivers, a study using erosion pin produced values ranging between 25 and 36 mm year^{-1} (Kronvang, Audet, Baattrup-Pedersen, Jensen, & Larsen, 2012). Similarly, in another study on a 16-km^2 Danish agricultural catchment, Veihe et al. (2010) estimated a loss of material of 17.6 to 30.1 mm year^{-1}. The results obtained for the current bank dynamics along a small stream are, therefore, comparable to the results of previous studies performed on small agricultural catchments.

3.2 | Quantifying bank erosion over the last 70 years along the Masniers River

The streambed morphology in 1944 was extracted from the historical data. The 3D details of these plans were used to reconstruct the morphology of these streams in 1944 and to quantify the volume occupied by the streams. For this quantification, 44 historical profiles were used. Postconstruction control with wooden templates suggests that the streams were rectilinear and very geometric. The elevation data have not been imported into the Geographic Information System (GIS) to limit georeferencing conflicts and positioning errors between the georeferencing systems used in 1944 and in 2013.

Using these historical plans, the morphology and the volume occupied by the stream in the Masniers stream could be estimated. An average profile of the stream before the stream redesign is presented in Figure 5. The average depth is 42 cm (σ 15 cm), whereas the volume occupied by this stream section has been estimated to be 505 m^3. The same operation has been performed for the profiles following the redesign in 1944. The volume of the stream increased by a factor of almost two, reaching a volume of 1032 m^3. The redesign resulted in an increase of the stream depth by 74%, resulting in a mean depth along the stream in 1944 of 73 cm (σ 10.6 cm).

The DGPS surveys have been processed according to the method proposed by Landemaine et al. (2014). Using the same location as the historical maps and cross sections, an average stream profile in 2013 has been estimated. The stream currently presents a mean depth of 179 cm (σ 38 cm), a top of the bank width of 353 cm (σ 61 cm), and a bottom of the bank width of 119 cm (σ 20 cm). Between the redesign in 1944 and 2013, the stream depth has increased by 145%. The DGPS data have been used to estimate that the stream occupied a volume of 3685 m^3 in 2013, corresponding to an increase of 257% in comparison with the original volume in 1944. Therefore, 2,653 m^3 have been exported over 69 years, corresponding to 38.4 m^3 per year on average.

With this methodology and by using the bank bulk density previously calculated, we can estimate that 3,494 tons (σ 200 tons, according variations in the dry bulk density) of sediment has been exported from the stream banks over 69 years, representing a mean input of 51 t $year^{-1}$ (σ 2 t $year^{-1}$) into the hydrosystem.

The 2013 stream morphology of the same area was estimated using airborne LiDAR data.

The major strength of this approach is that it overcomes the point-based nature of the DGPS survey to obtain a continuous DEM after processing. It is, therefore, able to more precisely define the current volume of the stream network and can be applied over larger areas. The drawbacks are that the elevation accuracy is lower (~10 cm) than that of the DGPS surveys and that vegetation and water exert a shielding effect (Vandromme et al., submitted). This methodology has been applied to calculate the volume occupied by the Masniers stream, and the results have been compared with those obtained with the DGPS profile technique.

The result obtained with the LiDAR methods yield a volume of 3,295 m^3 for this stream, corresponding to an average annual export of 42 t $year^{-1}$ (σ 3 t $year^{-1}$).

The two approaches produce similar values, with a difference between the stream volumes estimated with the DGPS and LiDAR methods of less than 11% (3,685 and 3,295 m^3, respectively) over the whole catchment. Thus, the margin of error is low (Vandromme et al., submitted).

For the Masniers stream, the bank erosion measured during the 2012–2013 hydrological year is almost twice as high as that based on the historical data. Several parameters may explain these differences. First, the high rainfall amount in this year may have led to an increase in bank erosional processes along the stream. The second reason is that there is a potential gradual increase of erosional processes with time associated with increasingly deep and less stable banks. One last explanation is that the noncohesive shelly sand substratum was reached after a given time, possibly accelerating the current bank erosion intensity compared with the long-term bank erosion records.

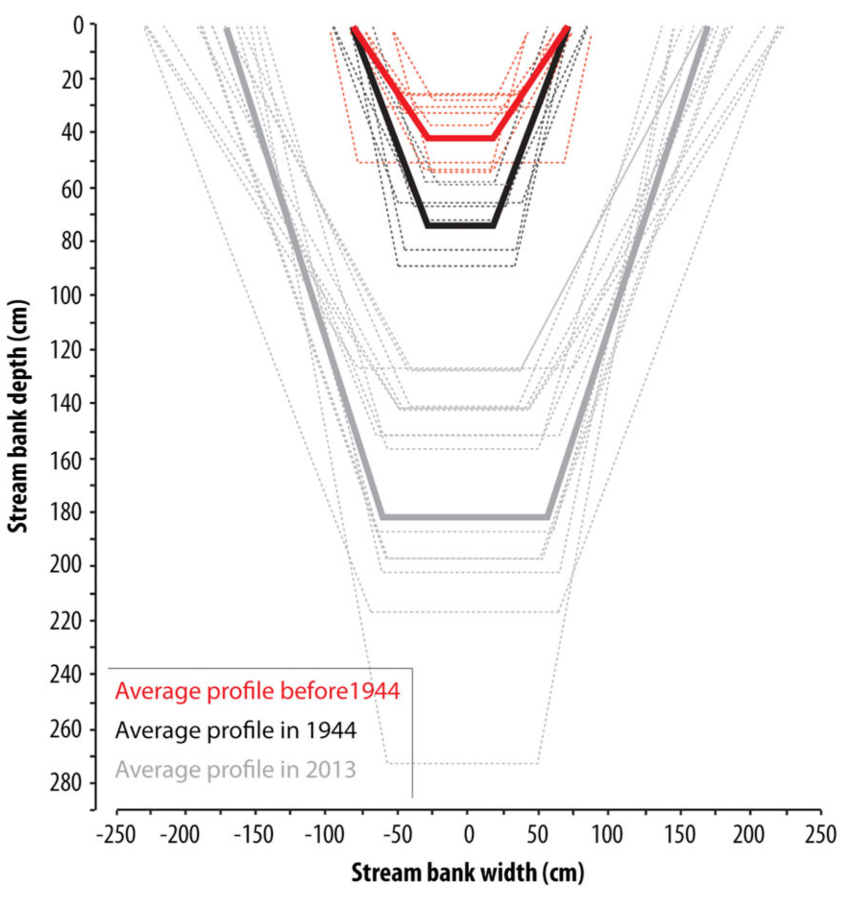

FIGURE 5 Stream profile evolution before and after the management in 1944 based on historical plans and differential global positioning system data for the Masniers sector

3.3 | Extrapolation of the LiDAR approach over a larger area

In addition to the historical data collected in the Masniers stream, the southwestern part of the watershed is well documented, with a total of 76 additional historical profiles. These additional data allow the estimation of the bank erosion across a larger area than just the Masniers stream.

The stream volume over the entire catchment after stream redesign in 1944 was calculated by two means. The first approach uses the mean profile estimated within the Masniers stream, but the second one uses the data from all 109 available profiles. The use of two methods, therefore, accounts for differences between the local approach within the Masniers stream and the approach including more historical data over a larger area. Using the 76 historical profiles available for the 4.72-km-long stream, we estimated a stream volume of 3935 m^3 for 69 years ago. For this same stream but using an average profile (the average profile includes a top bank width of 173 cm [σ 39 cm]), a bottom bank width of 64 cm (σ 17 cm) and a depth of 67 cm (σ 9 cm) based on the 109 historical profiles available in the Louroux catchment, the volume occupied by the stream in 1944 is estimated to be 3,731 m^3. The extrapolation of the average profile calculated with all of the historical plans available for this entire catchment is robust (an error of only ±6% is present in the area where the comparison is possible). Additionally the Bland–Altman comparison methods indicated that, at the stream scale (1.4 km), average biases of 17 cm (σ 15 cm) for the top width estimate and −6 cm (σ 10.5 cm) for the stream height exist between the method using the real historical data and the method using an average profile (Figure 6). These values correspond to an average error between these methods of 12% (top width estimate) and 14% (stream height estimate). The graphical interpretation of the Bland–Altman plot indicates an increase of difference between the methods (average profile vs. historical profiles) when the stream width decreases and when the stream deepens. All the profiles used for this comparison range between the limits of agreement, highlighting a similarity between the two methods at the stream scale. At the subcatchment scale, this method comparison between the historical data (4.72 km) and the average profile indicates an average bias of 13.8 cm (σ 15.5 cm) for the top width estimate and an average bias of 7.5 cm (σ 16 cm) for the height estimate. The average errors calculated between the two methods are 11.5% and 29.5% for the top width and depth estimates, respectively. These comparisons, therefore, indicate a similarity between the method based on the historical data and the method based on an average profile with only one type of profile within the limits of agreement (Figure 6).

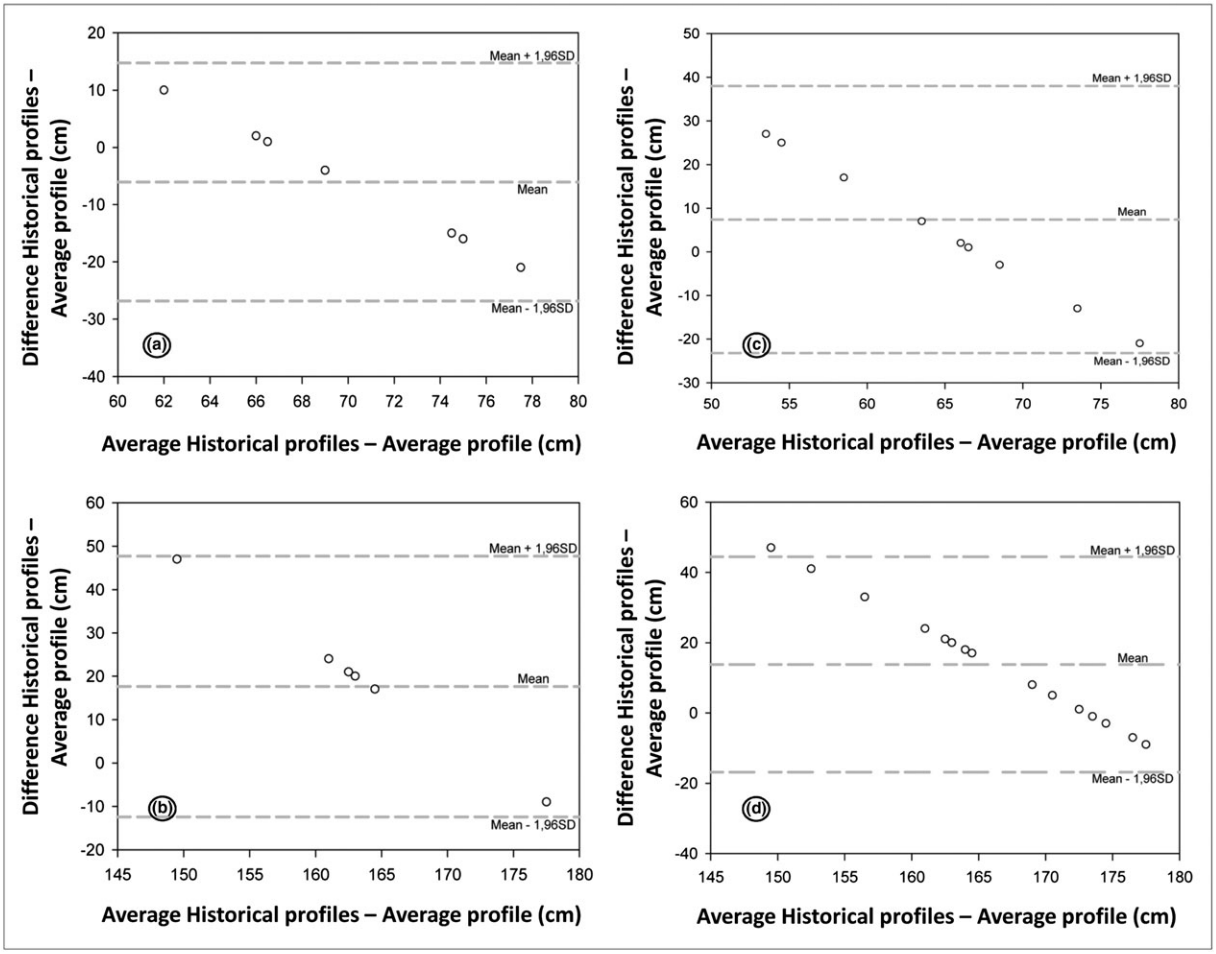

FIGURE 6 Bland and Altman plots comparing the methods using historical data and an average profile. (a) Comparison of bank height at the stream scale, (b) comparison of top bank width at the stream scale, (c) comparison of the bank height at the subcatchment scale, and (d) comparison of top bank width at the subcatchment scale

In 2013, the same 4.72-km-long stream represented a volume of 8740 m^3 according to the method based on LiDAR data (Vandromme et al., submitted). As previously noted for the Masnier stream, the LiDAR approach underestimated the stream volume by approximately 11% (underestimation of the stream depth based on LiDAR data). With a corresponding correction, we can, therefore, consider the actual volume of these ditches to be approximately 9700 m^3. Accordingly, 5,765 m^3 (estimated with historical profiles) to 5,969 m^3 (estimated with the average profile) of material has been exported in 69 years. This loss corresponds to average bank erosion values of 23 tons km^{-1} $year^{-1}$ (σ 1.3 tons km^{-1} $year^{-1}$, according to variations in the dry bulk density) using the real historical cross sections along the 4.72-km-long stream and 24 tons km^{-1} $year^{-1}$ (σ 1.4 tons km^{-1} $year^{-1}$) using the average profiles extracted from the 109 historical profiles.

These results obtained at the subcatchment scale are similar and can be extrapolated to the whole catchment scale.

3.4 | Importance of bank erosion as a sediment source at the catchment scale

The Louroux pond, located at the outlet of the catchment (Figure 1), has recorded an average terrigenous input of sediment ranging between 2,152 and 2,445 t $year^{-1}$ for the 2003–2013 period (Foucher et al.,2014). In this section, we will try to estimate the contribution of bank erosion to the sediment supplied to the pond.

The bank erosion recorded along the Masnier River with erosion pins has been extrapolated over the entire hydrographic network (45.5 km of stream length). This extrapolation results in an estimated loss of 20 m^3 km^{-1}, that is, an annual gross delivery of material of 869 m^3 $year^{-1}$ over the entire catchment (an average bank height of 1.17 m as estimated from LiDAR data and an average erosion rate of 17.7 mm/year as estimated from the pin records) or 1140 t $year^{-1}$ (σ 70 t $year^{-1}$). The exported material due to bank erosion therefore represents between 46% to 52% of the sediment delivered to the pond, if we consider the export values measured during the years 2012–2013 as representative of the 2003–2013 period.

An approximate gross delivery of bank material to the streams can be evaluated over the long term by calculating the current volume occupied by the streams in the entire catchment in 2013 and comparing it to the average stream profile after the stream redesign in 1944. With the mean profile previously used for the extrapolation, we can estimate that, immediately after their redesign, the streambeds occupied a volume of 34,933 m^3 (σ 2,095 m^3, the error associated with the use of an average historical cross section) for the entire catchment. The LiDAR approach at the catchment scale can be used to estimate a current volume of 69,138 m^3 (σ 7,600 m^3, the error corresponding to the underestimation of stream volume by the LiDAR method, Vandromme et al., submitted). Over 69 years, this estimate represents approximately 45,000 t (σ 2600 t) of eroded bank material that contributed to the filling of the pond and represents a mean sediment delivery of 652 t $year^{-1}$ (σ 38 t $year^{-1}$) between 1944 and 2013. Thus, with the use of the historical approach, we estimate that the sediment derived from the banks over the last 10 years has contributed between 27% and 30% of the total terrigenous input deposited in the pond (the total terrigenous input record in the pond ranges between 2,152 and 2,445 t $year^{-1}$, Foucher et al., 2014). Bank erosion seems to be a substantial source contributing to the filling of the Louroux pond.

Table 1 summarizes the relative contributions of this source based on the use of different methods, such as pin data, DGPS and LiDAR acquisition, and the use of historical plans.

The long-term results for different scales seem to indicate a decrease in the bank contribution to the pond filling at the larger scales. This scaling effect could be due to many parameters, such as the topography and the local climate or the geology. The geological units present in this catchment are variable. The noncohesive geological substratum present in the Masniers River and at the subcatchment scale could result in greater bank erosion dynamics compared to the other parts of the catchment with more cohesive substrata. The heterogeneity of the geological units within the catchment could therefore induce a spatial heterogeneity in bank erosion. Therefore, bank erosion rates estimated in the southwestern part of the catchment would overestimate the bank erosion over the whole catchment.

A previous fingerprinting approach study based on the ^{137}Cs activity performed in this catchment estimated that the subsurface source (bank erosion) contributed 18% (σ 1%) of the pond sediment over the last 10 years (Le Gall et al., 2016). This result is slightly different than the contribution estimated in this study (27% to 30%) but still on the same order of magnitude.

The long-term estimate presented in this study may have some limitations. One of the limitations of this historical approach is that we do not know the precise chronology of stream bank management. The majority of the streams were redesigned in 1944, but it is possible that some areas were managed later. However, these cases concern limited areas. It is assumed that these errors are minor over the last 69 years. Another limitation concerns the LiDAR measurements. The volume occupied by the streams is underestimated locally by the presence of vegetation (Vandromme et al., submitted).

Finally, we have assumed that the bank erosion dynamic have been constant over the last 70 years in order to estimate the current contribution of bank material to the pond sediment for the 2003–2013 period. However, no data are available to support this hypothesis, and we do not know whether the current bank dynamics in this catchment are greater than, less than or equal to the erosion dynamics in 1944 immediately after the stream design.

Despite these limitations, this study is the only one, to our knowledge, to quantify the contribution of bank material over the long term along 45.5 km of highly human-impacted streams and has widened the discussion on sources of sediments in streams.

TABLE 1 Proportion of bank source to pond filling for the last 10 years estimated with various extrapolation scales compared to a fingerprinting method implemented on the Louroux catchment (Le Gall et al., 2016)

Study scale	Contribution of bank source (%)	Average lose of material ($t\ km^{-1}\ yr^{-1}$)
Stream	46 to 52	36
Subcatchment	44 to 50	24
Catchment	27 to 30	14
Catchment (by fingerprinting)	18.8 ± 1	9.5

This study estimated a component of the Louroux pond sediment budget and highlighted the importance of bank erosion incision during the last 70 years in this lowland agricultural catchment.

4 | CONCLUSIONS

This study focused on estimating the magnitude of bank erosion at various spatial and temporal scales in a 24 km^2 cultivated lowland catchment. The long- and short-term results show that bank erosion is very dynamic. During the 2012–2013 winter discharge, an overall loss of material was recorded, with 105 t (σ 6 t) of material exported from a small 1400-m-long stretch of the Masnier stream. During the study period, an average erosion rate of 17.7 mm year^{-1} was measured, and this erosion dominantly occurred along the lower part of the banks, where every pin recorded erosive activity. These results are comparable with other studies performed in similarly sized catchments in temperate climates.

These short-term erosion rate estimates are higher than those of the long-term estimates based on small and large spatial scales, which yield an average erosion rate for the same stream of 36 t km^{-1} year^{-1}.

The difference between these two approaches can be principally attributed to incision phenomena. Over time, the banks and streambeds in this area have been progressively incised into the noncohesive geological substratum. Once the streams reached this geological substrate, the erosion dynamics increased gradually over time. This parameter explains the difference between the current record and the long-term bank erosion record.

At the Louroux pond catchment scale, the average erosion rate for the last 69 years has been calculated to be 14 t km^{-1} year^{-1} (σ 0.8 t km^{-1} year^{-1}). It is noticeable that the bank erosion seems to be an important source of material exported through the river system in this agricultural plain catchment. For the last 10 years, we estimate that bank erosion represents between 27% and 30% of the total sediment accumulated in the pond based on annual bank erosion rates measured over the entire catchment. Two others components are also potential sources of sediment in this agricultural context: soil erosion and the transfer of material through the drain networks. The contribution of the latter source is much less studied and represents interesting prospects for defining the origins of material involved in the degradation of water bodies in lowland drained environments.

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REFERENCES

Altman, D. G., & Bland, J. M. (1983). Measurement in medicine: The analysis of method comparison studies. *The Statistician*, *32*(July 1981), 307–317. doi:10.2307/2987937

Antrop, M. (2005). Why landscapes of the past are important for the future. *Landscape and Urban Planning*, *70*(1–2), 21–34. doi:10.1016/j.landurbplan.2003.10.002

Bartley, R., Keen, R. J., Hawdon, A. A., Hairsine, P. B., Disher, M. G., & Kinsey-Henderson, A. E. (2008). Bank erosion and channel width change in a tropical catchment. *Earth Surface Processes and Landforms*, *33*(14), 2174. doi:10.1002/esp.1678

Bull, L. J. (1997). Magnitude and variation in the contribution of bank erosion to the suspended sediment load of the River Severn, UK. *Earth Surface Processes and Landforms*, *22*(12), 1109–1123. doi:10.1002/(SICI)1096-9837(199712)22:12<1109::AID-ESP810>3.0.CO;2-O

Caitcheon, G. G., Olley, J. M., Pantus, F., Hancock, G., & Leslie, C. (2012). The dominant erosion processes supplying fine sediment to three major rivers in tropical Australia, the Daly (NT), Mitchell (Qld) and flinders (Qld) rivers. *Geomorphology*, *151–152*, 188–195. doi:10.1016/j.geomorph.2012.02.001

Ciszewski, D., & Czajka, A. (2015). Human-induced sedimentation patterns of a channelized lowland river. *Earth Surface Processes and Landforms*, *40*(6), 783–795. doi:10.1002/esp.3686

Collins, A. L., Zhang, Y., McChesney, D., Walling, D. E., Haley, S. M., & Smith, P. (2012). Sediment source tracing in a lowland agricultural catchment in southern England using a modified procedure combining statistical analysis and numerical modelling. *Science of the Total Environment*, *414*, 301–317. doi:10.1016/j.scitotenv.2011.10.062

Collins, A. L., Zhang, Y., Walling, D. E., Grenfell, S. E., & Smith, P. (2010). Tracing sediment loss from eroding farm tracks using a geochemical fingerprinting procedure combining local and genetic algorithm optimisation. *Science of the Total Environment*, *408*(22), 5461–5471. doi:10.1016/j.scitotenv.2010.07.066

CorineLandCover. (2002). EEA-ETC/TE. 2002. CORINE land cover update. I&CLC2000 project. Technical guidelines, http://terrestrial.eionet.eu.int

Couper, P., Stott, T., & Maddock, I. (2002). Insights into river bank erosion processes derived from analysis of negative erosion-pin recordings: Observations from three recent UK studies. *Earth Surface Processes and Landforms*, *27*(1), 59. doi:10.1002/esp.285

Couper, P. (2003). Effects of silt-clay content on the susceptibility of river banks to subaerial erosion. *Geomorphology*, *56*(1–2), 95–108. doi:10.1016/S0169-555X(03)00048-5

Darby, S. E., Rinaldi, M., & Dapporto, S. (2007). Coupled simulations of fluvial erosion and mass wasting for cohesive river banks. *Journal of Geophysical Research: Earth Surface*, *112*(3). doi:10.1029/2006JF000722

De Rose, R. C., & Basher, L. R. (2011). Measurement of river bank and cliff erosion from sequential LIDAR and historical aerial photography. *Geomorphology*, *126*(132). Retrieved from http://www.sciencedirect.com/science/article/pii/S0169555X10004861.

Foucher, A. (2015). Reconstruction of sediment supply in intensively cultivated lowlands: sources, pathways and sediment storage in the Louroux catchment (France). Université de Tours. doi:10.13140/RG.2.2.24718.56643

Foucher, A., Laceby, P. J., Salvador-Blanes, S., Evrard, O., Le Gall, M., Lefèvre, I., … Desmet, M. (2015). Quantifying the dominant sources of sediment in a drained lowland agricultural catchment: The application of a thorium-based particle size correction in sediment fingerprinting. *Geomorphology*, *250*, 271–281. doi:10.1016/j.geomorph.2015.09.007

Foucher, A., Salvador-Blanes, S., Evrard, O., Simonneau, A., Chapron, E., Courp, T., … Lecompte, F. (2014). Increase in soil erosion after agricultural intensification: Evidence from a lowland basin in France. *Anthropocene*, *7*, 30–41. doi:10.1016/j.ancene.2015.02.001

Green, T. R., Beavis, S. G., Dietrich, C. R., Jakeman, A. J., & Jakeman, A. J. (1999). Relating stream-bank erosion to in-stream transport of suspended sediment. *Hydrological Processes*, *13*(5), 777–787. doi:10.1002/(SICI)1099-1085(19990415)13:5<777::AID-HYP780>3.0.CO;2-P

Grove, J., Croke, J., & Thompson, C. (2013). Quantifying different riverbank erosion processes during an extreme flood event. *Earth Surface Processes and Landforms*, *38*(12), 1393. doi:10.1002/esp.3386

Henshaw, A. J., Thorne, C. R., & Clifford, N. J. (2013). Identifying causes and controls of river bank erosion in a British upland catchment. *Catena*, *100*, 107–119. Retrieved from http://www.sciencedirect.com/science/article/pii/S0341816212001646

Heritage, G., & Hetherington, D. (2007). Towards a protocol for laser scanning in fluvial geomorphology. *Earth Surface Processes and Landforms*, *32*(1), 66. doi:10.1002/esp.1375

Kauffman, J. B., Krueger, W. C., & Vavra, M. (1983). Impacts of cattle on streambanks in north- eastern Oregon. *Journal of Range Management*, *36*(6600), 683–685. doi:10.2307/3898184

Kessler, A. C., Gupta, S. C., & Brown, M. K. (2013). Assessment of river bank erosion in Southern Minnesota rivers post European settlement. *Geomorphology*, *201*, 312. Retrieved from http://www.sciencedirect.com/science/article/pii/S0169555X13003553

Kronvang, B., Andersen, H., Larsen, S., & Audet, J. (2013). Importance of bank erosion for sediment input, storage and export at the catchment scale. *Journal of Soils and Sediments*, *13*(1), 230–241. doi:10.1007/s11368-012-0597-7

Kronvang, B., Audet, J., Baattrup-Pedersen, A., Jensen, H. S., & Larsen, S. E. (2012). Phosphorus load to surface water from bank erosion in a Danish Lowland River basin. *Journal of Environmental Quality*, *40*, 304–314.

Laceby, J. P. (2012). *The provenance of sediment in three rural catchments in South East Queensland, Australia*. Griffith University. Retrieved from https://www120.secure.griffith.edu.au/rch/file/62989358-d23d-8782-1a86-a356cdcf312f/1/Laceby_2012_02Thesis.pdf

Landemaine, V., Gay, A., Cerdan, O., Salvador-Blanes, S., & Rodrigues, S. (2014). Morphological evolution of a rural headwater stream after channelisation. *Geomorphology*, *230*, 125–137. Retrieved from http://www.sciencedirect.com/science/article/pii/S0169555X14005650

Laubel, A., Kronvang, B., Hald, A. B., & Jensen, C. (2003). Hydromorphological and biological factors influencing sediment and phosphorus loss via bank erosion in small lowland rural streams in Denmark. *Hydrological Processes*, *17*(17), 3443. doi:10.1002/hyp.1302

Lawler, D. M. (1991). A new technique for the automatic monitoring of erosion and deposition rates. *Water Resources Research*, *27*, 2125–2128.

Lawler, D. M. (1993). The measurement of river bank erosion and lateral channel change: A review. *DOI*. doi:10.1002/esp.3290180905

Lawler, D. M., Grove, J. R., Couperthwaite, J. S., & Leeks, G. J. L. (1999). Downstream change in river bank erosion rates in the Swale–Ouse system, northern England. *Hydrological Processes*, *13*(7), 977. doi:10.1002/(SICI)1099-1085(199905)13:7<977::AID-HYP785>3.0.CO;2-5

Lawler, D. M., Thorne, C. R., & Hooke, J. M. (1997). Bank erosion and instability. In C. R. Thorne, R. D. Hey & M. D. Newson (Eds.), *Applied Fluvial Geomorphology for River Engineering and Management* (138–172). Chichester: Wiley.

Lawler, D. M., West, J. R., Couperthwaite, J. S., & Mitchell, S. B. (2001). Application of a novel automatic erosion and deposition monitoring system at a channel Bank site on the Tidal River Trent, U.K. *Estuarine, Coastal and Shelf Science*, *53*(2), 237. Retrieved from http://www.sciencedirect.com/science/article/pii/S0272771401907796

Le Gall, M., Evrard, O., Foucher, A., Laceby, J. P., Salvador-Blanes, S., Thil, F., … Ayrault, S. (2016). Quantifying sediment sources in a lowland agricultural catchment pond using 137Cs activities and radiogenic 87Sr/86Sr ratios. *Science of the Total Environment*, *566*, 968–980. doi:10.1016/j.scitotenv.2016.05.093

Le Gall, M., Evrard, O., Thil, F., Foucher, A., Salvador-Blanes, S., Cerdan, O., & Ayrault, S. (2015). Tracing sediment sources using strontium isotopes in a pond draining an agricultural catchment (Loire River basin, France). *Procedia Earth and Planetary Science*, *13*, 30–34. doi:10.1016/j.proeps.2015.07.007

Lefrançois J. (2007). Dynamiques et origines des matières en suspension sur de petits bassins versants agricoles sur schiste.Thesis, Université de Rennes 1. Retrieved from http://hal.archives-ouvertes.fr/docs/00/17/81/87/PDF/these.pdf

Lenhart, C. F., Verry, E. S., Brooks, K. N., & Magner, J. A. (2012). Adjustment of Prairie Pothole streams to land-use, drainage and climate changes and consequences for turbidity impairment. *River Research and Applications*, *28*(10), 1609–1619. doi:10.1002/rra.1549

Malavoi, J. R., & Adam, P. (2007). La restauration hydromorphologique des cours d'eau: Concepts et principes de mise en œuvre. *Ingénieries. Ingénieries*, *50*, 49–61. Retrieved from http://infodoc.agroparistech.fr/index.php?lvl=notice_display&id=135700

Malik, I., & Matyja, M. (2008). Bank erosion history of a mountain stream determined by means of anatomical changes in exposed tree roots over the last 100 years (Bílá Opava River — Czech Republic). *Geomorphology*, *98*(1–2), 126–142. doi:10.1016/j.geomorph.2007.02.030

Meneau M. (2000). Histoire de l'agriculture en Touraine des origines à nos jours (E l'Araignée, ed.).

Milan, D. J., Heritage, G. L., & Hetherington, D. (2007). Application of a 3D laser scanner in the assessment of erosion and deposition volumes and channel change in a proglacial river. *Earth Surface Processes and Landforms*, *32*(11), 1657. doi:10.1002/esp.1592

Mizugaki, S., Nakamura, F., & Araya, T. (2006). Using dendrogeomorphology and 137Cs and 210Pb radiochronology to estimate recent changes in sedimentation rates in Kushiro mire, northern Japan, resulting from land use change and river channelization. *Catena*, *68*(1), 25. Retrieved from http://www.sciencedirect.com/science/article/pii/S0341816206000907

Olley, J., Burton, J., Smolders, K., Pantus, F., & Pietsch, T. (2013). The application of fallout radionuclides to determine the dominant erosion process in water supply catchments of subtropical South-east Queensland, Australia. *Hydrological Processes*, *27*(6), 885–895. doi:10.1002/hyp.9422

O'Neal, M. A., & Pizzuto, J. E. (2011). The rates and spatial patterns of annual riverbank erosion revealed through terrestrial laser-scanner surveys of the South River, Virginia. *Earth Surface Processes and Landforms*, *36*(5), 695–701. doi:10.1002/esp.2098

O'Neill, M. P., & Kuhns, M. R. (1994). *Stream bank erosion and flushing flows. Stream notes July 1994*. Colorado: Stream System Technology Center, Fort Collins.

Owens, P. N., Walling, D. E., & Leeks, G. J. L. (2000). Tracing fluvial suspended sediment sources in the catchment of the River Tweed, Scotland, using composite fingerprints and a numerical mixing model. In I. D. L. Foster (Ed.), *Tracers in Geomorphology* (291–307). Chichester, UK: John Wiley & Sons Ltd.

Palmer, J. A., Schilling, K. E., Isenhart, T. M., Schultz, R. C., & Tomer, M. D. (2014). Streambank erosion rates and loads within a single watershed: Bridging the gap between temporal and spatial scales. *Geomorphology*, (0). Retrieved from http://www.sciencedirect.com/science/article/pii/S0169555X13006132

Peart M, Walling D. (1988). Techniques for establishing suspended sediment sources in two drainage basins in Devon, UK: a comparative assessment. In *Sediment budgets. IAHS publication* (174): 269–280. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Techniques+for+establishing+suspended+sediment+sources+in+two+drainage+basins+in+Devon,+UK:+a+comparative+assessment+M.+R.+PEART#0

Prosser, I. P., Hughes, A. O., & Rutherfurd, I. D. (2000). Bank erosion of an incised upland channel by subaerial processes: Tasmania, Australia. *Earth Surface Processes and Landforms*, *25*(10), 1085–1101. doi:10.1002/1096-9837(200009)25:10<1085::AID-ESP118>3.0.CO;2-K

Rasplus L, Macaire JJ, Alcaydé G. (1982). Carte géologique de Bléré au 1:5000, editions BRGM.

Rhoades, E. L., O'Neal, M. A., & Pizzuto, J. E. (2009). Quantifying bank erosion on the South River from 1937 to 2005, and its importance in assessing Hg contamination. *Applied Geography*, *29*(1), 125. Retrieved from http://www.sciencedirect.com/science/article/pii/S014362280800043X

Simon, A., Curini, A., Darby, S. E., & Langendoen, E. J. (1999). Streambank mechanics and the role of bank and near-bank processes in incised channels. In S. E. Darby, & A. Simon (Eds.), *Incised River channels: processes, forms, engineering and management* (pp. 123–152). London: *John Wiley & Sons Ltd*.

Ta, W., Jia, X., & Wang, H. (2013). Channel deposition induced by bank erosion in response to decreased flows in the sand-banked reach of the upstream Yellow River. *Catena*, *105*, 62–68. doi:10.1016/j.catena.2013.01.007

Thoma, D. P., Gupta, S. C., Bauer, M. E., & Kirchoff, C. E. (2005). Airborne laser scanning for riverbank erosion assessment. *Remote Sensing of Environment*, *95*, 493–501. Retrieved from http://www.sciencedirect.com/science/article/pii/S0034425705000556

Thorne, C. R. (1982). Processes and mechanisms of river bank erosion. In R. D. Hey, J. C. Bathurst, & C. R. Thorne (Eds.), *Gravel-bed rivers* (pp. 227–259). Chichester: Wiley.

Thorne, C. R. (1990). Effects of vegetation on riverbank erosion and stability. In J. B. Thornes (Ed.), *Vegetation and Erosion: Processes and Environments* (125–144). New York: John Wiley.

Trimble, S. W. (1994). Erosional effects of cattle on streambanks in Tennessee, U.S.a. *Earth Surface Processes and Landforms*, *19*(5), 451–464. doi:10.1002/esp.3290190506

Vandromme R, Foucher A, Cerdan O, Salvador-Blanes S. (submitted). Quantification of bank erosion of artificial drainage networks using LIDAR data. *Zeit. for Geomorph.*

Veihe, A., Jensen, N. H., Schiøtz, I. G., & Nielsen, S. L. (2010). Magnitude and processes of bank erosion at a small stream in Denmark. *Hydrological Processes*, *25*(10), 1597. doi:10.1002/hyp.7921

Walling, D. E., & Collins, A. L. (2005). *Sediment budgets* (pp. 123–133). Wallingford: IAHS Press.

Walling, D. E., Russell, M. A., Hodgkinson, R. A., & Zhang, Y. (2002). Establishing sediment budgets for two small lowland agricultural catchments in the UK. *Catena*, *47*(4), 323. Retrieved from http://www.sciencedirect.com/science/article/pii/S0341816201001874

Watson, A. J., & Marden, M. (2004). Live root-wood tensile strengths of some common New Zealand indigenous and plantation tree species. *New Zealand Journal of Forestry Science*, *34*(3), 344–353.

Wynn, T. M., & Mostaghimi, S. (2006). Effects of riparian vegetation on stream bank subaerial processes in southwestern Virginia, USA. *Earth Surface Processes and Landforms*, *31*(4), 399–413. doi:10.1002/esp.1252

Wynn, T. M., Henderson, M. B., & Vaughan, D. H. (2008). Changes in streambank erodibility and critical shear stress due to subaerial processes along a headwater stream, southwestern Virginia, USA. *Geomorphology*, *97*(3–4), 260. Retrieved from http://www.sciencedirect.com/science/article/pii/S0169555X07004060

Yao, Z., Ta, W., Jia, X., & Xiao, J. (2011). Bank erosion and accretion along the Ningxia-Inner Mongolia reaches of the Yellow River from 1958 to 2008. *Geomorphology*, *127*(1–2), 99–106. doi:10.1016/j.geomorph.2010.12.010

Yumoto, M., Ogata, T., Matsuoka, N., & Matsumoto, E. (2006). Riverbank freeze-thaw erosion along a small mountain stream Nikko Volcania area, Central Japan. *Permafrost and Periglacial Processes*, *17*(4), 325–339. doi:10.1002/ppp.569

Zaimes, G. N., & Schultz, R. C. (2015). Riparian land-use impacts on bank erosion and deposition of an incised stream in north-central Iowa, USA. *Catena*, *125*, 61–73. doi:10.1016/j.catena.2014.09.013

Zaimes, G. N., Schultz, R. C., & Isenhart, T. M. (2006). Riparian land uses and precipitation influences on stream bank erosion in central Iowa1. *JAWRA Journal of the American Water Resources Association*, *42*(1), 83. doi:10.1111/j.1752-1688.2006.tb03825.x

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