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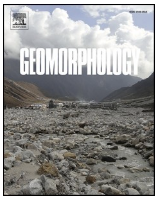

Contribution of the Loire River to knowledge about hungry Rivers – Three centuries of a lowland river trajectory

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ABSTRACT

Like many rivers, the Loire River (France) has been deeply altered by bed narrowing and incision, to the extent that it can now be considered a "hungry river." However, understanding its evolution over several centuries is complicated by the complexity of the control factors and the interactions between the various components of the fluvial system. There is also a lack of precise data with which to accurately assess the volumes of erosion and sedimentation.

This study aims to analyze the long-term (1755–2023) trajectory of a 72 km section of the Loire River in Burgundy to better understand the respective roles of potential drivers of river degradation, such as embankments, hydrological changes, and sediment mining. Recent developments in high-resolution elevation modelling provide an innovative solution that we have adapted to the Loire River in Burgundy — a stretch that was almost pristine in the 18th century.

Our results reveal that the riverbed evolved rapidly due to small dykes (groynes) being built during a period of high hydrology at the end of the 18th century. This induced a rapid readjustment of the riverbed. This initial phase was apparently not accompanied by significant sedimentation, except in artificially abandoned side meanders, emphasizing their role in river equilibrium.

The 19th-century embankment with longitudinal levees resulted in increased sediment trapping on the lateral margins of the newly embanked channel. However, the volume of erosion changed little between 1755 and 1953, but increased sharply during the third period (1953–2023). Calculations of the volume of sediment artificially extracted from the riverbed show that this accounts for at least 50–60% of the volume eroded from the channel.

Quantification suggests that, in the absence of sand and gravel mining, lateral erosion would have compensated for the sediment deficit during the second half of the 20th century. Consequently, the Loire River in Burgundy may have approached a new dynamic equilibrium within a century of the construction of the embankment. This study highlights the strongly negative impact of excessive mining of sand and gravel conducted over 20 years. The assessment of the sediment budget and the process-based understanding of the river's trajectory also provide solutions for river managers, promoting lateral sediment supply through bank erosion in this river with limited sediment supply.

1. Introduction

Artificial dyke systems were built to meet a wide range of societal needs, leading to a global artificialization of fluvial corridors (Grill et al., 2019). Rarely intentionally destroyed, dykes have been modified over centuries in line with socio-economic issues: agriculture and milling,

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improved navigation conditions, urbanization, and protection of populations against flooding (Cosgrove and Petts, 1990; Buijse et al., 2002; Lewin, 2013; Knox et al., 2022). Thus, the rivers of the Anthropocene are true palimpsests (Brenna et al., 2021; Downs and Piégay, 2019; Knox et al., 2022; Słowik et al., 2018). Based on a literature compilation, Gibling (2018) identified six main stages of relationships that societies have forged with rivers over time. The development of irrigation led to the multiplication of hydraulic infrastructure very early in the Near East, Egypt, China, and the Indian subcontinent. On most Asian rivers, dyking was carried out over centuries (Chen et al., 2015, 2019). However, it was not until the late 18th century or early 19th century (the “technological era” according to Gibling, 2018) that large-scale training works (dykes, dams) began to multiply. In the 19th and 20th centuries, navigation, industrialization, and urbanization (the three being closely related) were strong driving factors for river embankment. In Europe and North America, the engineering works to improve navigation on rivers were carried out over a few decades in the 19th and 20th centuries, even if discontinuous infrastructures already existed before systemic embankment (Arnaud-Fassetta, 2003; Hohensinner et al., 2022; Hudson et al., 2008; Pisut, 2002). In France, artificial levees and quays have been present since the Middle Ages in the lower and middle valleys of the Loire River (Dion, 1961; Burnouf and Carcaud, 1999). The riverbeds also represent a growing sediment resource today; sediment mining deals the final blow to already severely disrupted systems over the last decades, as massive in-channel mining has led to the depletion of sediment resources, worsening the impacts of dykes on sediment connectivity (Brenna et al., 2024; Brunier et al., 2014; Grivel et al., 2019; Kondolf, 1997).

Due to anthropogenic constraints that limit the river's replenishment in sediment through lateral erosion and that have partially deprived the river of its bed material stock, the Loire River can be considered a hungry river. Barneveld et al. (2025) note that although the concept of “hungry water” was initially used by Kondolf (1997) to highlight interruptions in sediment continuity, it currently includes all situations where the transport capacity exceeds the sediment load due to anthropogenic factors (embankment, weirs and dams, sediment mining, etc). For this reason, it can also apply to engineered rivers—a category that includes the Loire River. 500 km of the Loire River are embanked and it has been entrenching for several decades, leading, among other things, to the collapse of the Wilson Bridge in Tours. Bed erosion continues more than thirty years after sediment mining stopped (Gasowski, 1994; Gautier et al., 2007b) and river managers are thus seeking sustainable solutions to address the sediment deficit of the Loire River.

The multiplicity of anthropogenic impacts leads to geomorphic responses that are sometimes unintended (Brenna et al., 2024; Gregory, 2006), spanning different temporal and spatial scales. The effects of dykes are superimposed on impacts due to changes in land use at the basin scale, which are responsible for the aggradation of floodplains since the Neolithic (Brown et al., 2018; Gibling, 2018). Interactions and feedbacks between factors and fluvial responses are numerous and difficult to analyze and interpret. Characterizing and predicting the nonlinear interactions and feedbacks between factors and fluvial responses remain major challenges for the analysis of floodplains, even if hydrological, geomorphological, sedimentary, and biogeochemical consequences have been extensively studied (Brookes, 1991; Gregory, 2006; Knox et al., 2022). Although the morphological consequences of embankment vary from one river to another, depending on its intrinsic geomorphic parameters (Surian and Rinaldi, 2003) and the characteristics of the embankment, the geomorphologic community agrees on its negative impacts: simplification of fluvial forms in the embanked channel, reduction in lateral mobility, marked incision of the alluvial floor, hydrologic and sedimentary disconnection between the main channel and floodplain leading to the terrestrialization of numerous artificially abandoned side channels, etc. (Arnaud-Fassetta, 2003; Dépret et al., 2017; Hohensinner et al., 2004; Provansal et al., 2014; Seignemartin et al., 2023). Even if degradation of the fluvial bed is a common river response to channelization, several case studies have also documented accelerated deposition in the channelized channel, for example, the Yellow River (Chen et al., 2015), the Gumara River (Abate et al., 2015), the Tisza River before damming (Kiss et al., 2025) and the Severn River (Lewin, 2013). In any case, the construction of dykes has led to widespread alteration of hydrosystem landscapes since it resulted in drastic and irreversible changes in floodplain ecosystems and ecological succession: reduction in lakes, wetlands, and alluvial forests, soil artificialization, etc. (Amoros et al., 1987; Bravard et al., 1997; Chardon et al., 2022; Deiller et al., 2001; Dufour et al., 2007).

Finally, the pluri-centennial dyke edification interacts with changing hydro-climatic conditions, implying successive morphological responses. In Western Europe and North America, most of the longitudinal dykes were built during a period of high hydrological activity (18th–19th centuries), which corresponds to the last phase of the Little Ice Age (Blöschl et al., 2020; Lewin, 2013; Mesmin et al., 2024; Pisut, 2002). In addition, hydraulic infrastructure disrupts the temporal and spatial distribution of floods, increasing flood peaks and accelerating downstream conveyance (Hudson et al., 2008; Kiss et al., 2011; Middelkoop and Asselman, 1998; Pinter et al., 2006, 2010). The effect of past floods on morphological and sedimentary responses deserves to be analyzed in more detail. However, it faces a number of pitfalls: the absence of documents prior to channelization that are sufficiently reliable to reconstruct the evolution of fluvial forms in detail, and the lack of long hydrological series.

In the case of the Loire River in Burgundy, accurate and reliable ancient maps and archival documents from the 18th and 19th centuries provide the rare opportunity to precisely reconstruct the co-evolution of fluvial landforms and engineering works: the 1755 maps offer insight into a quasi-pristine reach of the Loire Valley in Burgundy. Maps and archives from the 18th and 19th centuries precisely document the joint progression of hydraulic infrastructures and fluvial planform changes. Furthermore, the analysis of recent HD LiDAR data helps overcome the difficulty of accurately assessing the vertical evolution of the alluvial floor (Kiss et al., 2018; Rusnák et al., 2024).

The main objective of the study of the Loire River in Burgundy is to analyze the multi-centennial trajectory of a European river in detail, focusing on three consecutive periods (1755–1848, 1848–1953, and 1953–2023). We aim to precisely document the successive planform readjustments of the 72 km reach and estimate the volumes of erosion and sedimentation in a 50 km section, where HD LiDAR data is available. The three centuries also provide insight into the potential impact of hydrological changes and anthropogenic disturbances, that the river has experienced during this time. Finally, for the most recent period, the study aims to precisely evaluate the additional impact of sediment mining on the morphological changes that affected the riverbed, a topic that is still being debated in the Loire River Valley.

To achieve this, on the one hand, we monitored planform, vertical, volumetric and sedimentary changes based on a combination of ancient maps, aerial photographs, LiDAR DTMs, geophysical surveys and sediment cores. We then calculated the volume of erosion and sedimentation to estimate the sediment balance over the three time spans. On the other hand, in order to determine the potential control factors, we reconstructed the trajectory of the embankment system, changes in hydrology and mining activity, based on cartographic and written archives, as well as hydrometrical data.

2. Study reach

2.1. The Loire River basin

The study reach is 72 km long, following the Loire River in Burgundy from the Gannay bridge to the Fourchambault bridge, just downstream of the Allier River junction (Fig. 1). This section of the Loire Valley was chosen for two main reasons: firstly, it was channelized later than the middle and lower Loire River, and secondly, accurate maps are available

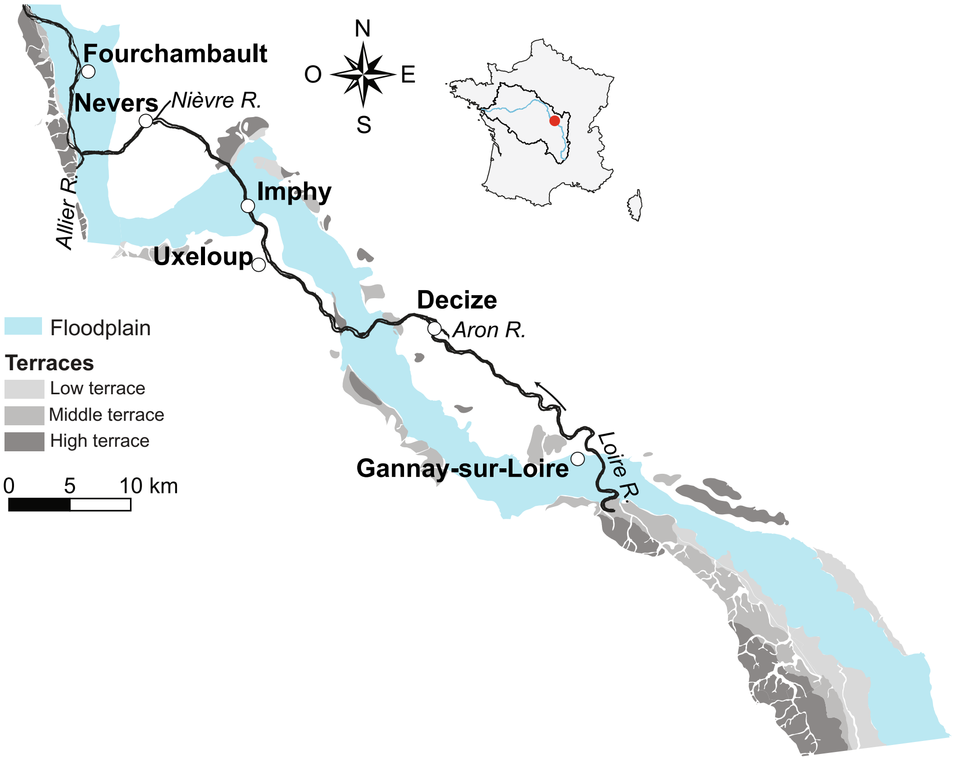

Fig. 1. Study area – The Loire River in Burgundy.

from the mid-17th century, prior to the main channelization phase. At its outlet into the Atlantic Ocean, the 1012 km-long Loire River drains 112,120 km^2 in France. The upper basin of the Loire River and the Allier River (the main tributary of the Loire River) drains the granitic French Massif Central. According to Babonaux (1970) and Brossé (1982), the upper mountainous basin determines an initial limited alluvial stock that varies very little downstream.

The Loire River leaves the Massif Central via Oligocene grabens ("Limagne"), which form to the upstream part of the study valley, from Gannay to Decize. In the "Petite Limagne", the Loire River flows in a wide plain (3.5–4 km) that narrows at Decize, where the river is constrained by Triassic terrain (sandstone, limestone, and clay) (Fig. 1; Suppl. Data S1). Further downstream, the Loire River enters the Parisian Basin and flows through Jurassic limestone and marl, migrating into a floodplain 2–3 km wide. Today, the Loire River develops a slightly sinuous main channel, accompanied by one or two secondary channels. In the study reach, the fluvial bed shows large bars and sandy islands colonized by a variety of softwood and hardwood forest. The mean active bed width (including main and secondary channels and barren bars) is currently about 130 m, with strong variations due to discontinuous embankments; the lateral mobility of the river in the floodplain is limited by numerous dykes and artificial "levees" (longitudinal dykes built of sand, some of which are paved at the top and even on the sides; Dion, 1961). The main function of the artificial levees was to improve navigation, as the Loire River is one of the longest waterways in France. The river has served as a major navigation route since Antiquity and the Gallo-Roman periods (Dion, 1961; Dumont, 2011). The Loire River can be navigated almost entirely downstream, and dominant westerly winds allow upstream navigation (southward). In Burgundy, the major ports are located on the east bank (right bank), and the main challenge was to prevent the river from migrating to the left bank, where it could flow freely on the floodplain. Dykes were built as early as the Middle Ages in the lower and middle valleys (Dion, 1961; Garcin et al., 2006). Upstream, in Burgundy, the engineering works were developed later. However, the riverbanks in Nevers and Decize were equipped as early as the Middle Ages (Foucher, 2024; Mesmin, 2025).

Nevers, the regional main city, and a smaller city, Decize, located upstream at the junction of the Loire River with the Aron River, were the main harbors of the region (Fig. 1). Imphy grew later thanks to steelworks. Around ten secondary ports were distributed between the three towns.

2.2. Water discharge and sediment load

The fluvial regime of the Loire River (Gilly and Nevers gauging stations, Fig. 2) is of the pluvio-evaporative type, and the hydrology of the Loire River is characterized by an excessive regime, i.e., long droughts during the summer alternate with high water levels during the winter. The mean annual discharge is 130 m^3.s^{-1} at the Gilly gauging station (23 km upstream of the study reach; draining an area of 13,007 km^2) and 174 m^3.s^{-1} at the Nevers gauging station (17,570 km^2) (Fig. 2). The Loire River in Burgundy receives few tributaries: mainly the Aron River at Decize (17.5 m^3.s^{-1}), which drains the humid Morvan Mountains, and

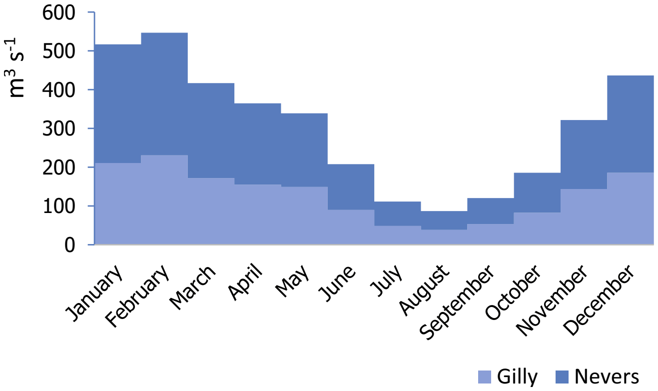

Fig. 2. Hydrology of the Loire River in Burgundy. Mean monthly water discharge of the Loire River at Gilly-sur-Loire (13,007 km^2; 1969–2024) and Nevers (17,570 km^2; 1955–2024) gauging stations.

the Nièvre River (5.28 $m^3.s^{-1}$) at Nevers, plus several smaller ungauged tributaries. The difference in water discharge between Gilly and Nevers is more pronounced in winter due to the significant contribution of the Morvan tributaries. The downstream reach (6 km) is located downstream of the Allier River junction, which is the main tributary of the Loire River. For this reason, the riverbed is much wider, as the Allier River represents a mean water supply of 137 $m^3.s^{-1}$.

Today, we estimate the bank-full discharge to be about 620 $m^3.s^{-1}$ in the upper reach and 660 $m^3.s^{-1}$ near Nevers (which corresponds to the annual flood). The biannual flood is about 1000 $m^3.s^{-1}$ at the Nevers gauging station. The Loire River floods can be intense, particularly when they are formed by the conjunction of heavy rainfall on the Parisian Basin due to Atlantic lows, combined with a Mediterranean storm in the upper basin (Dacharry, 1974; Ramond, 2015). There has been no major flood since the beginning of the 20th century. Furthermore, the seasonal variability in the Loire River floods has decreased since the first half of the 20th century (Mesmin et al., 2024). Summer floods became very rare and flood events mainly occurred between December and March.

The average longitudinal gradient of the river (from Gannay to Fourchambault) is 0.472 m per km. This gives the Loire River in the study area a specific stream power ranging between 20 W/m^2 at bank-full discharge to over 110 W/m^2 during major floods (with a return period greater than 50 years). The bed load was very recently precisely gauged using passive acoustic monitoring, which revealed a mean annual load of 32,000–41,000 tons for the Loire River upstream of Nevers and 78,000–99,000 tons for the Allier River (Le Guern et al., 2026). The suspended load is very low, the Loire River delivers 860,000 tons of suspended sediment to the Atlantic Ocean annually (Delmas et al., 2012). Brossé (1982) attributes the low proportion of silt and clays to the characteristics of the thin alteration mantle of the Massif Central rocks, which delivers only a small quantity of fine material to the river. The predominance of sand in the sediment load can be attributed to the geology of the upper basin (see Supplementary Data, S1). Much of the sand originates from the erosion of granitic rocks (granites and granulite), metamorphic rocks (gneiss and micaschist), as well as rhyolite in the upper crystalline basin of the Massif Central (Babonaux, 1970), and to a lesser extent from that of the Morvan (Brossé, 1982).

3. Data and methods

3.1. Historical evolution: Planform and vertical and volumetric changes

The quality and reliability of ancient maps of the Loire River have enabled us to study the historical trajectory of fluvial forms since the mid-18th century. Changes in planforms are analyzed across the entire study area (covering 72 km of river, from the Gannay Bridge to the Fourchambault Bridge).

3.1.1. Analysis of fluvial planform evolution

The analysis of long-term evolution precisely informs us about planform changes in the Loire River and the progression of fluvial engineering works in the riverbed. On every map, aerial photograph and satellite image, we digitized the riverbed by distinguishing the active units, including the main channel, secondary channels and bars, without vegetation or with very little riparian vegetation, following standard methods (Gautier et al., 2007a, 2007b; Hobo et al., 2014; Hohensinner et al., 2004). We calculated areas and their changes between two dates: i) areas that have remained active (the main and secondary channels with barren bars), ii) parts of the bed that have become vegetated between two dates, referred to as "abandoned," and iii) newly eroded areas in the floodplain. All data are orthorectified and integrated into GIS software (ArcGIS Pro 3.4). To assess the longitudinal variability, we divided the 72-km-long reach into 2 km units.

3.1.1.1. 1755 map. Because of the strategic importance of navigation on the Loire River for the Kingdom of France, a number of ancient maps are available. From the end of the 17th century onward, some of them became relatively reliable sources for documenting fluvial landforms and engineering works. However, although other documents exist (1692, 1727–1730, 1775), only the 1755 maps are sufficiently accurate and not too distorted to be georeferenced (Table 1; Suppl. Data S2). These maps cover the entire study area. The King's engineers surveyed the map using triangulation with a fair degree of accuracy thanks to the new "repeating circle" invented in the 1740s. Royal engineers of the "Service des Turcies et Levées" ("turcie" being an old word for dyke) were likely the commissioners. The 1755 map is probably one of the most accurate documents in France for the 18th century.

3.1.1.2. 1848 map ("Coumes"). The "Coumes Map" was surveyed under the direction of the chief engineer of the navigation service, Jules Coumes. The aim was to map the riverbed and the floodplain over the entire course of the Loire River as accurately as possible following the 1846 major flood, to document inundated areas and breaches in levees. The accuracy of this cartographic corpus has made it a key document in understanding the historical changes of the riverbed (Gautier et al., 2000; Gautier et al., 2007b; Grivel et al., 2019). The maps have already been georeferenced and are open-source on the Regional Environment Survey "Centre Val de Loire" (Table 1).

On the two maps (1755 & 1848), main and secondary channels,

Table 1

Main planimetric and topographic sources of the study (RMSE = Root mean square error, calculated as the square root of the sum of the squares of the errors of the control points used for georeferencing).

Source	Date	Scale	RMSE / Accuracy
"Maps of the course of the River Allier from Vichy to the Loire. Maps of the course of the Loire River from St. Aignan to Pont de Cé" - Unknown author (Bibliothèque Nationale de France, GEFF-17578). (85 plates) On line: https://gallica.bnf.fr/ark:/12148/btv1b52500127p/f1)	1755	1/35,000 (approx.)	16 m
Coumes Map (70 plates) DREAL Centre-Val de Loire On line: https://www.centre-val-de-loire.developpement-durable.gouv.fr/les-cartes-de-1850-georeferencees-a2075.html	1848	1/20,000	6.5 m
Aerial photographs (Institut Géographique National, France), BD ORTHO® Historique https://www.geoportail.gouv.fr	1953	1/20,000	4 m
Satellite image Google Earth ® CNRS Airbus	2023		
HD Lidar IGN https://geoservices.ign.fr/lidarhd	2024		Planimetric accuracy: 25 cm Altimetric accuracy: 5 cm
Longitudinal profile "Grandes forces hydrauliques » https://fiches-geodesie.ign.fr/fiches/index.php?module=e&action=e_profils&context=accueil	1933		Planimetric accuracy: 20 m Altimetric accuracy: 20 cm
Topographic survey Bonnie-Lasalle From Villerest to Bec d'Allier https://www.centre-val-de-loire.developpement-durable.gouv.fr/releves-topographiques-sur-la-loire-et-ses-a1696.html	1996		ND
Bathymetric survey Loire River in Burgundy and Allier River https://www.centre-val-de-loire.developpement-durable.gouv.fr/releves-topographiques-sur-la-loire-et-ses-a3058.html	2010	1/25,000	ND

barren bars, banks, vegetated islands and eroded riverbanks are precisely shown, as well as a wide range of structures: dykes (levees), groynes, and bank protections. Hamlets, cities and ports, roads, plots and forests are also accurately represented. In rural areas, buildings and roads have changed very little in the study area, which means we have a large number of points for georeferencing.

3.1.1.3. Recent aerial photographs and satellite images (20th–21st century). Two dates are analyzed to document the recent planform evolution in the study reach: 1953, using aerial photographs, and 2023, using a satellite image provided by Google Earth (Table 1; Suppl. Data S3). The aerial photographs from 1953 were acquired from the National Geographic Institute (IGN, BD ORTHO® Historique, Table 1). The photographs have already been georeferenced by IGN.

3.1.2. Characterization of vertical evolution

To estimate the river's vertical evolution, two complementary approaches were employed. The first one, based on the analysis of LiDAR data, provides information on changes in the relative elevation of the active channels successively occupied by the river since 1755. The second approach is based on topographical surveys of the riverbed dating back to 1933.

3.1.2.1. Construction of DTM, deFHM and age map (1755–2023). High-definition LiDAR data are available from Decize to the Fourchambault Bridge, i.e. along a 50 km reach. Along this reach, ancient maps, aerial photographs and satellite images are combined with topometric data extracted from HD LiDAR for three time-spans (1755–1848, 1848–1953, and 1953–2023). The construction of DEMs has advanced considerably over the last decade. Based on precise topographic and bathymetric surveys, this method has recently become widespread thanks to the use of multibeam echosounders, and above all to LiDAR surveys, which enable the area to be extended and save a great deal of time (Rusnák et al., 2024; Barneveld et al., 2025). In France, the National Geographic Institute (IGN) has produced a HD LiDAR survey of France and made it available in 2024 as an open data project (Table 1). The surveys were made by airplane using topographic LiDAR, with a wavelength in the infrared (1000–1100 nm). According to the IGN, the density of points is at least 10 pulses per m^2, reaching more than 70 in the case of dense vegetation (IGN, 2023).

To conduct a precise analysis of the three-dimensional evolution of the riverbed since the 18th century, we firstly created a DTM from HD LiDAR data. Then, we associated the active bed limit for each date with the precise topographic data of the DTM derived from HD LiDAR. For this, we adapted the method described by Greco et al. (2007), Williams et al. (2014), Provansal et al. (2014), and Rusnák et al. (2024).

We extracted the limit of the “genetic floodplain” (Nanson and Croke, 1992), crossing topographic data provided by the DTM with geological maps (provided by the French Geological Survey – BRGM) that indicate alluvial terraces (Fig. 1). We also verified the extension of the floodplain with the limit of the 1846 large flood reported on the 1848 map. Thus, we clearly determined the limits between the genetic floodplain and the terraces.

Secondly, by digitizing the centerline of the 2023 riverbed and interpolating the river elevation extracted from the LiDAR DTM along the centerline, we produced a Detrended Floodplain Height Model (deFHM) by subtracting the interpolated riverbed from the first DTM, effectively removing the influence of the present topography and providing the height of the floodplain relative to the current low water level. The 2023 riverbed elevation thus represents the “reference level”. For each 2 km unit, we calculated the median relative height computed from the height of each cell of the deFHM. Terrace relative elevation is also based on HD LiDAR data.

Thirdly, we created an age map of the genetic floodplain. For that, we performed a spatial union of the active beds for each of the four dates (1755, 1848, 1953, and 2023). Where a more recent active bed overlaps an older active bed, it replaces it. This gives us a map of the age of the floodplain surface. We then combined the deFHM with the age map of the successive active beds: this gives us the relative height of the parts of the floodplain corresponding to the riverbed in 1755, 1848, and 1953. In every 2 km section, the median elevation of the successive beds is determined. Therefore, incision or accumulation corresponds to the height difference between the median elevation of an ancient bed (one period) and the elevation of the following period.

3.1.2.2. Topographic surveys of the Loire River bed (1933–2010). To assess the analysis of the fluvial bed's vertical change and to precisely evaluate the potential impact of sediment mining, we compared various topographical surveys from the last hundred years. First, we used the longitudinal profile of the river surveyed in 1933 (October) by the “Service du Nivellement Général de la France,” commissioned by the “Service des Grandes Forces Hydrauliques” (Ministry of Agriculture) (Table 1). The elevation of the water surface was measured at low flow with a mean precision of about 10 cm (Liébault et al., 2013). We made a number of corrections: i) as the French altitudinal system changed in 1969, the 1933 datum was corrected using the conversion grids provided by IGN (Lallement to NGF69); ii) due to the mobility of the channel, some points may be offset: they were repositioned by calculating the distance from bridges, hydrometric scales (mentioned on the document), flood marks on bridges or dykes (still present), tributary junctions, and municipal boundaries. Thanks to numerous points marked on the 1933 profile and still marked on the field, the correction is acceptable (about 20–25 m in planimetry).

We compared the 1933 longitudinal profile with recent cross-wise riverbed profiles (topographic and bathymetric surveys) that were surveyed from Gannay to Imphy in 1996 and 2010 (provided by the Loire River Basin Environment Service; Table 1). Downstream of Decize, only the 1996 profile is available. By comparing points located in the same area in 1996 and 2010, we calculated an average difference of around 0.2 m except at two points. To pinpoint certain points on the 1933 and recent profiles, fixed elements were surveyed using RTK GPS (bridges, hydrometric scales, etc.). Finally, we obtained 42 comparable points distributed along the reach for the three dates. When comparing the longitudinal profiles, one must keep in mind that the 1933 profile represented the water level, whereas recent profiles represent the riverbed. Knowing the 1933 longitudinal profile was surveyed at low-water level, we applied a mean correction by subtracting an average height of 1 m.

Data derived from LiDAR processing and topographic profiles do not provide the same information. Age maps and their median elevation per 2 km-unit provide information on the general vertical variation of the successive active beds, whilst topographic profiles document the evolution of the talweg.

3.1.3. Sediment balance quantification

By combining the area data with the vertical evolution of the Loire River bed extracted from the HD LiDar (median elevation) of the successive active beds, it was possible to estimate the volume of sediment deposited and eroded between two dates. Three volumes are calculated: i) lateral sedimentation was calculated by multiplying the vertical difference between two dates by the abandoned area; ii) lateral erosion was calculated by multiplying the difference between the floodplain mean elevation and the riverbed; iii) bed erosion was calculated by multiplying the vertical difference between two successive active strips. Thus, it was possible to estimate volumes trapped in the lateral margins and the minimal volume of sediment exported from the Loire River bed (since we ignore the sediment input from upstream). For an enhanced assessment of the variation in area and sediment volume, these operations are carried out on 2 km sections, enabling us to calculate a number of statistics on the river.

3.1.4. *Limit and uncertainty*

The comparison of models could be distorted by potential recent overbank deposits. To ensure that the topography of the abandoned parts of the riverbed has not been modified by thick deposits, we conducted numerous core drillings in the floodplain, in the abandoned parts that we had previously dated using the maps. The core drillings revealed very thin overbank deposits (a maximal thickness of about 10 cm). This can be explained by the very poor suspended load of the Loire River (Gautier et al., 2007b; Mesmin, 2025).

In order to determine whether the evolution is or is not statistically significant, we conducted different tests. First, with a Shapiro–Wilk test we have checked that the planform and topographical data are indeed non-normally distributed. Second the statistical significance of the temporal evolution of active landforms and of vertical evolution in the study years was analyzed by a pairwise Wilcox test (p-value$<$0.0001).

Finally, for evaluating the uncertainty of sedimented and eroded volumes, we proceeded as follows:

Eq. 1: Planimetric uncertainty

$$\sigma_{xy} = P_{T1-T0} \times \sqrt{(RMSE_{T1}2 + RMSE_{T0}2)}$$

Eq. 2: Volume uncertainty

$$\sigma_{Volume} = \sqrt{SDz_{T1-T0} \times area)2 + (\sigma_{xy} \times \partial alt)2}$$

With:

- *RMSE*: Planimetric error associated with maps and aerial photographs (see Table 1);
- P_{T1-T0}: Perimeter of eroded or sedimented area between $T0$ and $T1$, the start and end dates of a period, respectively
- *SDz*: Standard Deviation of elevation between $T0$ and $T1$
- *area*: Area of sedimented or eroded zone
- ∂alt: vertical evolution between $T0$ and $T1$

3.2. *Analysis of potential control factors*

3.2.1. *Cartography of fluvial engineering works and bank protections*

To establish the chronology, location, and type of each structure, we associated different sources and methods. First, the aforementioned ancient maps are reliable documents for the main infrastructures (mainly dykes and bridges). Additional ancient maps were also analyzed (see Suppl. Data S3). The "Grenier plans," designed between 1851 and 1852 in the study area, were produced by the navigation service to map all infrastructures relating to river navigation (Temam and Grivel, 2009). Numerous other documents were consulted at the Nièvre Departmental Archives and the National Archives. In particular, they enabled us to specify the dates of construction (or reconstruction following destruction during a flood) and the location of the structures.

We were also able to use a survey of bank protection structures carried out in the downstream part of our study area by a regional association for environmental management ("Conservatoire d'Espaces Naturels de la Région Bourgogne"). Finally, field surveys on foot and by canoe enabled us to verify and complement the database on the structures. Consequently, we identified and digitized all engineering infrastructures, such as groynes, longitudinal dykes (so-called levees), and facilities associated with ports. All data are integrated into the GIS, in a table indicating the construction date and the length of each infrastructure.

3.2.2. *Uxeloup site – impact of embankment on sedimentary features*

Finally, to better understand the effect of dykes on the sedimentary characteristics (texture and stratigraphy) of the floodplain, we focused our attention on the "Uxeloup site". The Uxeloup site, a 12 km-long reach, was chosen because we found numerous documentary archives concerning the site, allowing us to precisely reconstruct the history of hydraulic infrastructure (mainly groynes and a 7 km-long dyke). As Uxeloup is a rural site, we were able to conduct precise topographic surveys (using RTK GPS) along cross-sections in the floodplain across the ancient active beds. Along the cross-sections, we also determined the main stratigraphic units by conducting Electric Resistivity Tomography surveys and core drillings were carried out to sample the stratigraphic units. As every stratigraphic unit was sampled, grain-size was measured in the lab with a laser granulometer. Finally, to precisely determine the texture of overbank deposits, we sampled various zones after the floods that occurred during the 2023–2024 winter.

3.2.3. *Historical floods and current water discharge*

To establish a precise chronology of floods for the study period, three approaches were adopted. Firstly, for floods prior to 1846, Mesmin et al. (2024) carried out research in four archival collections: the National Archives, the archives of the "*Département de la Nièvre*", and the municipal archives of Nevers and Decize. For this period, there is no precise discharge data. In order to overcome this bias, Mesmin et al. (2024) identified periods of high and low hydrological activity using indexes that are based on the intensity of flood events, not only their number.

Secondly, for the following period (1846–1954), we analyzed hydrological data reconstructed by the Loire River basin hydrological service (SHC, 1975). Water level data are available thanks to the systematic installation of hydrometric scales along the river. The first scales were installed in 1820–1830 and became widespread by 1850 with a daily survey. In addition, flood water heights are marked on a large number of buildings and bridges and reported in documents such as the 1933 longitudinal profile. On the basis of daily water level, maximal water stage on buildings and rating curves, the Loire basin hydrological service (SHC) constructed a hydraulic model and calculated maximal water discharge for floods from 1846 to 1954 (SHC, 1975). Dacharry (1974) also recalculated certain flow rates as part of an in-depth hydrological analysis of the Loire River basin. More recently, Ramond (2015) reanalysed water discharge for several gauging stations along the Loire River.

Thirdly, for recent decades (i.e. after 1954), we worked on daily water discharge (https://hydro.eaufrance.fr).

3.2.4. *Estimates of sand and gravel mining volumes*

To precisely estimate the impact of extractions on the sediment deficit, it is important to determine the volume industrially extracted from the riverbed. After the Second World War, sand and gravel from the Loire River were extensively quarried to help rebuild numerous French cities. To evaluate the volumes extracted from the riverbed, we relied on official reports from government engineers (Dambre and Malaval, 1993; Dambre, 1995). However, the reported quantities are very likely to be underestimated, as it is well known that a certain proportion of mining was not declared to the authorities. According to the engineers currently responsible for river management, production was probably 50% higher. We therefore propose a minimum estimate based on reports from the 1990s (primarily Dambre, 1995), to which we have added an extra 50% to arrive at an upper range. Additionally, we examined a series of aerial photographs from the 1950s to the 1990s to identify mining zones and determine their precise locations.

4. Results

4.1. *River planform trajectory since the 18th century*

From Gannay to Fourchambault, active planforms (channels and unvegetated bars) occupied 32 km^2 in 1755, which accounts for more than 20% of the floodplain area. Today, the active units represent less than 12 km^2, i.e., 7.54% of the floodplain surface (Fig. 3A, B). The median active area per 2 km-reach was 0.762 km^2 in 1755, 0.660 km^2 in 1848, 0.440 km^2 in 1953, and 0.298 km^2 today (Fig. 3A, B).

In 1755, in several reaches, the Loire River occupied very wide areas,

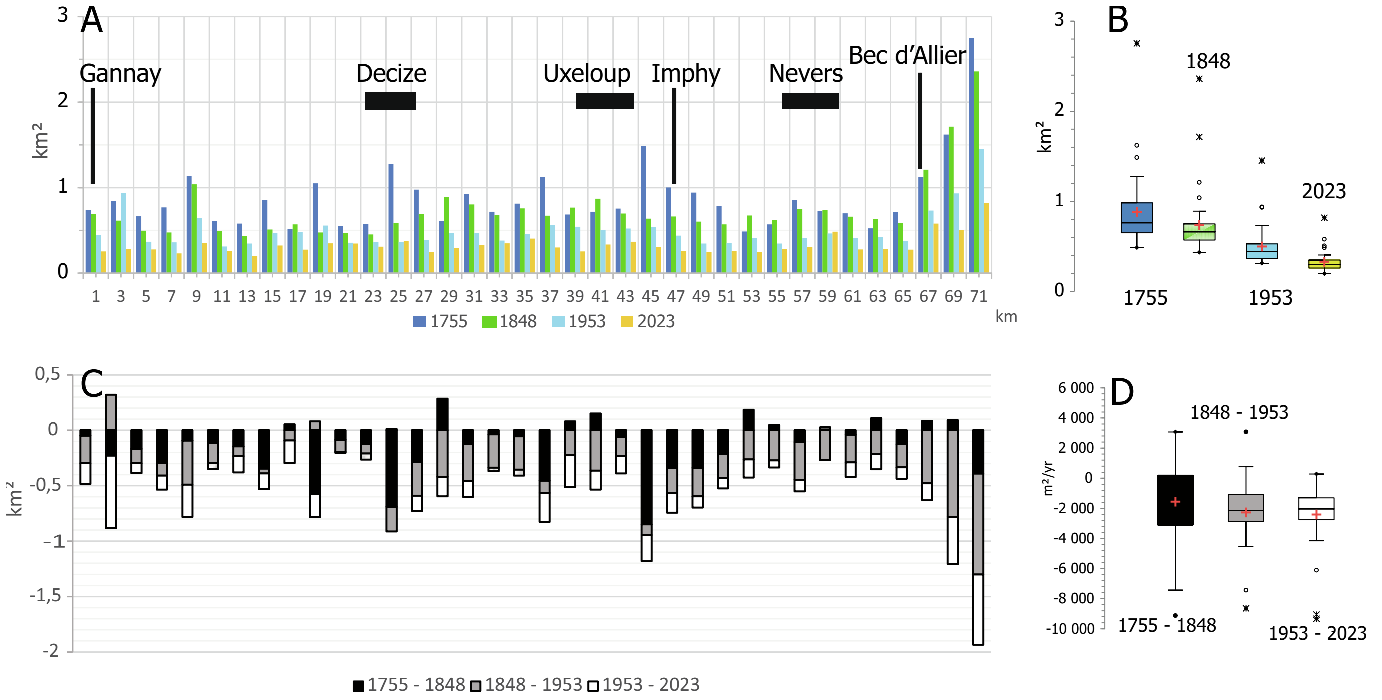

Fig. 3. Historical change of active forms of the Loire River between Gannay and Fourchambault (1755–2023). A. Area of active bed for the four dates (per 2 km-unit); B. Box-plots: active bed area (1755, 1848, 1953 and 2023); C. Evolution of the active bed area per 2 km-unit; D. Box-plots: annual evolution of the active bed area. The boxplot whiskers represent the 10th and 90th percentiles, the boxes mark the interquartile range (25th to 75th percentiles), and the mean value is indicated by a cross. Points are maximal and minimal values.

exceeding 1 km^2 (Fig. 3A): km 8–10, km 24–26 near Decize, km 44–48 near Imphy, and, of course, downstream of the Allier River junction (2.7 km^2). The Loire River therefore had a wide, fairly sinuous bed, with a pattern similar to wandering, including numerous islands, according to the 1755 maps (Suppl. Data S4, S5). It can also be noted that some reaches were much narrower, especially in the vicinity of Nevers, where the smallest active areas are measured.

4.1.1. 1755–1848

Between 1755 and 1848, an initial phase of reduction in the active bend is recorded, averaging 16%, which represents a total decrease of 5.2 km^2 (±1.7 km^2). Half of the 2 km-units lost annually at least 1200 m^2 (±360 m^2), and several 2 km-reaches had already abandoned more than 3000 m^2 (±900 m^2) per year (Fig. 3C, D). The reaches located upstream and downstream of Decize (km 18–20; 25–26) and upstream of Imphy (km 44–46) had already lost more than half of the 1755 active area.

4.1.2. 1848–1953

From 1848 to 1953, the Loire River shows a continuous decrease in its active landforms, abandoning numerous secondary channels and lateral bars that were colonized by vegetation. Therefore, during this period, the Loire River “lost” 8.6 km^2 (±1.892 km^2) of its active bed. The trend varies from upstream to downstream. The zone (km 0–22) upstream of Decize saw its active bed decrease by 15%, while the middle section (km 22–48) and downstream zone (km 48–72) decreased by 35% and 40%, respectively.

4.1.3. 1953–2023

During the last period (1953–2023), the river abandoned about 6 km^2 in 70 years (2036 m^2 per year). The active forms in 2023 accounted for 40% of the 1953 active bed upstream of Decize and 31% downstream. Width and river sinuosity diminished over the course of the 19th century, and by the following century, downstream of Decize, all that remained was a rectilinear pattern, locally occupied by a secondary channel (Suppl. data S4). In the upper reach, a cutoff of the sole meander occurred. Furthermore, the graphs for 1755 and 1848 show a dispersion of the area value per 2 km-unit (between 0.5 and 1.5 km^2), whereas those for the 20th and 21st centuries are much tighter, reflecting a homogenization of riverbed widths (Fig. 3A). Lastly, for the three timespans, the difference in planform evolution between successive periods is statistically significant (pairwise Wilcoxon test, p-value <0.0001).

4.2. Vertical evolution of the Loire River Bed (1755–2023)

The vertical evolution of the fluvial bed is analyzed from Decize (km 22) to Fourchambault (km 72) using the relative height constructed for each age map. The bed of the Loire River has been deeply incised since the mid-18th century, as the 1755 active bed is 3 to 4 m higher than the current bed (Fig. 4A). Over the 50 km of the study area, the historical change in bed elevation exceeds 4 m over 18 km (Fig. 4B). The relative elevation of the 1755 alluvial floor near Decize and Nevers was significantly lower than the rest of the riverbed.

An initial phase of incision occurred between 1755 and 1848, averaging 64 cm (a rate of 0.7 cm per year; Fig. 4B, D). The Decize and Nevers reaches were incised by more than one meter. For the second period (1848–1953), the entrenchment accelerated (1.2 m; Fig. 4C & 4D), reaching an average of 1.23 m over the 50 km, which represents −1.17 cm per year, almost double the previous period. It was very pronounced between km 42 and 67. Incision is 2 m downstream of Decize and reaches 2.6 m in the Nevers reach. The last period saw the highest incision: the alluvial floor in 1953 is 1 to 3 m above the current level. Annual incision exceeded 3 cm from Decize to Imphy (km 27–47) and downstream of Nevers (km 61–72). The highest degradation is recorded near Imphy (−4.2 cm per year). For the entire study period, the entrenchment of the riverbed therefore exceeds 4 m over more than a third of the river length.

4.3. Volumetric changes and sediment balance

The combined analysis of sedimented and eroded areas by the

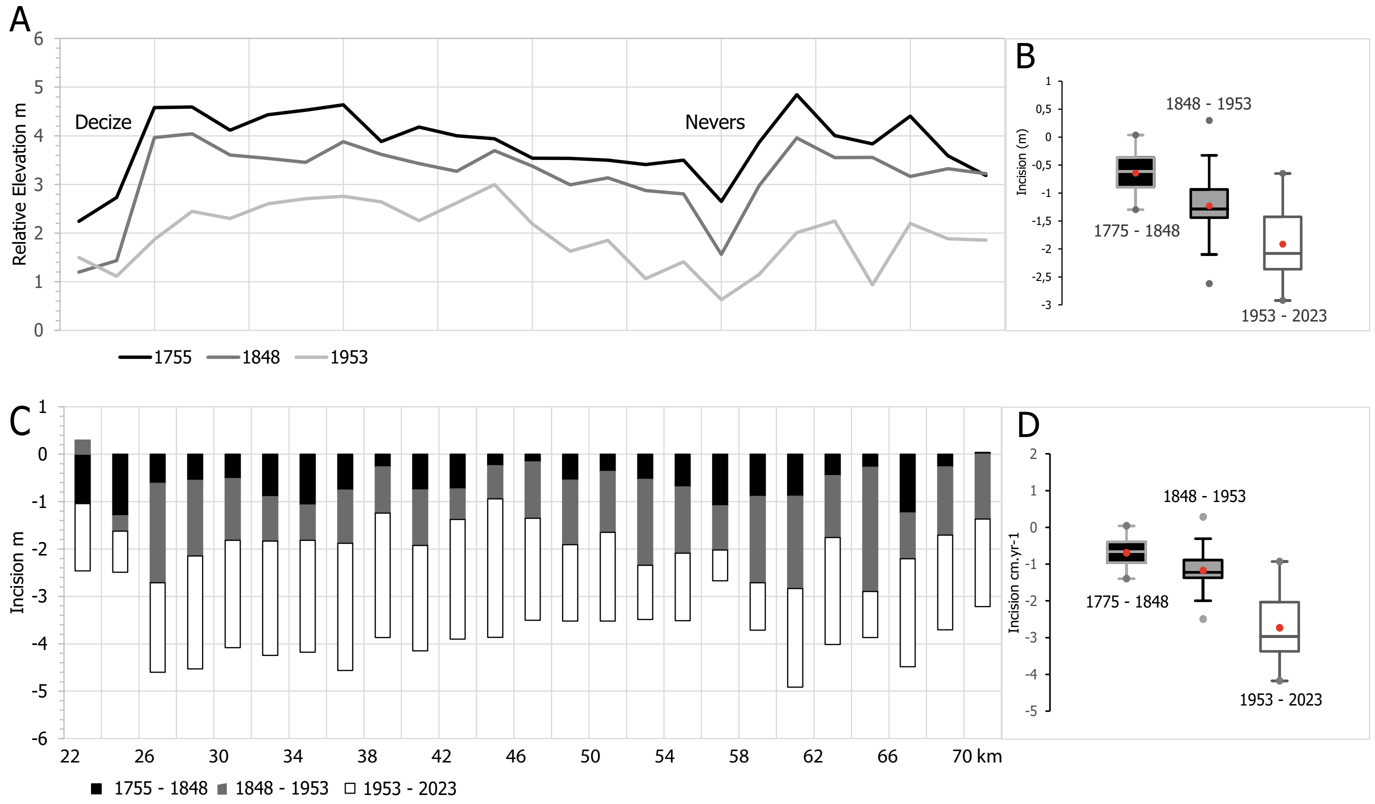

Fig. 4. Temporal evolution of the relative height of the Loire River bed from 1755 to 2023 extracted from the height model of age maps. A. Vertical evolution: median height of the 2 km-units for 1755, 1848, 1953, 0 being the 2023 median height; B. Box-plots: bed vertical evolution in m. C: incision in m per 2 km unit; D. Box-plots: annual rate of incision (cm per year). The boxplot whiskers represent the 10th and 90th percentiles, the boxes mark the interquartile range (25th to 75th percentiles), and the mean value is indicated by a cross. Points are maximal and minimal values.

vertical evolution of the channel between two dates provides a sediment balance (Fig. 5). Over the entire period, the Loire River has incised mainly by retracting into the previously occupied active bend. For the 50 km from Decize to Fourchambault, 58.56 million m^3 (±8.48 million m^3) of sediment were eroded (218,500 m^3 per year), while 29 million m^3 (±10 million m^3) were trapped in the lateral margins (i.e., 108,209 m^3 per year).

The ratio of eroded to sedimented volume has varied considerably over time. The period 1755–1848 was characterized by a negative balance: this section of the Loire River lost 12.24 million m^3 (132,000 m^3 per year; Fig. 5A). The erosion volume represented 18.2 million m^3 (±7 million). Three sites had a marked negative balance: downstream of Decize (km 32–36), Uxeloup (km 40–42), and downstream of Nevers. Each 2 km unit lost an average of 0.73 million m^3. Sediment trapping was limited during the first period: about 5.96 million m^3, i.e. 64,100 m^3 annually (with an important uncertainty exceeding ±80% for nine 2 km-units, Fig. 5A). However, three main zones of accumulation are observed; they correspond to large abandoned meanders (upstream of Uxeloup, km 36–38; near Imphy, km 44–50; and Nevers city, km 56–58). Each 2 km unit lost an average of 0.73 million m^3. The accumulation near km 24–25 is probably overestimated, as the active bend was very wide in 1755 at this point, most likely for man-made reasons (probably a harbor). Uncertainty is relatively high for sedimented volume between 1755 and 1848. It is lower for the two other periods, however, generally speaking, uncertainty is greater for sedimented volume than for eroded volume during the three observation periods.

The eroded volume from 1848 to 1953 (Fig. 5B) was fairly close to that of the previous period: the reach lost 18.9 million m^3 (±1.64 million m^3); however, the annual erosion rate increased slightly (about 180,800 m^3 annually). The main difference from the previous period is the volume of trapped sediment, which rose sharply to 12 million m^3 (±2736 million m^3), four times higher than between 1755 and 1848 (i.e. 113,400 m^3 per year). During the second period, a large volume of sediment was trapped on lateral margins downstream of Decize, near Nevers, and especially downstream of the Allier River junction (Fig. 5B).

Finally, for the last period, erosion increased to 21.4 million m^3 (±963,000 m^3), which represents 305,400 m^3 per year (Fig. 5C). Sediment loss was significant from Decize to Imphy (km 28–44) and at Bec d'Allier. Accumulation on the lateral margins also increased (11.15 ± 2.31 million m^3, i.e. 159,300 m^3 per year).

We also quantified bank erosion, which drastically changed. The contribution from lateral erosion was much greater during the first period: 6.3 million m^3 (±1.16 million m^3), representing 34.6% of the total eroded volume. From Decize to Imphy (km 22–48), the active bed migrated laterally, eroding 3.85 million m^3. Downstream of Imphy (km 48–72), the Loire River was more stable, as the lateral erosion represented 2.4 million m^3 (±737,000 m^3). Lateral erosion was very low in the vicinity of Nevers.

The lateral contribution halved between 1848 and 1953, with 3.23 ± 0.282 million m^3 (17% of the total eroded volume). Thus, the lateral mobility was limited, with only one new meander in the upper zone. The lateral erosion showed renewed activity after 1953 (22% of the total eroded volume, with 4.7 ± 0.217 million m^3), especially between Decize and Imphy, with 3.15 million m^3, whereas the downstream section underwent marked lateral stability (1.58 million m^3). In any case, the volume of sediment supplied by lateral erosion was much less than the volume lost in the active channel.

To summarize, an initial phase of bed degradation was observed during the first period (1755–1848); it appears that this initial phase was likely not accompanied by pronounced sedimentation of the river margins, except in abandoned meanders. However, uncertainty on sedimented volumes is important for the first period. The trapping effect can

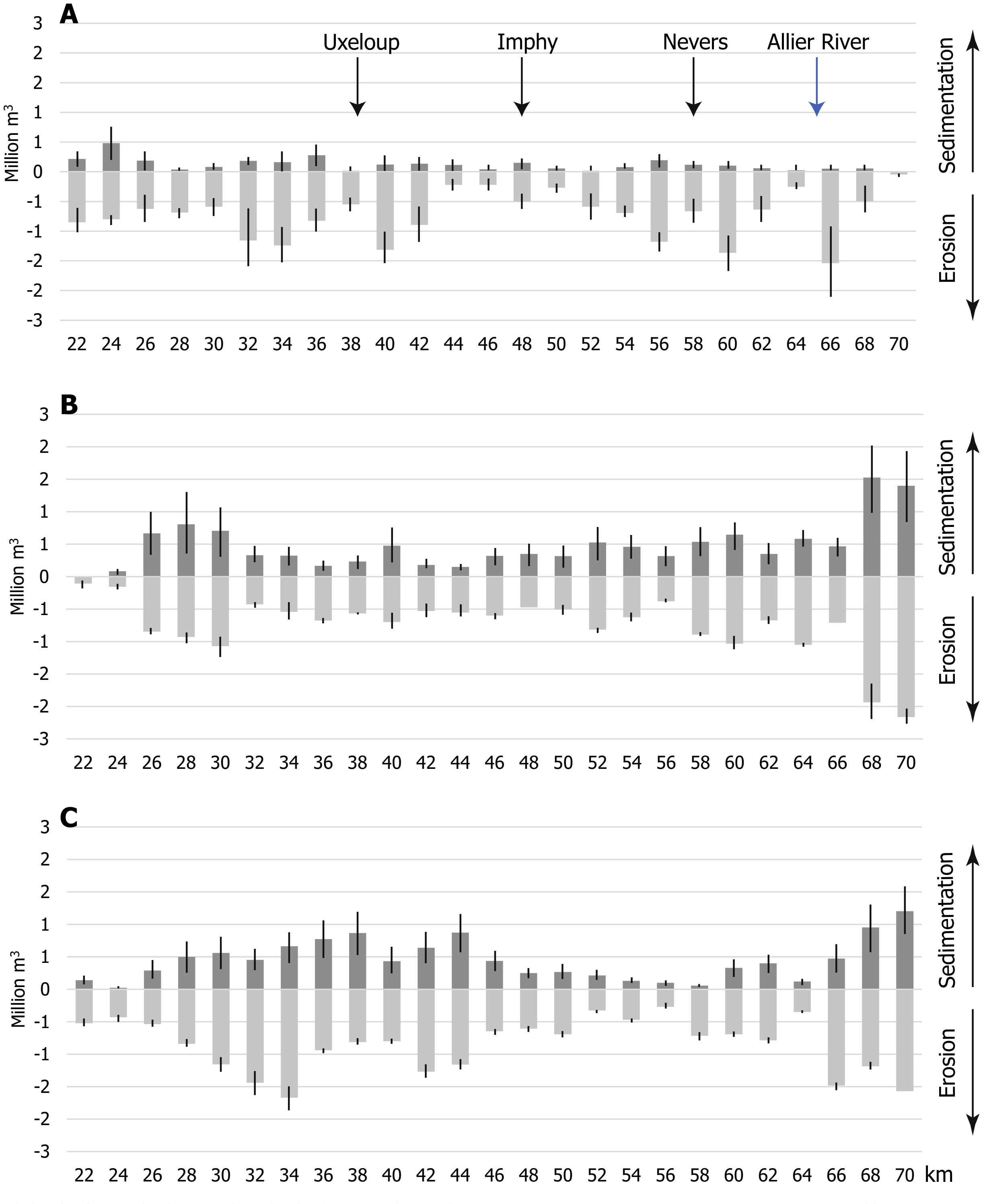

Fig. 5. Eroded and sedimented sediment volume for the three periods per 2 km unit. A. 1755–1848; B: 1848–1953; C: 1953–2023. Vertical bar represents uncertainty (uncertainty lower than ±2% is not presented).

be observed during the second and third periods. Eroded volumes changed little between 1755 and 1953 but rose sharply during the third period.

4.4. Anthropogenic disturbances

4.4.1. From groynes to levees

The total length of engineering structures (including submersible and non-submersible groynes, artificial levees, etc.) was 23 km in 1755 (about 16% of the total bank length). However, the 1755 map shows two contrasting situations in terms of embankment (Fig. 6). Nevers in 1755 was surrounded by more than 9 km of dykes and levees. In Decize, 1.5 km of protection was present in 1755. Another 2.5 km of groynes and dykes can also be seen at the "Bec d'Allier," just at the junction of the Loire River with the Allier River, which was a major navigation "hub."

In contrast, rural areas were equipped with discontinuous groynes. The 1755 and 1848 maps, as well as archival plans ("Grenier plans", 1851–1852), provide precise insight into engineering works, helping to

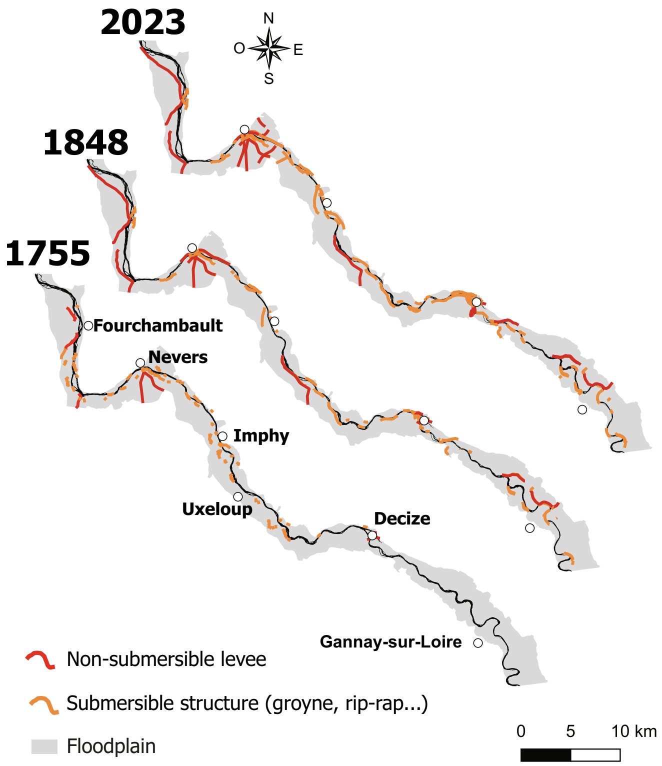

Fig. 6. Evolution of the Loire River engineering works.

understand the management strategy, as the cartographers carefully recorded all fluvial infrastructures. The hydraulic structures were built in two stages: i) the closure of secondary channels during the 18th century, mainly with groynes (in 1755, these groynes were brand new, as they are not drawn on older maps); and ii) the general embankment at the beginning of the 19th century with longitudinal levees. In 1755, in rural sections, ancient maps and archival plans show groynes along the banks of secondary channels; these hydraulic structures were obviously built to prevent the Loire River from migrating, to preserve the main channel very close to the ports located on the right bank. Consequently, the groynes tended to force sedimentation and therefore cause the abandonment of secondary channels.

At the beginning of the 19th century, the management plan drawn up by the King's engineers before the French Revolution was completed: there are around 50 km of non-submersible infrastructures along the study reach (Fig. 6). The individual groynes evolved into continuous embankment systems composed of longitudinal non-submersible artificial levees. Three levees were constructed upstream of Decize, and there are around ten dykes further downstream, including those at the Uxeloup and Imphy sites (Fig. 7). The cities of Nevers, Decize, and the Bec d'Allier were definitely stabilized by continuous levees. Over the course of the 20th century, the hydraulic infrastructure changed very little: additional bank protection (rip-rap type) was locally added. Consequently, today, 8 km are not controlled by structures along the 22 km studied upstream of Decize (i.e. 36% of the river length). Between Decize and the Fourchambault Bridge, 9 km are preserved from embankment along the 50 km (i.e. 18% of the river course, Fig. 6).

4.4.2. *Uxeloup site – sediment trapping effect of hydraulic structures*

The rural site at Uxeloup, between Tinte and Imphy, serves as an example to synthesize the changes that the Loire River has undergone over the past three centuries (Fig. 7). In 1755, the reach was equipped with groynes, and according to archival documents, the aim was to maintain the main channel's connection with three secondary ports: Béard, Port des Bois (a port dedicated to wood-log transport for Nevers), and Imphy. Three artificial cutoffs were realized on side meanders (Fig. 7).

Between 1806 and 1813, a continuous 7 km levee was built on the left bank (Fig. 7, Fig. 8). Two shorter dykes were also built upstream (in front of Béard) and downstream (in front of Imphy). Consequently, in 1848, the Loire River adopted a straight course with a main channel along the right bank. The three large side meanders on the left bank were definitively closed and replaced by very narrow channels, which were finally dewatered. Therefore, artificial cutoffs and general embankment deeply altered fluvial forms; in 2023, the active bed was only 37–48% of the 1755 riverbed (Fig. 8).

The first phase of management triggered a slight incision of about 50 cm. Erosion in the middle part of the embanked section at Uxeloup reached 1.3 million m^3 (km 40–42, Fig. 5A), which represents a mean annual loss of about 14,000 m^3.

The electrical resistivity cross-sections combined with cores reveal the effect of incision on the texture of the sediments that have been deposited (Fig. 9). Cross-section A is located in the current proximal floodplain near Uxeloup, between the levee (SW, 0–50 m on Fig. 9A) and the current active bed (NE). The western part (70–220 m) corresponds to the active bed of the second half of the 18th century. The sediment is composed at the surface (0–45 cm, blue color, low resistivity) of sand (medium and fine sand, with D_{50} ranging from 80 to 50 μm). Lower deposits (45–180 cm) are coarser (D_{50}: 100–500 μm), revealing a vertical grain-size decrease observed in abandoned channels. The sand deposit has a thickness ranging between 2 and 2.5 m. Under the sand deposit, gravel and small cobbles (b-axis: 2–5 cm) are observed; they likely correspond to the 1755 active channel. The central part (200–290 m on cross-section A) was a secondary channel surrounding an island in the middle of the 19th century, where coarser sediment was deposited (medium sand to gravel with a D_{50} ranging between 500 and 700 μm, green color). The small mound (290 m) corresponds to a groyne visible on the 1775 map. Finally, the eastern, lowest part of the proximal floodplain (300–360 m) is formed by the channel of the mid-20th century. It is 2–2.5 m lower than the older surface. Its deepest part was a

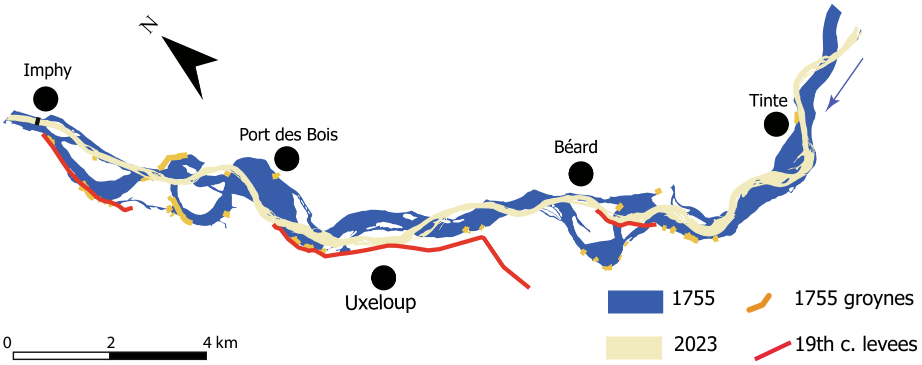

Fig. 7. Evolution of the fluvial bed and engineering works – Uxeloup reach.

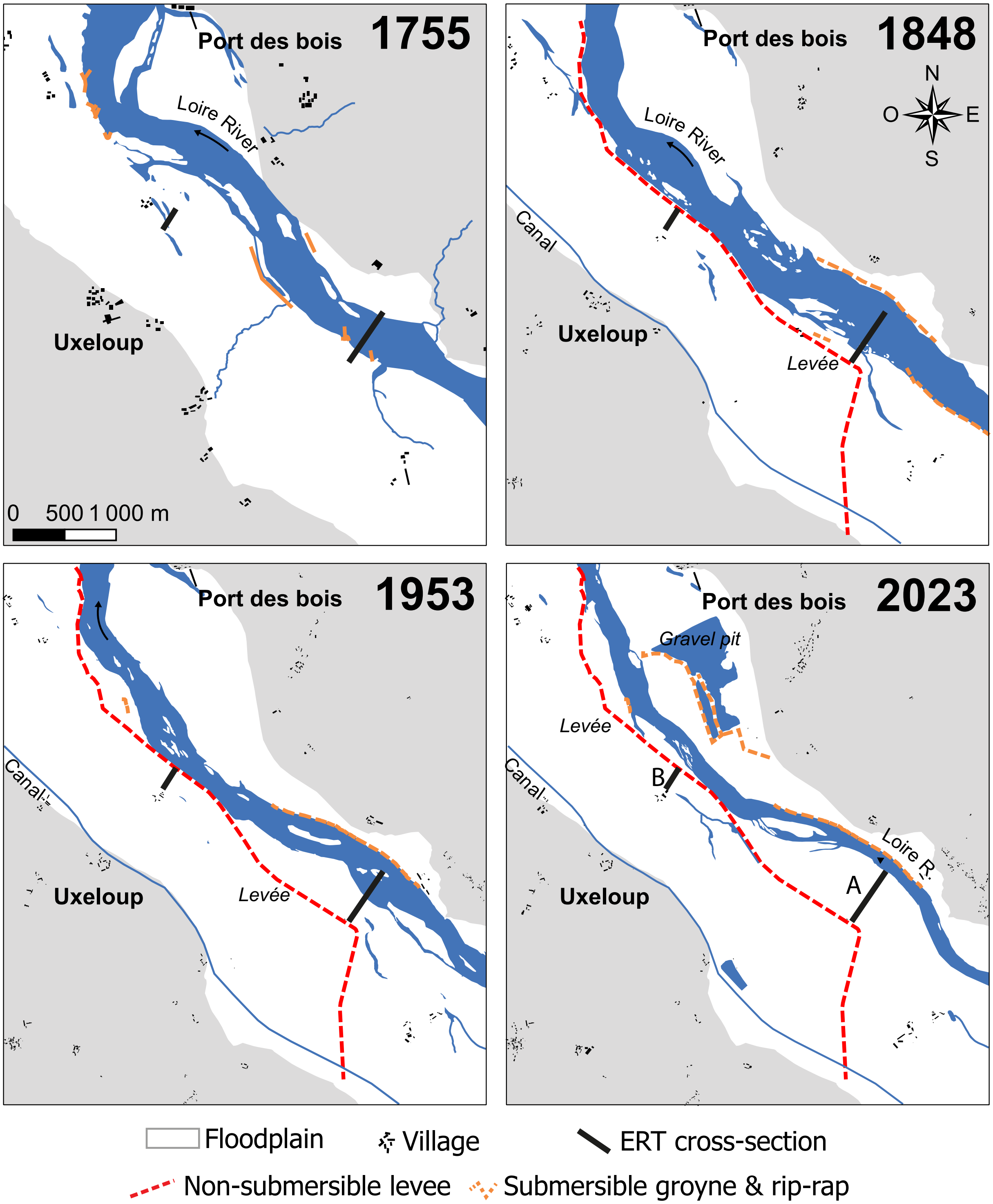

Fig. 8. Diachronic landform evolution along the main levee near Uxeloup.

channel filled with a two-meter-thick deposit composed of a succession of fine sand and coarse sand. At a two-meter depth, deposits are exclusively coarse (gravel and cobbles, red and purple in color).

The second profile is located further downstream in the floodplain, just behind the levee (Fig. 9 Profile B); it is mainly composed of sand deposits. It crosses an abandoned channel visible (Fig. 8) on the western part of the cross-section (0–70 m on cross-section B, blue color): the channel was already abandoned in 1755. This part of the floodplain is still submerged by flood backwaters today. The surficial sediment is fine (1 m of silt and fine sands with a D_{50} of about 15–30 μm), corresponding to overbank deposits. The deeper deposit (1–3 m in depth) shows an alternation of layers of fine sand and silt. Between 3 m and 5 m in depth, the deposit becomes coarser (coarse sand, gravel, and small cobbles 5 cm in b-axis). The central part of cross-section B (100–150 m on profile B, red and orange colors) probably corresponds to a former bar or island, with coarse sand and gravel. The last part of the cross-section (160–180 m) is a small depression, which was the second branch of the abandoned channel; it is filled with medium sand.

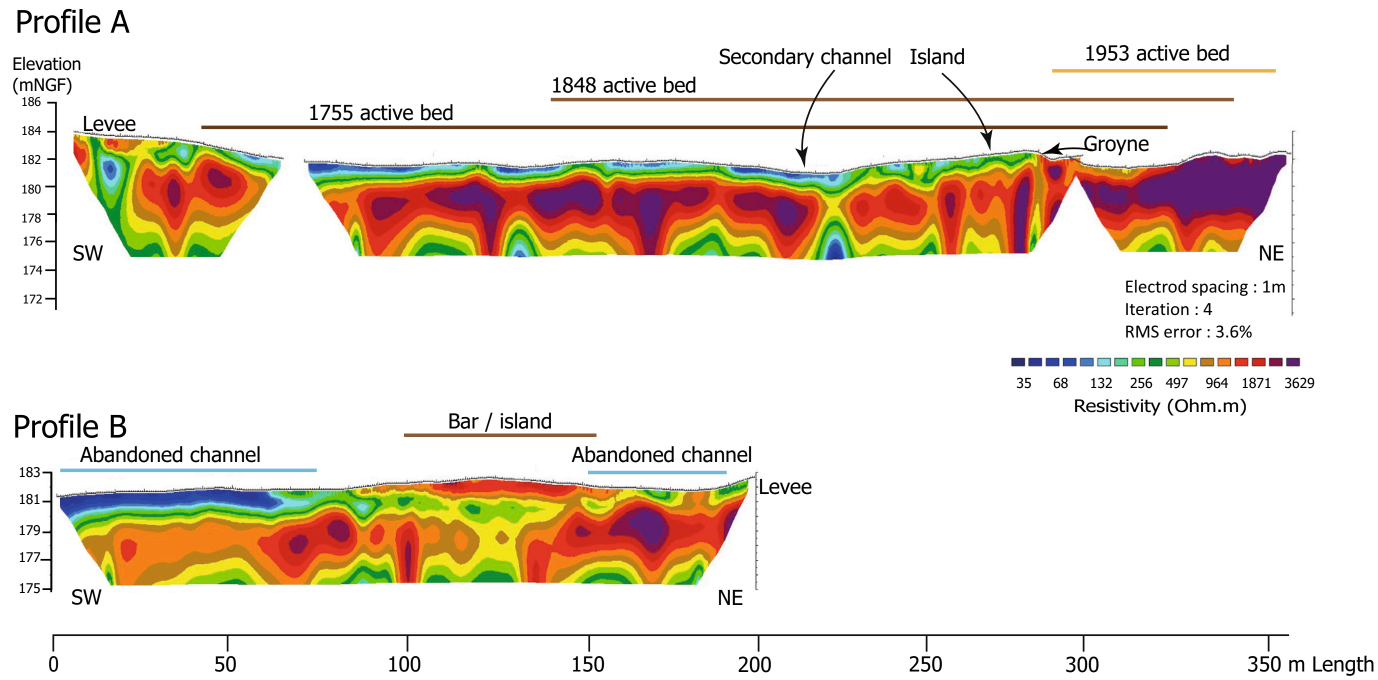

Fig. 9. Electric Resistivity Tomography cross-sections of the Uxeloup site. A: proximal floodplain; B: central floodplain (see location on Fig. 8).

4.5. *Hydrological changes since the 18th century*

The 270-year period under analysis has been marked by significant changes in river discharge, and in particular in flood magnitude. These changes may have had an influence and may partly explain the intensity of the readjustments that took place over the period. Large floods likely played a part in the fluvial bed readjustment during the first period, which was very rich in major hydrologic events. The end of the Little Ice Age (late 18th–late 19th century) was a period of very heavy flooding in the Loire River basin (Mesmin et al., 2024) (Fig. 10A). More specifically, the last two decades of the 18th century recorded the highest number of floods since the 14th century. This period is particularly marked by winter floods with brutal ice break-up (1784, 1789, 1792, 1795, 1820, and 1823).

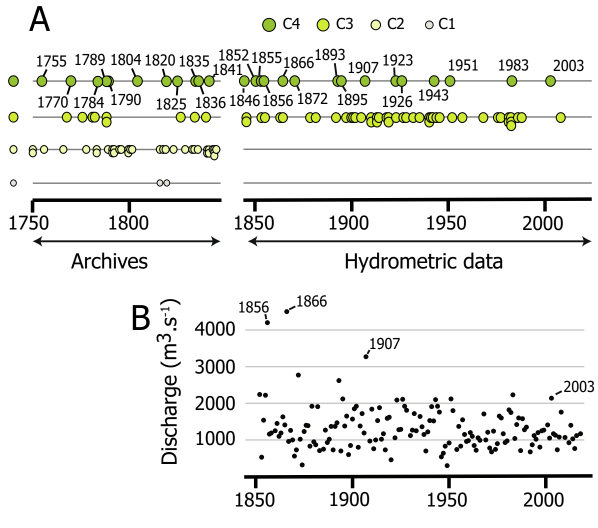

Fig. 10. Flood chronology (1750–2025). A: Intensity class, with: C1: no information; C2: return period <5 yrs. and no damage reported; C3: 5 yrs. < return period <20 yrs., damages on dykes, bridges, etc., reported; C4: return period >20 yrs., destructions of bridges, breaches in dykes, widespread flooding, etc. (adapted from Mesmin, 2024). B: Flood peak discharge of the Loire River at the Nevers gauging station since 1856.

The huge 1789 ice-break-up occurred in January and provoked numerous dyke breaches and bridge destructions. After 20 "quieter" years, a long period of intense hydrologic activity (1820–1870, Fig. 10B) is recorded. Three very large floods (1846, 1856, 1866) affected the entire Loire River basin. According to different hydrological estimates (Dacharry, 1974; SHC, 1975), the three events exceeded a 150-year return interval, and the latest major flood reached 4500 $m^3.s^{-1}$ at the Nevers gauging station (September 1866, Fig. 10B). The 1890–1950 period underwent frequent floods, even if peak discharges were much lower than during the previous period (Fig. 10B). The last large flood occurred in October 1907: approximately 3270 $m^3.s^{-1}$ at Nevers (exceeding a 50-year return interval) was estimated. The magnitude of recent floods was much lower; the December 2003 event, for example, only reached 1990 $m^3.s^{-1}$ at the Gilly gauging station and 2140 $m^3.s^{-1}$ at the Nevers station, which corresponds to a 20-year return interval. Summer floods also showed a decreasing trend from the beginning of the 20th century. Furthermore, 1955–1975 was a dry period with rare small floods. After the short and more humid period recorded in the 1980s, the recent decades (1988–2023) corresponded to a very low-hydrology period, one of the longest low-intensity phases since the Middle Ages. Floods were not only rare, they were also characterized by short flooding: the mean duration of overbank flow was about 6 days per year, whereas during more humid periods of the 20th century, flooding was much longer (exceeding 15 days per year).

4.6. *Quantification of mining volume and recent incision (20th – 21st century)*

According to Dambre and Malaval (1993), 220 million tons of gravel and sand were extracted from the Loire River between 1949 and 1992, which represents a mean thickness of about 1.5 m on a 150 m-wide strip of the riverbed. For the study reach, we have an estimation for 1981–1988: a minimum of about 2.6 million tons and probably more than 4 million tons, i.e. between 325,000 and 570,000 tons per year (Dambre, 1995); extractions were progressively limited by law during the 1980s. According to the aerial photographs that we examined, mining began in the early 1970s, and a dozen sites were in operation

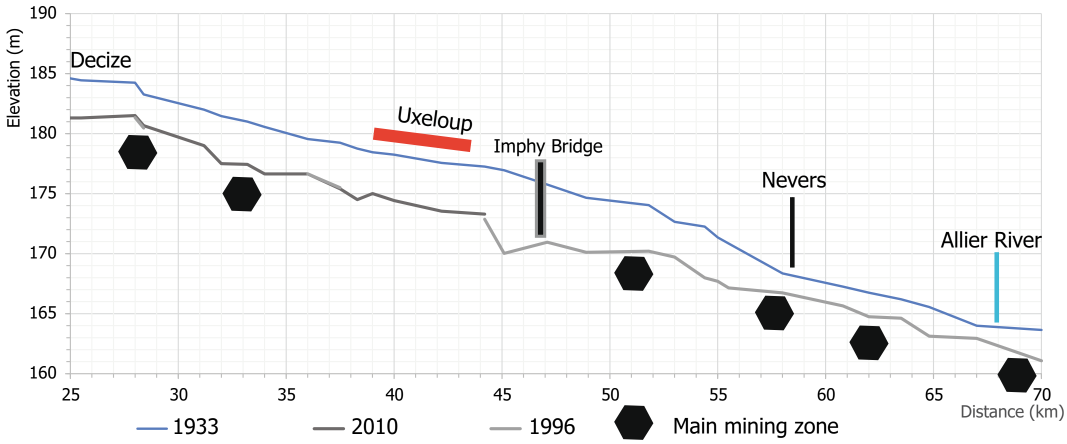

Fig. 11. Evolution of the longitudinal profile of the Loire River (1933–2010) from Decize to Fourchambault and main mining sites.

(Fig. 11). The pits were located downstream of Decize (with a possible ephemeral pit near the Gannay bridge). For the 1970s, we estimate that 650,000 tons (minimum) – 975,000 tons (maximum) were annually mined from the study reach. Thus, for the entire period (1970–1989), we calculated that a minimal volume of about 15.75 million tons (probably 22–23 million tons) of sediment were industrially extracted from the study reach (representing about 400,000–600,000 tons per year). This represents more than 6.05–7.87 million m^3 (with a density of 2.6 and a porosity of 0.1 and 0.3, respectively). Consequently, the annual volume ranged between 2400 and 3600 m^3 per linear km.

The mined volumes likely explain the recent bed entrenchment. The comparison of three longitudinal profiles (1933, 1996, and 2010, Fig. 11) confirms the recent incision, which ranged between 2.5 and 3.2 m. The strongest incision is observed at the Imphy bridge (6.9 m). Incision in the upper reach is much less pronounced, with a mean value of 0.86 m. A 2.5 m incision is measured just near the Gannay bridge, where we suspect an ephemeral mining pit in the 1970s.

5. Discussion

The compiled hydromorphological data provided by HD LiDAR DTM, in conjunction with accurate old maps, provide a new opportunity to analyze the combined effects of river channelization and hydroclimatic change from 1755 onward. This makes it possible to study in detail the respective and successive impacts of engineering works, changes in floods, and finally, sediment mining. The 270-year period covered by this study is strategic for two main reasons. Firstly, it covers the hydrological transition between the last phase of the Little Ice Age and the 20th century. Secondly, in the case of the Loire River, massive sediment mining conducted during the 1970s–1980s is commonly considered to be the main factor in the entrenchment of the riverbed (Gasowski, 1994; Gautier et al., 2000; Latapie et al., 2014).

5.1. The successive river readjustments

During the 1755–1848 period, the Loire River moved from discontinuous embankment, concentrated on three sites, to quasi-continuous channelization between levees. In rural areas, even if little is known concerning ancient fluvial engineering structures on this part of the Loire Valley, two archaeological studies have highlighted Roman and Medieval infrastructures (Steinmann et al., 2011). We also know that the main harbors, Nevers and Decize, faced two distinct problems, which led them to equip the riverbed very early on. In the case of Nevers, the Loire River tended to migrate southward into the floodplain; therefore, the aim was to force the Loire River to stay on the right bank and to flow under the two bridges. Consequently, submersible structures (groynes and bank protections) were built as early as the 14th century (Foucher, 2024). In the case of the city of Decize, it was necessary to maintain the bridge crossing the river on both sides of the island (which is a structural island). Consequently, since the 15th century, hydraulic structures were built to preserve the bridge, to maintain access to the port facilities, and to prevent one of the two channels from sedimentation (Mesmin, 2025). Thus, the river was harnessed by groynes and dykes in the two main ports before the other reaches along the river (Suppl. Data, S3). The old structures could likely explain why, in 1755, the active channel in the area of Decize and Nevers was 1.5–2 m lower than the other reaches: the channel was likely already incised (Fig. 4). Early modern river management probably led to an initial phase of incision of the alluvial floor in the Nevers and Decize reaches (km 22–26 and 52–57, Fig. 4).

The first study period (1755–1848) is strategic for understanding the fluvial landform readjustment. As a reminder, eroded surfaces were high, whereas surfaces lost in the active bed mainly concerned side meanders closed by groynes. The secondary channels equipped with groynes accumulated thick sandy deposits (Imphy, Uxeloup). Several explanations can be suggested. One of them could be the efficiency of the groynes: by decreasing current velocity, they increase bed roughness, and this is probably the main factor explaining the rapid deposition of the sand load in side channels (Fig. 12). Numerous similar cases are described in previous articles. Rapid aggradation behind groynes was also observed on the Po River (Brenna et al., 2024) and along the Waal and Meuse rivers (Hobo et al., 2014; Middelkoop and Asselman, 1998), where minor dykes promoted the highest sedimentation rates. On the lateral margins of the Vistula River, groynes also triggered an exceptional accumulation of sediment (up to 5 cm per year) (Ciszewski and Czajka, 2015). The Vistula River case study presents several similarities with the Loire River in Burgundy, as the rapid sedimentation was accompanied by channel incision and narrowing since the end of the 19th century, which accelerated over the 1940s.

Thus, the first generation of groynes, even though very discontinuous and limited, could likely have provoked a rapid sediment sequestration in the closed side arms. The Uxeloup site demonstrates that behind the levees, the “fossilized” floodplain sequestered the finest sediment load (mainly sand), while the active beds post-18th century are poorer in fine sand, being mainly composed of coarse sediments (coarse sand, gravel, and cobbles). The hydraulic infrastructure has thus created disconnected sedimentary environments.

Even if no map covering the entire study reach is available between the 1755 map and the 1848 map, archival plans, precisely designing the fluvial bed at the beginning of the 19th century, suggest a rapid infilling of artificially abandoned side channels. This is also evidenced by the quasi-absence of oxbow lakes still in water on the 1848 map. Thus, the terrestrialization of the abandoned channels could have occurred just after the first phase of dyking; this is likely due to the conjunction of their rapid infilling and the entrenchment of the main channel. When

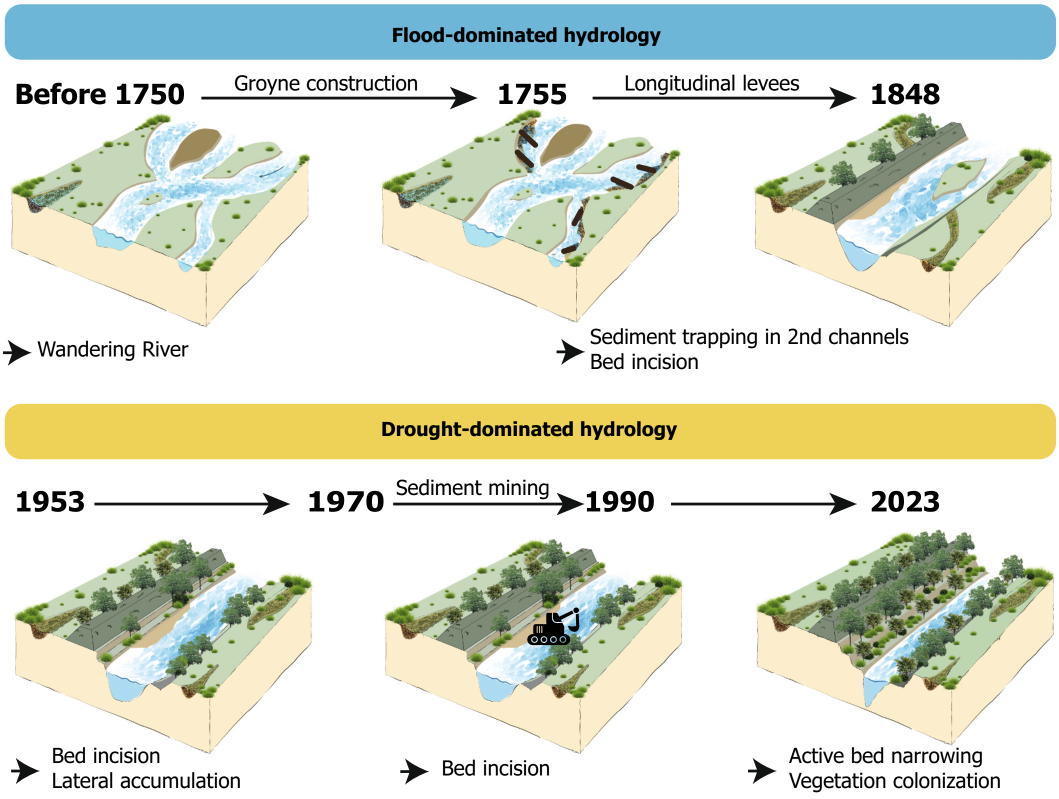

Fig. 12. Synthesis of the Loire River trajectory since the 18th century.

analyzing various factors controlling the terrestrialization of secondary abandoned branches, the degradation of the main channel is significant (Dépret et al., 2017). However, on the Rhône River, dykes have also frequently limited the infilling of the channels with bedload (Dépret et al., 2017; Riquier et al., 2017; Seignemartin et al., 2023). This is not the case for the Loire River in Burgundy, where the sand load transported by graded suspension and real suspension was trapped by the groynes.

Hydraulic infrastructure has also disrupted the spatial distribution of the sediment transported by the Loire River. In the study section, our measurements show that gravel and cobbles currently account for 70–80% of the river bottom, whereas bars are mainly (60–70%) formed by sand. The embanked main channel has probably been affected by coarsening due to an increase in bed shear stress (Frings et al., 2014). Gravel and coarse sand (non-sorted, $D_{50} > 500$ μm) are transported by rolling and graded suspension, whereas finer sand and silt ($D_{50} < 100$ μm, well-sorted sand) are transported in suspension (Gautier et al., 2007b). Secondary channels currently connected with the main channel mainly transport coarse sand and gravel. We observed that the current secondary channels are progressively aggraded with coarse sand deposit on the outlet, forming thick alluvial plugs. For this reason, recent secondary channels rarely evolved toward lotic systems.

The second generation of engineering works with longitudinal levees had two probable combined impacts (Fig. 12). The artificial longitudinal levees built in the early 19th century disconnected the abandoned side channels from the active bed. We can therefore suppose that deposition within artificially abandoned channels decreased rapidly after the second phase with longitudinal levee edification. The “perched position” of the floodplain and the lack of fine suspended load may also explain the decrease in deposition in the abandoned channels et more generally, on the floodplain. Furthermore, the reduction of depositional area in the disconnected floodplain likely promoted the significant increase in sedimentation rate measured in the embanked new channel since the mid-19th century (Fig. 5B). The same observation of a rapid sedimentation within the embanked channel was made along the “battures” of the middle Mississippi River (Remo et al., 2018), and along the Waale River (Hobo et al., 2014).

The Loire River morphology changed drastically as it evolved from a wandering pattern composed of multiple channels and sinuous or meandering secondary branches connected to a low-lying floodplain, to a rectilinear pattern dominated by one or two channels flowing between steep banks. This evolutionary trajectory is unfortunately common to many rivers that have been embanked (Arnaud-Fassetta, 2003; Brenna et al., 2021, 2024; Euzen et al., 2024; Frings et al., 2014; Hohensinner et al., 2004; Kiss et al., 2011, 2025). The wandering fluvial pattern of the Loire River in Burgundy, which associated a sinuous and multi-channeled course, may have made this river with a moderate energy prone to a rapid readjustment and a pronounced entrenchment. On the Apalachicola River, Alruzuq et al. demonstrated that the most severe bed degradation is due to artificial cutoffs (Alruzuq et al., 2026). And, according to Surian and Rinaldi (2003), multiple-channel systems are more sensitive to anthropogenic impacts than single-thread rivers. Rapid incision has also been observed on the Po River just after embankment (Brenna et al., 2024). The vertical difference between the abandoned lateral margins (including abandoned secondary channels) and the main channel on the study reach of the Loire River is very similar to the value measured on Italian rivers (Po River and Parma River), ranging between 2.5 and more than 7 m (Brenna et al., 2021; Brenna et al., 2024): more than 6 m in the Loire River (Imphy reach).

A comparison of the volume of eroded or sedimented material with that of other rivers can help to underline its significance. The volume eroded in the Loire River is very similar to the volume calculated along the embanked Rhône River before the construction of large dams (Provansal et al., 2014). On the study reach, each kilometer annually delivered, on average, 3900 m^3 (1755–1848), 3616 m^3 (1848–1953), and 6108 m^3 (1953–2023). The comparison highlights the exceptional sediment deficit measured on the Loire River, as the Rhône River is a larger river in terms of catchment area and water discharge. The in-channel sediment is the main part of the sediment origin, as bank erosion represented a maximal value of about 34% during the first period on the study reach. The Loire River case study demonstrates, for the three study periods, a negative balance: the sediment volume trapped on lateral margins is much lower than the in-channel volume that the river exported downstream. As previously mentioned, sediment trapping on the margins was likely lower during the first period: each kilometer trapped annually 640 m^3 on average. It increased sharply thereafter, as every linear kilometer trapped 2270 m^3 annually (1848–1953) and 3200 m^3 (1953–2023). However, these values are much lower than those measured on the Rhône River, where the suspended load is much higher (Provansal et al., 2014; Riquier et al., 2017).

5.2. The potential part played by large floods at the end of the little ice age and by recent drought

The very active period recorded in the Loire River basin at the end of the 18th century has also been recorded in the Seine River basin (Blöschl et al., 2020), in the Rhône River and its alpine tributaries (Pichard et al., 2017; Coeur, 2008). On the Danube River, upstream of Bratislava, Pisut (2002) also described high-magnitude floods accompanied by frequent ice-break-up events (1766–1774). According to the author, the flood impacts were amplified by riverbed channelization. England and Wales also underwent frequent major floods during the last decades of the 18th century (1768–1795) (Lewin, 2013). The long period of intense hydrologic activity (1820–1870) is also recorded in northwestern and central Europe (Blöschl et al., 2020; Schillereff et al., 2019) and Spain (Barriendos et al., 2019).

The recent decades (1988–2023) correspond to a very calm period in the Loire River basin (Fig. 10B). It seems to be an exception, as the great majority of European rivers underwent frequent floods, and even very large events, during the same period. The Loire River basin has largely been spared from recent major events that occurred in Western and Central Europe (2021, 2024–2025; Dessers et al., 2026, Steinritz et al., 2024).

Changes in water discharge interact with morphological and biological adjustments. We can suggest that this recent drought-dominated period also contributed to the colonization of bars and lateral margins by riparian vegetation, which accelerates sediment trapping. After the 2003 flood, we measured thick deposits on bars and banks colonized by pioneer sequences (up to 60 cm; Gautier and Grivel, 2006). Although thick sand deposits were also observed on the very proximal floodplain, the sediment deposited in the more distal floodplain was thin. This can be explained by the low suspended concentration of the Loire River, and by the short submersion duration of channel margins that is aggravated by the entrenchment. At Uxeloup, the channelized riverbed is entirely submerged for a flood exceeding a 20-year return interval.

Finally, the change in morphology implies an increasing specific stream power of the river, as the levees have sharply reduced the width of the fluvial corridor and concentrated the river flow in the narrower channelized channel. Several previous studies have demonstrated that highly engineered rivers are subjected to important changes in hydraulics in terms of flood level and flood peak, inducing an increase in stream power (Biedenharn et al., 2000; Frings et al., 2014; Pinter et al., 2006; Roccati et al., 2019). If we take the value of 4500 $m^3.s^{-1}$ for the major floods of the Loire River, their specific stream power has risen from about 45–50 W/m^2 (before embankment) to over 100 W/m^2 since the mid-19th century. The 1907 last large flood exceeded 120 W/m^2, and the recent "moderate" floods (10- or 20-year return interval) developed a specific stream power of about 75–80 W/m^2, mainly because of the active channel narrowing. The increasing stream power may have also contributed to the longitudinal transfer of the sand load, partly explaining the coarser grain-size of the current riverbed (see Uxeloup site). Additionally, the increasing specific stream power could also be the origin of the renewed bank erosion that we measured during the 1953–2023 period, which partly compensated for the sediment deficit created by mining.

5.3. The final blow

On many rivers, it has been demonstrated that a significant proportion, if not the main part, of in-channel erosion over recent decades is directly linked to sediment mining (Bravard et al., 1997, 2013; Brenna et al., 2021, 2024; Collins and Dunne, 1990; Depret et al., 2021; Kondolf, 1997; Padmalal et al., 2008; Rentier and Cammeraat, 2022; Rovira et al., 2005; Rusnák et al., 2024; Sear and Archer, 1998; Wyzga, 2007…).

We calculated that 50–59% at least of the volume entrenched in the channel (without bank erosion) can be explained by sand and gravel industrial exploitation. Consequently, the value demonstrates that the erosion measured for 1953–2023 is mainly caused by the excessive mining conducted in the active fluvial bed until the end of the 1980s, which triggered sediment starvation in the Loire River. Furthermore, the huge sediment volume extracted from the riverbed greatly exceeded annual sediment fluxes: as mentioned above, sediment mining was about 400,000 tons per year (as a minimal estimation), whereas annual bed load transport is 32,000–41,000 tons for the Loire River near Nevers (Le Guern et al., 2026). One year of mining therefore represented the equivalent of 10 years of sediment transport, which is the same order of magnitude as the deficit caused by sediment mining in other rivers worldwide (Table 2). The Allier River sediment supply is much higher (78,000–99,000 tons per year; Le Guern et al., 2026), which probably limited the impact of mining conducted downstream of the Loire–Allier junction. On the Allier River, a proactive policy is being pursued to enhance the lateral mobility of the river. However, a comparison of two rip-rap removals had contrasting results, with the efficiency depending on coarse sediment availability in banks and local geomorphic conditions (Arfeuillère et al., 2023).

Finally, if we consider that mining accounts for 50–60% of the volume eroded in the channel, then lateral erosion would have compensated for at least some of the sediment deficit during the second half of the 20th century. This leads us to think that, in the absence of sand and gravel mining, the readjustment processes might have enabled the Loire River to be closer to a new dynamic equilibrium one century after embankment.

6. Conclusion

In this study, we investigated the interactions between the embankment, changes in hydrology, and sediment mining to gain a better understanding of the morphodynamic readjustment of a lowland river since the 18th century. The Loire River in Burgundy is one of the many unfortunate examples of rivers that have been subjected to successive engineering works involving the 'training' of the river and excessive sediment mining. By combining HD LiDAR data with ancient maps, aerial photographs, and longitudinal profiles, we created age maps and we evaluated deposition and erosion in a long reach of the Loire River. This long-term approach provides the basis for a comprehensive analysis of the fluvial bed readjustment step by step through three different generations of management and uses.

Although the Loire River lost only 16% of the area of its active planforms between 1755 and 1848, it underwent an initial phase of significant erosion of its riverbed. One of the study's key contributions is highlighting the potential impact of seemingly 'harmless' groynes that were discontinuous and likely triggered a rapid change in river processes by trapping part of the sandy load. We therefore suppose that the disruption originated from the change in secondary channels, which played a significant role in maintaining the river's equilibrium. It also appears that the volume eroded in the newly embanked bed changed little over the following period (1848–1953), whereas deposition on the channel margins increased significantly. The second stage of embankment, involving longitudinal levees, coincided with a period of high flooding. Together, these factors probably accentuated bed incision due

Table 2
Examples of mining volume and sediment transport volume.

River	Length (km)	Period	Extractions (m^3 y^{-1})	Transport (m^3 y^{-1})	Ratio Extractions / Bedload vol	Source
Stony Creek, California, United-States	8	post 1963	260,000 min 730,000 max	20,000	13–36,5	Kondolf and Swanson, 1993
San Luis Rey River, California, United-States	8		300,000	6500	46	Kondolf and Larson, 1995
Humptulips River, Washington, United-States	19	25 years	30,400 min 12,800 max	1900 min 5000 max	2,6–16	Collins & Dunne, 1989
Wynoochee River, Washington, United-States	15	19 years	24,700	3800	6,4	Collins and Dunne (1989)
Wooler Water, England			32,153	145	222	Sear and Archer, 1998
Tyne, England			92,791	6514	14	Sear and Archer (1998)
Swale, England			458,715	1667	275	Sear and Archer (1998)
Breamish, England			40,000	317	126	Sear and Archer (1998)
Wisloka, Poland		1950–1960	2,1 × 10^6 total		500	Osuch (1968), cited in (Wyzga, 2007)
Lower Manawatu River, New-Zealand	37	1965–1985	191,000	76,500 min 99,400 max	1,9-2,5	Page and Heerdegen (1985), cited in Collins and Dunne (1989)
Tordera, Spain		1958–1987	3 × 10^6 min (total)		40	Rovira et al., 2005
Meuse River, The Netherlands	250	1916–2021	240,000	5000–63,400	>100	Barneveld et al., 2025
Tagliamento, Italy			1.1 × 10^6	150,000	7,3	Surian et al., 2009
Parma River, Italy		20th – 21st c.	3.3 × 10^6 (total)	15,000–31,000	50–100	Brenna et al., 2021
Ardèche, France		20 years	4 × 10^6 (total)	1.5 × 10^6 total	2,7	Malavoi et al. (2011)
Drôme, France		1930–1990	2.5 × 10^6 max	350,000	7	Malavoi et al. (2011)
Chalakudy, India	27	1980–2005	5.6 × 10^6 t	10,000 t	56	Padmalal et al., 2008; Sreebha and Padmalal, 2011
Periyar, India	50	1980–2005	4 × 10^6 t	80,000 t	50	Padmalal et al. (2008); Sreebha and Padmalal (2011)
Muvattupuzha, India	35	1980–2005	1.09 × 10^6 t	20,000 t	54,5	Padmalal et al. (2008); Sreebha and Padmalal (2011)
Meenachil, India	24	1980–2005	80,000 t	10,000 t	8	Padmalal et al. (2008)
Manimala, India	20	1980–2005	170,000 t	20,000 t	8,5	Padmalal et al. (2008)
Pamba, India	27	1980–2005	180,000 t	30,000 t	6	Padmalal et al. (2008)
Achankovil, India	38	1980–2005	490,000 t	10,000 t	49	Padmalal et al. (2008)
Mekong River, Cambodia		2016–2019	24–59 × 10^6 t	3.7–10.9 × 10^6 t	1600	Bravard et al., 2013; Hackney et al., 2021

to an increase in specific stream power. The final period (1953–2023) experienced pronounced bed degradation, which the increase in lateral erosion may have limited. However, we demonstrated that the huge quantities of sand and gravel mined within the active bed widely exceeded the annual sediment load on the Loire River, which is sediment-supply limited. Even if mining was stopped at the end of the 1980s, bed incision continues, with a lower rate than during the second half of the 20th century.

Recovering a new fluvial equilibrium poses significant challenges: the Loire River has large areas of riparian forest, many of which are Priority Habitats of Community Interest under the European Union Habitats Directive, and the entire fluvial corridor is a Natura 2000 site. Protecting populations from floods is also important, as the floodplains in Burgundy play a key role in controlling flooding in the downstream urbanised valley. In the absence of large tributaries upstream of the Allier River junction, and due to the extremely limited longitudinal bedload input, the lateral supply of sediment is crucial along the Loire River in Burgundy. This observation not only supports riverbank restoration by removing rip-raps and, where possible, embankments, but also a detailed geomorphic evaluation. The forthcoming partial removal of the Uxeloup levee in 2027 has been made possible by the area's low vulnerability to flooding and a lengthy consultation process with the local population. This will enable in the future a thorough evaluation of the effectiveness of the restoration work.

CRediT authorship contribution statement

Emmanuèle Gautier: Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Evan Mesmin:** Writing – original draft, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **Clément Virmoux:** Writing – original draft, Methodology, Investigation, Data curation. **Thomas Dépret:** Writing – original draft, Investigation, Formal analysis. **Ségolène Saulnier-Copard:** Resources, Investigation. **Gilles Arnaud-Fassetta:** Writing – original draft, Investigation. **Guillaume Martins:** Resources, Investigation. **Valentine Fichet:** Visualization, Investigation. **Stéphane Braud:** Resources.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Emmanuele Gautier reports financial support was provided by French National Research Agency. Evan Mesmin reports financial support was provided by LTSER Zone Atelier Loire. Emmanuele Gautier reports financial support was provided by Labex DynamiTe. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2026.110415.

Data availability

Data will be made available on request.

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