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1 **Can lateral mobility be restored along a highly domesticated**
2 **low-energy gravel-bed river?**

3
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19 **Abstract**

20 Fluvial engineering works such as weirs, rip-rap, groynes, and dykes have constrained for
21 decades and more the lateral mobility of rivers, one of the key drivers of aquatic and riparian
22 diversity. Preserving or restoring a sufficient space for river mobility has therefore become a
23 major river management focus. Because the success and relevance of management actions are
24 conditioned by the level of energy and sediment supply of rivers, such actions are generally
25 considered unsuitable for low-energy rivers. However, some low-energy rivers have

26 numerous ancient engineering works along their length, especially bank protections,
27 suggesting a potential capacity for bed migration. In this context, it is essential to determine to
28 what extent planform dynamics is disturbed, and if lateral mobility can be restored. Herein, a
29 case study was done on a 146 km stretch of the low-energy meandering gravel-bed Cher
30 River (France). The goal of the study was to estimate the remnant shifting capacity, identify
31 the factors controlling the location and intensity of lateral erosion, determine the potential for
32 preserving and restoring lateral mobility, and examine management measures that could be
33 implemented to this end. For that, field surveys, analysis of existing databases, aerial
34 photographs, and laser imaging detection and ranging digital elevation model (LiDAR DEM)
35 data were combined. The study revealed a strong longitudinal fragmentation of the river, with
36 most of it laterally constrained due to the presence of anthropogenic structures such as bank
37 protections, former gravel pits in the alluvial plain, bridges, and weirs. The river is now
38 composed of a string of constrained and unconstrained reaches, and the space available for
39 river shifting has been dramatically reduced. Due to these fluvial engineering works and
40 anthropogenic legacies, the potential for lateral movement of the riverbed, and, therefore,
41 diversification of riparian and aquatic habitats, is limited. Furthermore, lateral mobility could
42 be preserved or restored only for very short sections of the river. It is therefore highly unlikely
43 that good ecological status could be achieved on the entire river corridor through removal of
44 bank protections. Nevertheless, a possible solution could be combining bank protection
45 removals with a series of gravel augmentations close to each other.

46

47 **Keywords**

48 Lowland river; Erodible corridor; Anthropogenic constraints; Stream restoration; Meander
49 migration; Ecological status

50

51

52 **Highlights**

- 53 • Potential for lateral mobility on a low-energy gravel bed river is estimated
- 54 • A strong decrease in the shifting capacity due to anthropogenic constraints is found
- 55 • A short cumulative length of river along which the lateral mobility is still possible
- 56 • Good ecological status is not achievable on the entire river corridor even with rip-rap
57 removal

58

59

60 **1. Introduction**

61 Due to their widespread presence on Earth, their tremendous attraction for human societies,
62 and because their morphology reflects changes occurring from basin to reach scale, rivers are
63 among the landscape units most influenced by anthropogenic constraints. In response to these
64 constraints, river forms and processes have been heavily altered, causing homogenization of
65 their aquatic and riparian habitats, degradation of their ecological quality, and
66 impoverishment of the social and ecosystem services they provide (Basak et al., 2021;
67 Borgwardt et al., 2019; Culhane et al., 2019; Dudgeon, 2019; Dudgeon et al., 2006; Ekka et
68 al., 2020; Elozegi et al., 2010; Florsheim et al., 2008; Vörösmarty et al., 2010). Increasing
69 awareness of this damage has led to attempts to mitigate the negative effects of these
70 alterations, and an era of river repair has begun (Downs and Gregory, 2004; Fryirs and
71 Brierley, 2016). Indeed, many countries have enacted legal frameworks aimed at protecting or
72 improving the ecological status of rivers. One of the most striking examples is the Water
73 Framework Directive (WFD), adopted in 2000 by the European Union, that commits member

74 states to achieve good ecological status of rivers, and to implement restoration measures to
75 achieve this status (European Parliament and Council, 2000; Grizzeti et al., 2017).

76 From the Neolithic to the Middle-ages, anthropogenic constraints were mainly, if not
77 exclusively, indirect, consisting of the modification of land cover in watersheds and
78 floodplains, thereby affecting water and sediment fluxes and connectivity from hillslopes to
79 rivers (Brown et al., 2018; Hoffmann, 2015; Hoffmann et al., 2010; Notebaert and
80 Verstraeten, 2010). Over the last millennium, local constraints, most involving direct
81 modification of river channels and acting at segment or reach scales, have strengthened, first
82 with the development of weirs connected to mills from the 11th century, followed by the
83 channelization and/or rectification of river courses from the 19th century, then the exponential
84 installation of large dams and massive gravel mining areas in riverbeds and floodplains from
85 the mid-20th century (Brown et al., 2018; Downs and Piegay, 2019; Lehner et al., 2011; Maas
86 et al., 2021; Overeem et al., 2013; Rinaldi et al., 2005; Surian, 2021; Wohl, 2020). These
87 local constraints have resulted in a dramatic loss of lateral mobility of rivers (Dépret et al.,
88 2017; Fremier et al., 2014; Friedman et al., 1998; Reid and Church, 2015), even though lateral
89 mobility is one of the main drivers of aquatic and riparian habitat diversity (Choné and Biron,
90 2016; Florsheim et al., 2008; Stanford et al., 2005; Tockner et al., 2010; Williams et al.,
91 2020). For altered rivers, achieving good ecological status may be impossible without
92 restoration of a sufficient space to allow rivers to move laterally.

93 Restoration of space for lateral movement is grounded on process-based principles through
94 which rivers are believed to be able to self-restore, namely to recover fluvial landforms and
95 functions, with minimal anthropogenic intervention (Beechie et al., 2010; Ciotti et al., 2021;
96 Fryirs and Brierley, 2021). Self-restoration actions promote longitudinal and cross-wise
97 topographic as well as grain size heterogeneity, which increases the diversity of habitats,
98 particularly aquatic habitats (Gaeuman, 2012; Yarnell et al., 2006; Hauer et al., 2018;

99 Staenzel et al., 2020). Moreover, shifting riverscape mosaic processes guaranteed by the
100 lateral mobility of rivers allow rejuvenation of riparian succession associated with pulse
101 disturbance (e.g., Diaz-Redondo et al., 2018; Gonzalez del Tanago et al., 2021; Hauer et al.,
102 2016; Stanford et al., 2005; Tockner et al., 2010). These approaches are especially relevant
103 when natural lateral constraints and socio-economical issues (SEIs) in the floodplain are rare,
104 and when river energy and bedload are high (Kondolf, 2011). Nonetheless, these approaches
105 also could be appropriate for low-energy rivers, providing that the bed material is mobile and
106 alluvial material is sufficiently erodible to allow such rivers to be inherently behaviourally
107 sensitive (Fryirs, 2017).

108 At the reach scale, river mobility often is determined through reconstruction of
109 planimetric trajectory evolution (Khan and Fryirs, 2020; Piégay et al., 2005; Reid and
110 Brierley, 2015). For low-energy rivers, such methods can be unsuitable where lateral
111 anthropogenic constraints occur that may block channel movement, causing channel
112 responsiveness to be underestimated. Bank protection on such rivers often are not archived,
113 and they may be difficult to determine in the field unless a careful survey of the bed is carried
114 out at low flow (Dépret et al., 2017). Disentangling the natural and anthropogenic drivers
115 responsible for the weak planform shifting of low-energy rivers may, therefore, be
116 challenging. Such disentangling is yet crucial because it influences river responsiveness
117 appraisal and the design of preservation or restoration strategies, acting on forms or processes,
118 and depending on the trade-off between the timescale needed for recovery and the timescale
119 desired by managers. Determining to what extent lateral mobility can be restored along highly
120 domesticated low-energy gravel-bed rivers requires first examining if lateral processes are
121 still active, and if so to what extent, and whether there is enough space for river shifting.

122 To answer these questions, a case study was done on a 146 km stretch of the Cher
123 River (France), for which the long-term anthropogenic influence on planform displacements

124 as well as the potential for self-restoration of lateral dynamics have been demonstrated on
125 several short discrete reaches (8–12 km) (Dépret et al., 2015, 2017, 2021; Vayssière et al.,
126 2016, 2020). The aims of this study were to estimate the remnant shifting capacity, to identify
127 the factors controlling the location and intensity of lateral erosion, to determine the potential
128 for preservation and restoration of lateral mobility, and to examine the management measures
129 that could be implemented to this end. Therefore, a methodological framework was developed
130 combining (1) thorough field surveys and preexisting databases to identify the constraints on
131 lateral mobility and the current SEIs in the floodplain; (2) geographic information systems
132 (GIS) analysis aimed at reconstructing the planimetric evolutionary trajectory of the river
133 from aerial photographs, to quantify the available space for river shifting with and without
134 lateral constraints and/or SEIs, and to compute some of the main factors assumed to control
135 retreat rates (specific stream power, curvature, lateral constraints, availability of the coarse
136 bed-material load); and (3) statistical analysis to determine how these factors influence the
137 occurrence and intensity of lateral erosion.

138

139

140 **2. Characteristics of the study reach**

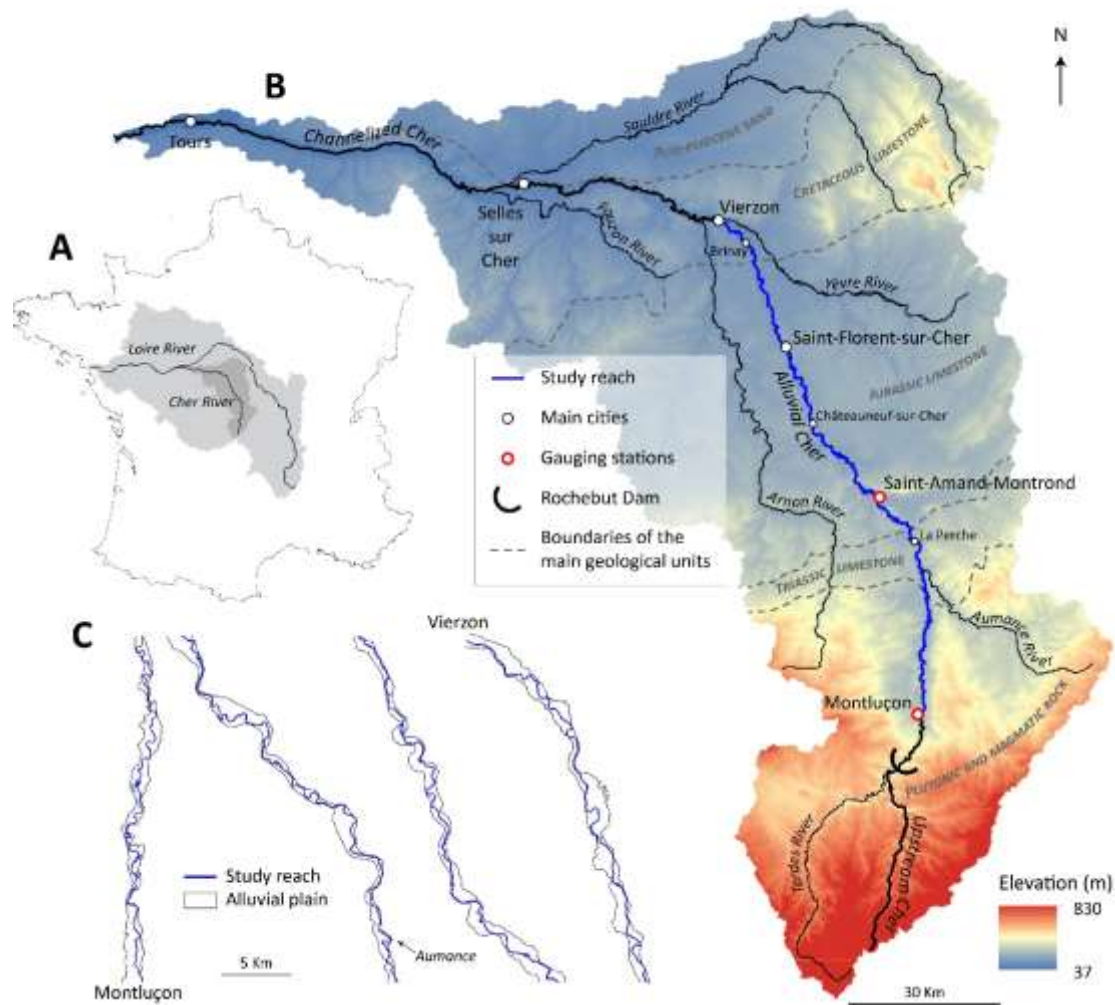
141 After leaving its source at 713 m above sea level, the Cher River mainly flows through gorges
142 across steep slopes or in deep valleys with a very narrow floodplain (upstream Cher in Figure
143 1). The upstream section of the river is located at the northwest end of the low-altitude
144 mountainous Massif Central, which mainly consists of crystalline and metamorphic rocks
145 (Larue, 1981, 2011). After 63 km, the Cher alluvial plain begins (Alluvial Cher in Figure 1)
146 and the river becomes single thread with a meandering pattern developed over recent
147 millennia (Vayssière et al., 2020). After first occupying the Tertiary graben of Montluçon,
148 which continues for 45 km to the confluence with the Aumance River (Larue, 1981, 2011;

149 Simon-Coinçon et al., 2000), the river then crosses the sedimentary domain of the Parisian
150 Basin, where it joins the Loire River at 38 m asl. The study reach extends over 146 km,
151 between Montluçon at the beginning of the Alluvial Cher, and Vierzon at the junction with
152 the Yèvre River, one of the main tributaries of the Cher River (Figure 1). With a surface
153 median sediment diameter (D_{50}) of around 15–45 mm and a mean specific stream power of 20
154 $W m^{-2}$ (calculated from the width of the active channel formed by flow channels and
155 unvegetated bars) for a discharge not exceeded 99% of the time (close to bankfull discharge),
156 it is a low-energy river with coarse gravel (Dépret, 2014; Dépret et al., 2015).

157 The alluvial infill is organized into two or three main stratigraphic levels. The base of
158 the infill is composed of sand, gravel, and pebble, while the upper part consists of overflow
159 deposits of clay, silt and sand (Dépret, 2014; Lablanche et al., 1994; Manivit et al., 1994;
160 Larue, 1994; Turland et al., 1989c). A predominantly sandy layer is frequently interspersed
161 between these two levels. Because of this composite structure and the coarse nature of the
162 material, the banks are highly erodible (Dépret et al., 2015, 2017). Moreover, bed mobility
163 occurs over several days per year (Dépret et al., 2015, 2017).

164 The rainfall-evaporation regime of the Cher is essentially influenced by western flows.
165 High water occurs in winter, generally in February, and low water occurs in summer,
166 typically in August. On the upstream part of the middle course of the river, the hydrological
167 regime, in particular for low flow, is partly artificialized since the construction of the
168 Rochebut Dam at the beginning of the 20th century. Along the 146 km stretch studied, along
169 with the Aumance River, the Cher River receives contributions from one major tributary
170 (Figure 1).

171



172

173 Figure 1 - Location of the study reach. A: The Cher River watershed within French territory.

174 B: The study reach in the Cher River watershed. C: Diagram of the course of the Cher River
 175 and its alluvial plain.

176

177

178 3. Materials and methods

179 3.1 Reconstruction of bank retreat rates and length since the mid-20th century

180 The bank retreat rates and length of the river were reconstructed from aerial
 181 orthophotographs from the Institut Géographique National (IGN; National Geographic
 182 Institute) dated 1950s and 2016 using ArcGIS 10.6 (Table 1). For the 1950s, photographs

183 were dated 1954, 1959, and 1960, and they are subsequently referred to using the 1959 date
184 alone, for which the majority of the active channel was digitized.

185 Quantification and characterization of bank retreat rates and length were based on the
186 identification and digitization of the active channel at each date. Between the two successive
187 dates, all areas occupied by perennial vegetation (islands and alluvial plain) at date t and
188 active channel at date $t+1$ were considered eroded.

189

190 Table 1 – Date, scale, resolution (m) and rectification error (m) of aerial photographs used in
191 reconstruction of bank retreat rates and length of the Cher River since the mid-20th century.

Date	Scale	Resolution	Rectification error
1954–1960	1/25000–1/27000	0.5	3.3
2016		0.2	3.2

192

193

194 Two main types of errors are inherent with the method used to generate the data
195 (Gaeuman et al., 2003). The first corresponds to the rectification error (E1). The errors
196 reported by the IGN for the 1959 and 2016 images are 2 m and 1 m, respectively. These errors
197 are equal to the root mean squared error, which “summarizes the continuous deviations
198 encountered over the ground surface (rather than at a few specific points)” (IGN, 2016). The
199 second type of error corresponds to the active channel digitizing error (E2). It corresponds to
200 the maximum uncertainty in locating the active channel boundary under overhanging forest.
201 Obtained by iterative digitizing of its outline (Gurnell et al., 1994), it is equal to plus or minus
202 3 m for 1959 and 2016. Since these two errors are independent of each other, the total error,

203 equal to 3.3 m for 1959 and 3.2 m for 2016 (Table 1), was obtained by calculating the square
204 root of the sum of the square of these errors (Taylor, 1997): $Totalerror = \sqrt{E1^2 + E2^2}$.

205 Once total error was determined, eroded areas were delineated. For each date, a buffer
206 zone with a width equal to twice the value of the total error was created along each of the
207 banks. The buffer zones of the active channel at two successive dates were then merged,
208 denoting the spatial extent within which any change was considered unproven. Finally, any
209 eroded polygon that was entirely within this merged buffer zone was excluded from the
210 analysis. Conversely, when polygons exceeded the merged buffer zone, the change was
211 considered proven and these polygons were retained. From these final eroded polygons the
212 normalised retreat rates were computed at 50 m spaced cross-sections positioned
213 perpendicular to the centerline of the active channel (ratio of retreat rate to the active channel
214 width at the initial date expressed per year) (Roux et al., 2015). The normalised retreat rates
215 were calculated for both banks combined and for concave banks alone. As there were no
216 major changes in the river course, the longitudinal position of the cross-sections in 1959 and
217 2016 was determined from an origin located at the level of the Glacerie footbridge, in
218 Montluçon. In addition, a certain number of river sections where gravel mining has led to an
219 artificial widening of the bed were excluded from the analysis. Next, from the 50 m spaced
220 cross-sections, the percentage of river length affected by lateral erosion was quantified every
221 km. Finally, the longitudinal pattern of retreat rates and of the percentage of river length
222 affected by lateral erosion were examined.

223

224 **3.2 Evaluation of lateral constraints and space potentially available for channel** 225 **shifting**

226 Natural and anthropogenic structures, both present and from 1959, that directly constrain the
227 potential lateral mobility of the river were characterized at each of the 50 m equidistant cross-

228 sections previously described. For natural constraints, digitized 1:50,000 scale geological
229 maps from the Bureau de Recherches Géologiques et Minières (BRGM; French Geological
230 Survey) were used (Debrand-Passard et al., 1977a, 1978; Lablanche, 1984, 1994; Manivit and
231 Debrand-Passard, 1994; Obert et al., 1997; Turland et al., 1989a, 1989b). The maximum
232 space available for channel shifting in absence of anthropogenic constraints was assigned to
233 the location of the present and recent alluvium (fy/fz). Any cross-section with at least one
234 bank abutting hillslope, alluvial or colluvial fan, or terrace was considered laterally
235 constrained (Fryirs et al., 2016). Because of the relative spatial uncertainty of the boundaries
236 between the alluvium and the hillslopes, fans or terraces, it was considered that abutting
237 occurred when the distance between the river and the natural constraints is less than 50 m.
238 The same approach was applied for concave banks only.

239 Four types of anthropogenic constraints were distinguished: bank protection, bridges,
240 weirs, and gravel pits installed in the alluvial plain. If gravel pits could have been classified as
241 a SEI, their presence also is a direct constraint on lateral mobility to the extent that lateral
242 displacement of the river would be completely blocked for decades in the case of capture by a
243 pit. For this reason, they were classified as a constraint to lateral mobility rather than as a SEI.

244 Bank protection works were identified and their positions surveyed by GPS in the field
245 during the 2018 summer low flow. Bank protection works in 2018 located on sections of
246 river not eroded between 1959 and 2016 were considered to be present in 1959. Bridges and
247 weirs were identified and located from 1959 and 2016 aerial photographs and from the
248 *Référentiel des Obstacles à l'Écoulement* (Repository of obstacles to flow, ROE;
249 <https://www.sandre.eaufrance.fr/atlas/srv/fre/catalog.search#/map>). On cross-sections located
250 within 50 m of bridges and weirs, the river was considered constrained. Finally, gravel pits
251 currently present in the alluvial plain were digitized by Cossalter (2011) from 2005 aerial
252 photographs. This digitization was updated in the present work using 2016 aerial photographs.

253 Similarly, 1959 gravel pit locations were digitized from 1959 aerial photographs. Any cross-
254 sections located within 50 m of a gravel pit were considered constrained.

255 Moreover, all current SEIs encountered in the floodplain, except those related to
256 agricultural lands, also were integrated into the GIS analysis. Taking SEIs into consideration
257 allows determination of the space potentially available for river shifting in the absence of
258 lateral constraints, specifically in the case of restoration of lateral mobility. For each cross-
259 section, the distance to the nearest SEI was measured, but SEIs were not prioritized. The raw
260 data used were from the IGN Topo database. The GIS layers including important buildings,
261 industrial buildings, cemeteries, sports grounds, water reservoirs, pylons, pipes of any kind,
262 electricity lines, electrical substations, marshalling areas, stations, railroads, and the Berry
263 Canal were used without modification. For the ‘undifferentiated buildings’ layer, polygons
264 representing buildings judged non-essential were excluded (shelters, huts, etc.). Finally, the
265 ‘primary road’ layer was kept unchanged, whereas the ‘secondary road’ layer was selected
266 since roads and paths not accessing one of the objects listed above were excluded.

267 The extent of lateral constraints and/or SEIs in the floodplain was considered in two
268 distinct but complementary ways. First, the percentage of river length affected by the different
269 types of constraints and/or SEIs were quantified. We considered that a SEI is present along
270 the river when it is located <50 m from the closest bank. The percentage of river length
271 laterally constrained was calculated every km. In a second step, the space potentially available
272 for channel shifting was measured at each 50 m spaced cross-section after taking into account
273 the different types of constraints and/or SEIs. Here, all SEIs present in the floodplain were
274 considered. The constrained length and the space potentially available for channel shifting
275 were determined by considering both banks or just concave banks. Concave banks were the
276 focus because this is where most of lateral erosion occurs. Thus, in a relatively short timescale
277 (years to decades), and from the perspective of improving the ecological status of the river by

278 restoration of lateral erosion, the available floodplain space adjacent to this concave side is of
279 direct interest for river managers. Finally, visual examination and Hubert's segmentation
280 (Hubert et al., 1989; Hubert, 2000) were applied to determine the longitudinal pattern of (1)
281 the percentage of river length affected by the different types of constraints and/or SEIs, and
282 (2) the space potentially available for channel shifting.

283

284 **3.3 Factors controlling lateral erosion**

285 Bank retreat rates for the 1959–2016 period were related at different spatial scales to four of
286 the main potential controlling factors reported in the literature: specific stream power
287 (calculated for a discharge not exceeded 99% of the time) (e.g., Richard et al., 2005),
288 curvature (e.g., Furbish, 1988; Sylvester et al., 2019), lateral constraints (Dépret et al., 2017),
289 and the density of bars and alluvial riffles, used as an indicator of the coarse material
290 available for bedload, the availability of a sufficiently large load of mobile coarse sediment
291 being an indispensable condition for the self-maintenance of lateral mobility (e.g., Donovan et
292 al., 2021). The assumed trends are an increase in retreat rates and in the occurrence of lateral
293 erosion with an increase in each of these four factors.

294 First, the presence of any spatial correspondence between the longitudinal pattern of
295 retreat rates or the percentage of river length affected by lateral erosion on one hand, and the
296 longitudinal pattern of specific stream power, curvature, lateral constraints, and the density of
297 bars and alluvial riffles on the other hand was evaluated.

298 Second, at the scale of unconstrained cross-sections, the extent to which specific
299 stream power and curvature at the initial date differed between cross-sections with erosion
300 and cross-sections without erosion was examined. Then, for cross-sections subjected to
301 erosion only, correlations between retreat rates and specific stream power or local curvature

302 were calculated. In a second step, a Chi-square test was performed to determine the influence
303 of lateral constraints present in 1959 on the manifestation of lateral erosion.

304 Specific stream power was obtained using the formula: $\rho_w g Q S / w$, where ρ_w is the
305 density of water (1000 kg m^{-3}), g is the gravitational acceleration (9.81 m s^{-2}), Q is the
306 discharge ($\text{m}^3 \text{ s}^{-1}$), S is the bed slope (m m^{-1}), and w is the active channel width (m). The
307 specific stream power was determined for each 50 m equidistant cross-section using the low-
308 water line slope from the laser imaging detection and ranging digital elevation model (LiDAR
309 DEM) data of the Cher Valley (2011) and the 1959 active channel width. A discharge with
310 the same non-exceedance frequency (not exceeded 99% of the time) was used upstream and
311 downstream of the confluence with the Aumance River in order to make the two sub-reaches
312 comparable. It was equivalent to $90 \text{ m}^3 \text{ s}^{-1}$ for the upstream sub-reach (Montluçon reference
313 gauging station) and $190 \text{ m}^3 \text{ s}^{-1}$ for the downstream sub-reach (Saint-Amand-Montrond
314 reference gauging station), values similar to the bankfull discharge on each of the sub-reaches
315 ($85 \text{ m}^3 \text{ s}^{-1}$ upstream and $178\text{--}245 \text{ m}^3 \text{ s}^{-1}$ downstream) (Dépret, 2014).

316 Curvature was calculated locally at each cross-section. This corresponds to the angle
317 (in radians per m) between the centerline segment connecting the upstream cross-section and
318 the cross-section in question on the one hand, and the centerline segment connecting the
319 cross-section in question and the downstream cross-section on the other. The curvature was
320 then normalized against the width of the active channel to make comparable the sub-reaches
321 upstream and downstream of the Aumance junction ($\text{rad m}^{-1} \text{ m}^{-1}$). Lateral constraints in 1959
322 were identified as described in Section 3.2.

323 Bars, alluvial riffles, and rocky riffles were identified and their positions surveyed by
324 global positioning system (GPS) in the field during the 2018 summer low flow. During this
325 same campaign, the presence of bedrock in the bed (other than in the form of rocky riffles)
326 also was systematically surveyed. Thereby the length of the sections along which bedrock is

327 outcropping and the distance between the sections in question were acquired. However, these
328 sections are somewhat heterogeneous, since they include both sections of the river along
329 which the alluvium has been completely evacuated and sections where the bedrock outcrops
330 are laterally and/or longitudinally more or less discontinuous. Due to the different widths of
331 the river upstream and downstream of the confluence with the Aumance, the distance between
332 two successive units or the length of the bedrock sections was normalized against the width of
333 the river.

334

335 **3.5 Preservation and restoration of lateral mobility**

336 Herein, identification of river sections for which measures to preserve or to restore lateral
337 mobility could be undertaken is done. The main objective was to propose a synthetic image of
338 each of these sections that could be used by managers as a decision-making tool. The sections
339 likely to be most suitable for restoration of lateral mobility are those equipped with bank
340 protection, the only type of constraint that can be removed. The approach utilized included
341 three stages. First, sections presenting *a priori* a minor interest in terms of preservation or
342 restoration of lateral mobility were excluded (see paragraph below for detailed explanation).
343 Next, based on the remaining sections to be preserved, the intensity of retreat rates can be
344 explained from the values for tested controlling factors in 1959 using logistic regression
345 models. Finally, the generated models were applied using the values of controlling factors in
346 2016 to predict retreat rates for the sections to be preserved or restored. The various criteria
347 taken into account in this analysis were incorporated at an elementary level at the scale of
348 cross-sections spaced 50 m apart. The values finally retained at the scale of the considered
349 sections correspond to the mean or median of values informing the cross-sections encountered
350 on each section.

351 For preservation, sections with at least one of the following criteria were excluded:
352 maximum retreat rate in concave bank $<0.017 \text{ m m}^{-1} \text{ y}^{-1}$, length $<100 \text{ m}$, space potentially
353 available for channel shifting in concave bank $\leq 100 \text{ m}$, specific power in 2016 for a discharge
354 not exceeded 99% of the time $\leq 13 \text{ W m}^{-2}$. The use of a threshold value for retreat rates allows
355 the exclusion of sections without erosion between 1959 and 2016. This criterion appears to be
356 essential because a section without erosion in recent decades is unlikely to present lateral
357 erosive activity in the future. The chosen threshold of $0.017 \text{ m m}^{-1} \text{ year}^{-1}$ corresponds to the
358 value for which the performance of the logistic regression model used to explain and predict
359 retreat rates at the section scale was optimized. In addition, this threshold allows the focus to
360 be exclusively on the most historically active reaches. The section length and the space
361 potentially available for channel shifting criteria were set so that the manifestation of lateral
362 erosion could ensure a sustained and long-lasting injection of coarse sediments into the active
363 channel. The selected length of 100 m corresponds to the median of the length of the eroded
364 sections between 1959 and 2016. The minimum envelope of 100 m retained for the space
365 potentially available for channel shifting makes it possible to ensure maintenance of erosion
366 over several decades without having to intervene to protect SEIs currently relatively far from
367 the bed. This value of 100 m corresponds to the most important bank retreat measured
368 between 1959 and 2016 along the study reach. The space potentially available for channel
369 shifting retained is equal to the median of the values on the concave side at the level of the
370 cross-sections present at each river section. Finally, the value of 13 W m^{-2} was chosen based
371 on monitoring of eroded banks between 2009 and 2013 at two sites located upstream and
372 downstream (kilometric point (kp) 26.45-37.1 and kp 61.4-69.9) of the confluence with the
373 Aumance (Dépret, 2014). The value of 13 W m^{-2} corresponds to the lowest specific stream
374 power for a discharge not exceeded 99% of the time at these different monitoring sites.

375 Once sections meeting at least one of these criteria were excluded, a logistic regression
376 model adapted to beta-type distributions (values taken by individuals of the dependent
377 variable between 0 and 1) was applied. For this, the GAMLSS package of R (Rigby and
378 Stasinopoulos, 2005) was used. Two regression models were constructed to explain the mean
379 and maximum concave bank retreat rates between 1959 and 2016 along the sections to be
380 preserved. The two independent variables ultimately selected were the maximum specific
381 power in 1959 for a discharge not exceeded 99% of the time and the mean local curvature in
382 1959. The generated models then were applied to predict retreat rates from the maximum
383 specific stream power in 2016 and the mean local curvature in 2016.

384 For restoration of lateral mobility, the considered sections include river sections with
385 concave bank protection extending from contiguous upstream and/or downstream river
386 sections without bank protection. As a result, there is a partial overlap between some sections
387 to be preserved and some sections that may be restored. The same exclusion criteria as
388 presented for the sections to be preserved were applied, with the exception of the criterion
389 relating to erosion. Two other criteria also were added: a very small amount of bank
390 protection (proportion of river length $\leq 20\%$ of the length of the sections or a length of bank
391 protection equal to 50 m, which corresponds to the minimum length of the protection since
392 the latter were informed on the scale of the cross-sections), and the presence of SEIs
393 immediately downstream of the sections equipped with bank protection. Logistic regression
394 models then were used to predict the mean and maximum erosion rates along each of the
395 sections identified as suitable for restoration.

396

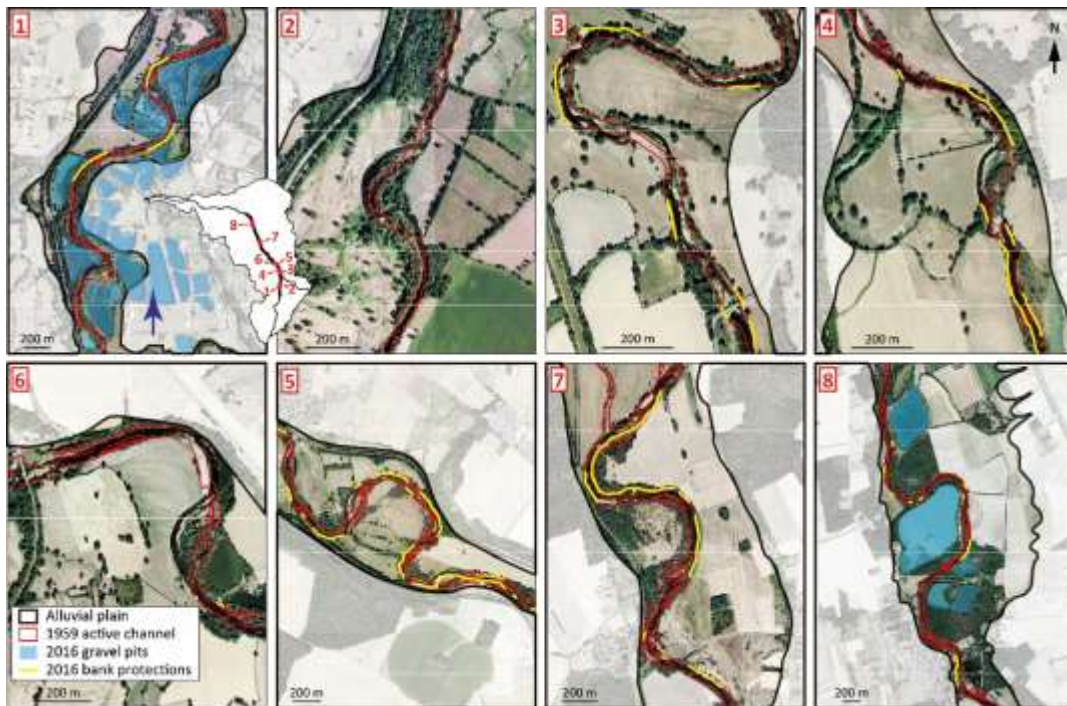
397

398 **4. Results**

399 **4.1 Characteristics of planimetric erosion between 1959 and 2016**

400 Mean and median bank retreat reached 0.0107 and 0.0067 $\text{m m}^{-1} \text{ year}^{-1}$, respectively, when
401 both banks were considered, and 0.012 and 0.0075 $\text{m m}^{-1} \text{ year}^{-1}$ when only concave banks
402 were taken into account (Figure 2). The retreat rates showed a main break at kp 70.15 when
403 both banks were considered and kp 69.8 when only concave banks were taken into account
404 (Figure 3A). Downstream of these points, retreat rates were on average 4.1 and 2.7 times
405 lower for both banks and concave banks, respectively. A less sharp break also occurred at kp
406 44.6. The reach upstream of this point had the highest retreat rates.

407
408

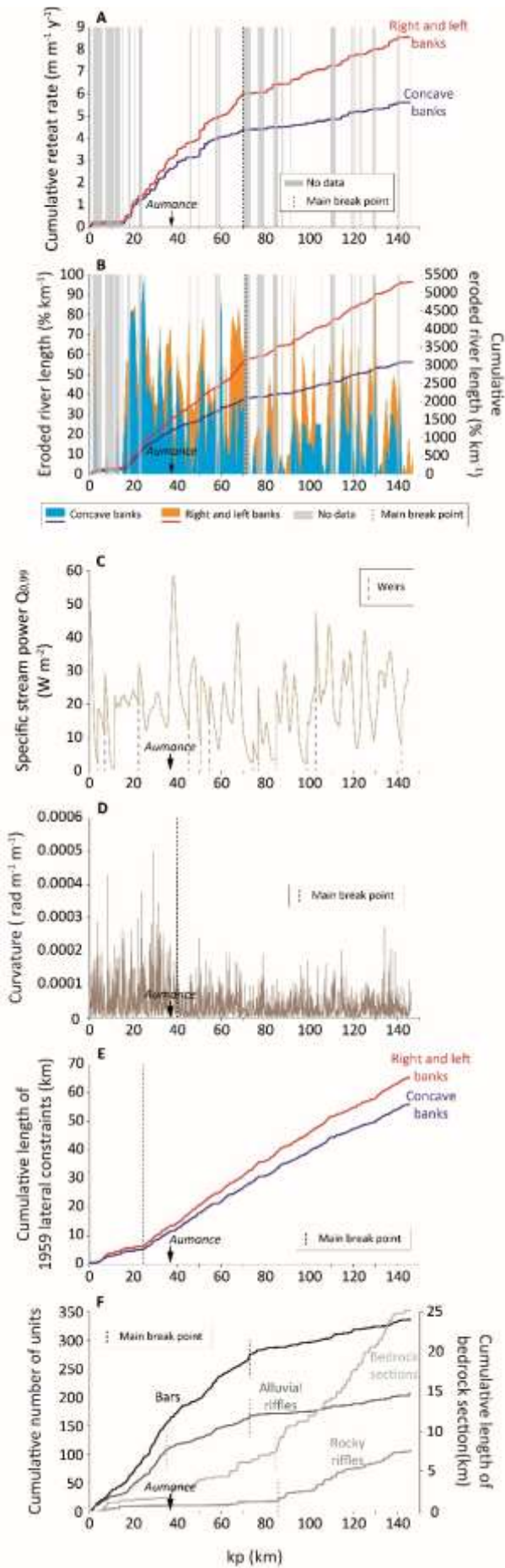


409
410 Figure 2 – Examples of active channel displacements from 1959 to 2016, and some of the
411 main current constraints of bed mobility. The reaches are numbered in ascending order from
412 upstream to downstream (with their location indicated between subfigures of reaches 1 and 2).

413

414 Between 1959 and 2016, bank erosion occurred on at least one bank along 380
415 discrete sections (comprising 40% of the river length). The 380 eroded sections have a mean-

416 median length of 130–100 m. The longitudinal pattern shows a main break at kp 71, very
417 close to the main break identified for the retreat rates (Figure 3B). Downstream of this point,
418 the percentage of eroded river length per km is 1.6–1.9 (mean-median) and 2.3–2.9 times
419 lower than upstream, when considering all banks or only concave banks, respectively.



421 Figure 3 – Longitudinal pattern of (A) planimetric retreat rates between 1959 and 2016, (B)
422 percentage of eroded river length and cumulative percentage of eroded river length between
423 1959 and 2016, (C) 2016 specific stream power for a discharge not exceeded 99% of the time,
424 (D) 2016 local curvature, (E) cumulative length of lateral constraints in 1959 and (F) bars,
425 alluvial riffles and rocky riffles in 2018.

426

427 **4.2 Bed confinement and space potentially available for channel shifting**

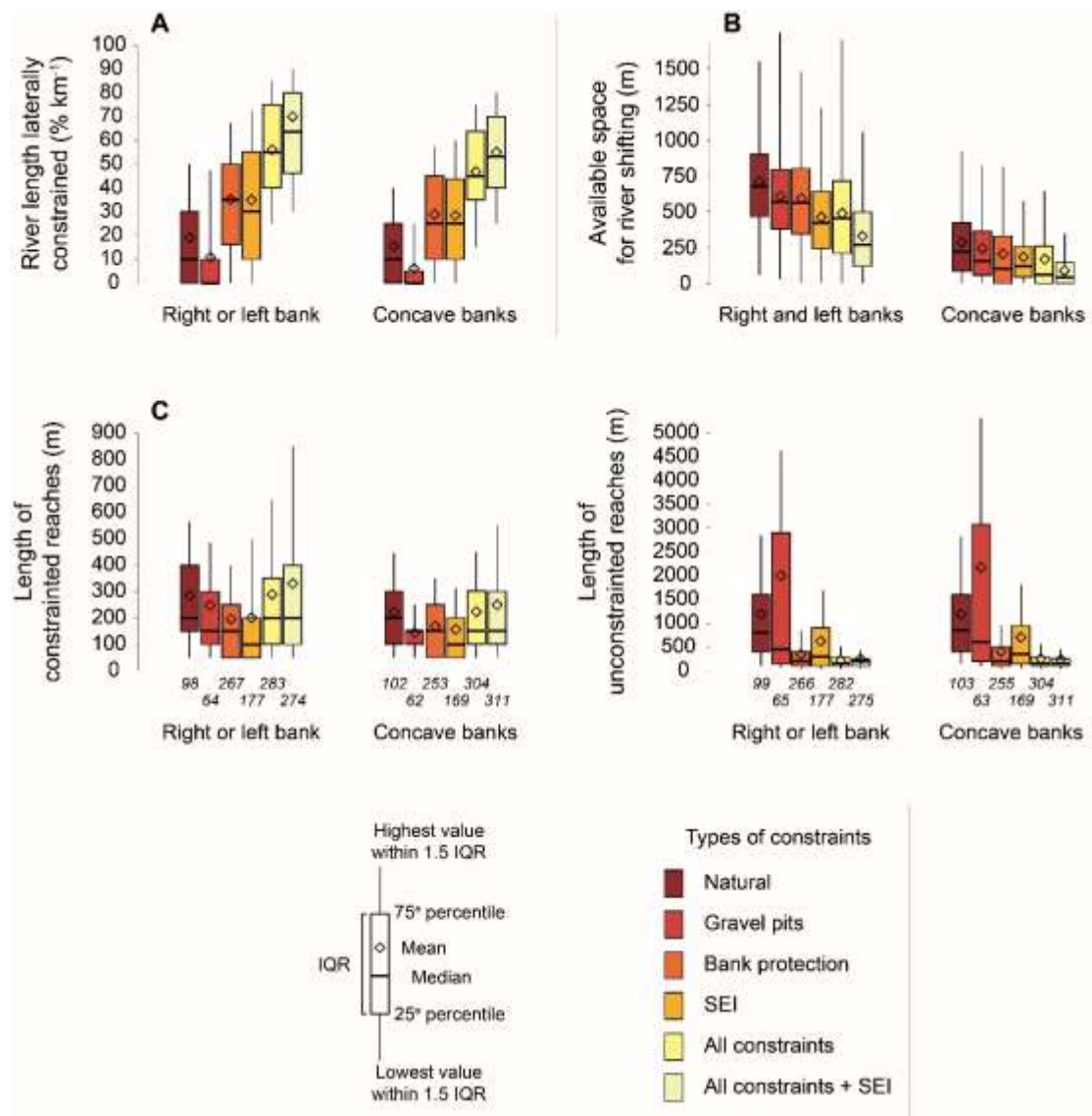
428 In this section, the extent to which engineering works, the legacy of human activities, and
429 SEIs identified in the valley bottom contribute to the current lateral confinement of the Cher
430 is examined (see examples in Figure 2). The initial focus is on the river length affected by
431 these constraints, then the focus shifts to the space potentially available for channel shifting.

432

433 **4.2.1 Description and quantification of laterally constrained river length**

434 The Cher River is a partially confined river based on criteria established by Fryirs et al.
435 (2016); 19.2% of its length is within 50 m of a terrace, alluvial or colluvial fan, or hillslope
436 (Figure 4A). Its mobility is, therefore, naturally constrained in many locations. If we add to
437 these natural constraints all the anthropogenic physical obstacles, the channel cannot shift
438 over 56% of its length (Figure 4A and Figure 5). Engineering works or legacy of human
439 activities are, therefore, responsible for a 2.9-fold increase in the length of the river along
440 which lateral erosion is now impeded. If we add to these ‘primary’ anthropogenic constraints
441 all of the SEIs identified in the alluvial plain <50 m from the banks, the length laterally
442 constrained reaches 63% (Figure 4A). Bank protection accounts for the largest proportion of
443 the constraints on lateral mobility, since they occupy 35.1% of the river length on either bank
444 (Figure 4A), followed by gravel pits at 10.9%. If only concave banks are considered, the
445 length along which the river cannot move laterally rises to 46.9% (compared with 15.6% for

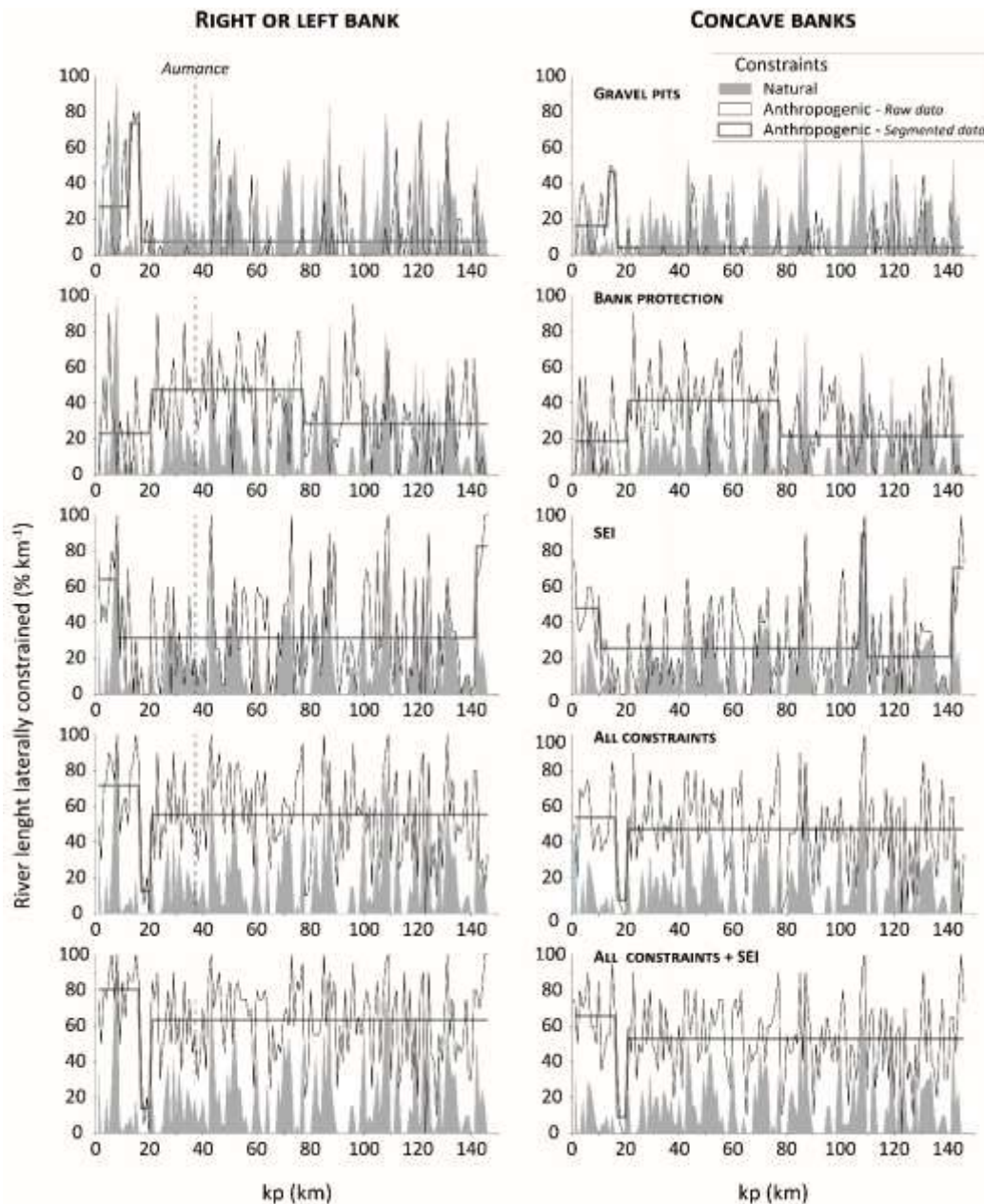
446 natural constraints alone) after all constraints are taken into account, and to 53.1% when SEIs
 447 are added (Figure 4A). Bank protection occupies 29% of the total length, and gravel pits
 448 account for another 6.1%.
 449
 450



451
 452 Figure 4 – Boxplots of the current percentage of river length laterally constrained as a
 453 function of types of lateral constraints (A), current maximum space available for channel
 454 shifting as a function of types of lateral constraints (B), and current length of constrained and
 455 unconstrained reaches as a function of types of lateral constraints (C).

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Despite important local variability, the longitudinal pattern of the different types of constraints tends to be stable (Figure 5). For gravel pits, four main sections are nevertheless visually identifiable (Figure 5). However, Hubert’s segmentation (Hubert et al., 1989; Hubert, 2000) indicates only the upstream section (Figure 5). Although bank protection is present along the entire length of the river, Hubert’s segmentation highlights a long central reach that is more densely equipped, extending from kp 21 to 76 (Figure 5). The reduced presence of bank protection in the first 21 km of the study reach could be because a significant proportion of the river length of this section had its course and banks artificially modified during gravel mining. With the exception of two short peaks at the upstream and downstream ends of the study reach, SEIs are distributed in a relatively regular and stable manner (Figure 5). The constraints or constraints plus SEIs show a similar pattern, with maximum values for the first 16 km, a short section with very few constraints and/or SEIs (kp 17–20), then stability for the rest of the length (Figure 5).



472

473 Figure 5 – Current longitudinal pattern of the percentage of river length laterally constrained
 474 as a function of constraint types. Segmented data were obtained by applying the Hubert
 475 method (Hubert et al., 1989; Hubert, 2000).

476

477 This foregoing reduction in river length along which bed migration is prevented is
 478 automatically accompanied by an increase in the longitudinal fragmentation of the bed
 479 (Figure 4C). The number of laterally unconstrained reaches is 99 when only natural
 480 constraints are considered, whereas it is 282 when all constraints are included. As a result, the

481 distance between two consecutive sections abutting against constraints decreases sharply;
482 1190–800 m (mean-median) with only natural constraints considered, compared with
483 227–150 m after incorporating anthropogenic constraints and 201–100 when SEIs are added
484 (Figure 4C). The length of laterally constrained sections varied much less; 285–200 m with
485 natural constraints, 290–200 m with all constraints and 330–200 m after incorporating all
486 SEIs (Figure 4C).

487 For concave banks alone, the number of sections without natural lateral constraints is
488 103 and 304 once anthropogenic constraints are incorporated (Figure 4C). The distance
489 between two consecutive constrained reaches is 1195–850 m with natural constraints alone,
490 255–150 m once all constraints are incorporated, and 220–150 m with additional
491 consideration of SEIs (Figure 4C). The length of constrained reaches is 220–200 m with
492 natural constraints, 224–150 m with all constraints, and 249–150 m after addition of SEIs
493 (Figure 4C).

494

495 **4.2.2 Space potentially available for channel shifting**

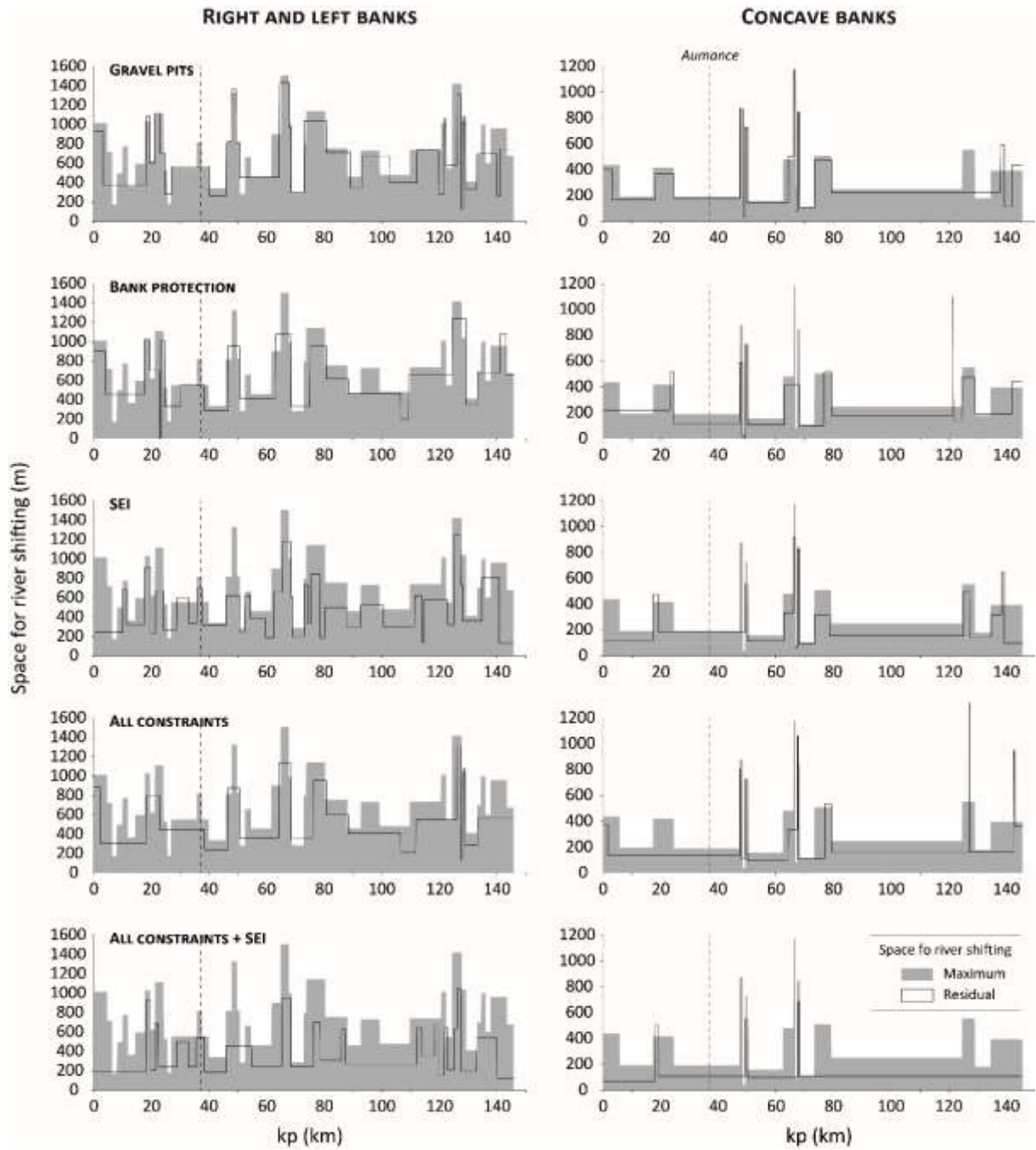
496 The alluvial plain width (i.e., the maximum space potentially available for channel
497 shifting) is 707–678 m (mean-median; Figure 4B), and slightly lower upstream of the
498 confluence with the Aumance River. However, the confinement index (ratio between the
499 width of the alluvial plain and the width of the active channel) is higher in this upstream reach
500 (18.3–17.6 vs. 14.3–13.7).

501 If all anthropogenic physical obstacles (bank protection, bridges, weirs, gravel pits) are
502 added to the natural lateral constraints, the space potentially available for channel shifting
503 decreases to 489–455 m (Figure 4B). This is equivalent to a reduction of 31–33%. After
504 taking into account both constraints and SEIs, the space potentially available for channel
505 shifting is only 330–267 m (i.e., a reduction of 53–61%; Figure 4B).

506 If we focus only on concave banks, the contraction of the maximum space potentially
507 available for channel shifting is even larger. The maximum envelope shrinks from 281–221 m
508 (mean-median) to 168–61 m when anthropogenic constraints are taken into account (i.e., a
509 reduction of 41–73%; Figure 4B). After incorporating SEIs, the maximum space potentially
510 available for channel shifting is then only 111–43 m, equivalent to a reduction of 61–81%
511 (Figure 4B).

512 Regardless of the type of anthropogenic constraints considered, the longitudinal
513 pattern of space potentially available for channel shifting remains relatively stable despite
514 significant local variations (Figure 6). Moreover, the integration of anthropogenic constraints
515 tends to homogenize this longitudinal variability.

516



517

518 Figure 6 – Current longitudinal pattern of the space potentially available for channel shifting
 519 as a function of the types of constraints. For the sake of readability, data have been
 520 ‘smoothed’ using Hubert’s segmentation method (Hubert et al., 1989; Hubert, 2000).

521

522 4.3 Factors controlling the intensity and location of lateral erosion

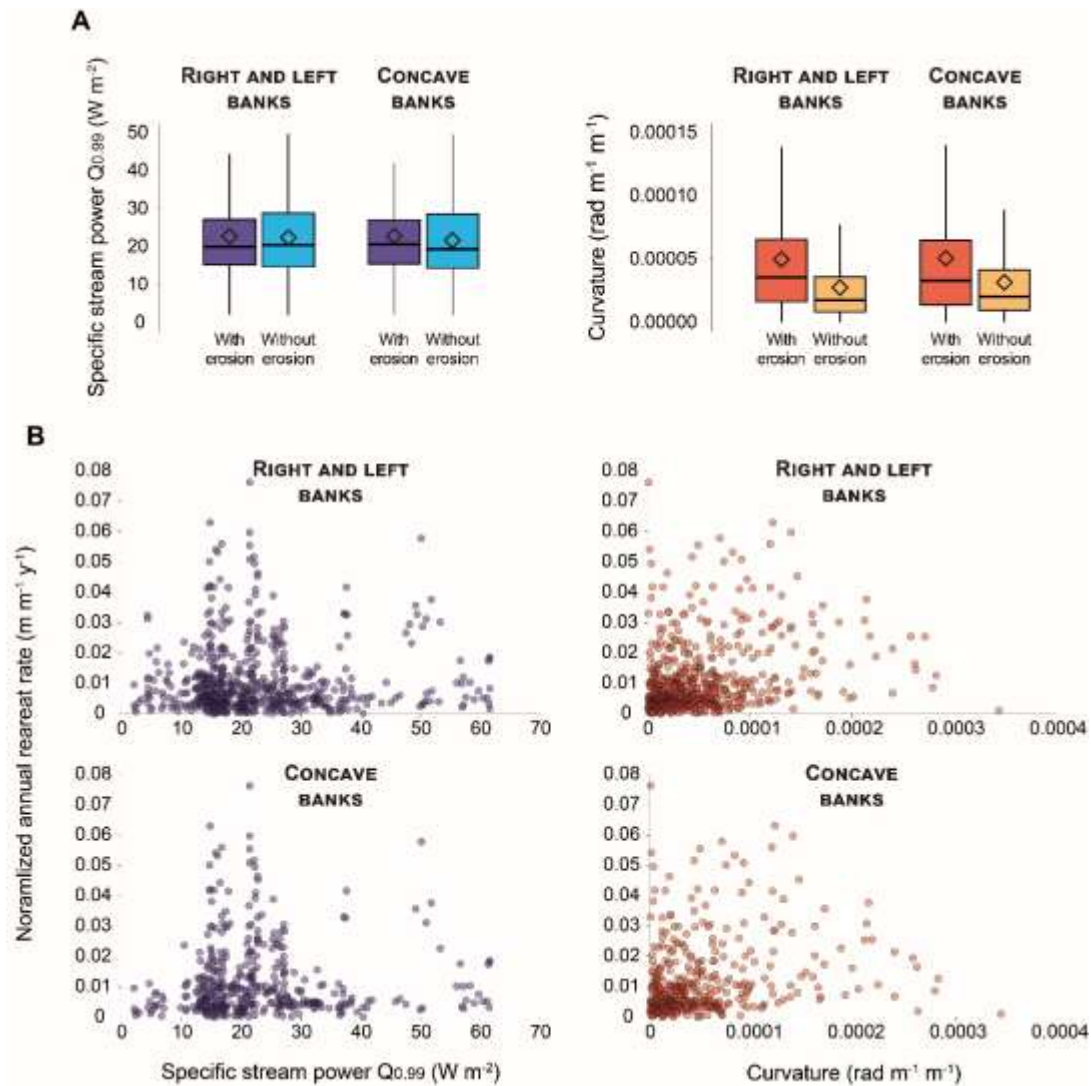
523 The longitudinal pattern of the specific stream power shows local variations that can
 524 be high, but no overall tendency to decrease or increase (Mann-Kendall test, $p > 0.1$; Figure

525 3C). One of the main causes of these variations is the existence of many weirs, which results
526 in a strong reduction of specific stream power in their reservoirs, and an even more marked
527 increase immediately downstream. The decrease in erosive activity observed from about kp
528 70 during the 1959–2016 period (Figure 3A, B) is, therefore, not the result of an associated
529 decrease in specific stream power. Regarding curvature, a main break is visible at kp 39.6,
530 just downstream of the junction with the Aumance River, with a two-fold diminution of
531 curvature values (Mann-Whitney test, $p < 0.05$; Figure 3D). This could explain the second
532 highest decrease in retreat rates, reported from kp 44.6. For lateral constraints in 1959, a
533 twofold decrease is observed downstream of the main break, located at kp 24.45 (Figure 3E).
534 On both sides of this point, lateral constraints are quite regularly distributed. There is
535 nevertheless an important uncertainty regarding the density of lateral constraints in 1959
536 along this upstream reach; most of this reach has been artificially redesigned due to gravel
537 mining in the 1970's, and it is not known to what extent bank protection was present before.
538 The reduced presence of bank protection in the first 24 km of the study reach could thereby
539 result from a significant proportion of the river length in this section having its course and
540 banks artificially modified during gravel mining. In any case, there is no spatial
541 correspondence between the longitudinal patterns of erosive activity during the 1959–2016
542 period and of lateral constraints in 1959 (or even in 2016, see Figure 5).
543 The 2018 longitudinal pattern of bars, alluvial riffles, rocky riffles, and bedrock sections
544 indicates two main reaches (Figure 3F); in the upstream reach, bars and alluvial riffles are
545 frequent, while rocky riffles and bedrock sections are rare, and this trend is reversed in the
546 downstream reach. For bars and alluvial riffles, the main break, located at kp 72.8 and 72.7,
547 respectively, is slightly downstream of the break in erosive activity (kp 70). The mean spacing
548 between bars and between alluvial riffles, therefore, increases from 6.3 to 23.8 bankfull
549 widths for the former and from 10.6 to 36.8 bankfull widths for the latter (Mann-Whitney test,

550 $p < 0.05$; Figure 3F). In addition, for alluvial riffles, the upstream reach can be divided into
551 two sub-reaches with a limit located at kp 34.9, with a mean spacing of 8.9 bankfull widths
552 upstream and 13.5 bankfull widths downstream (Mann-Whitney test, $p < 0.05$). For rocky
553 riffles, the break is located at kp 85.5 (Figure 3F). The mean spacing between rocky riffles
554 decreases significantly from upstream to downstream, from 110 to 13.8 bankfull widths
555 (Mann-Whitney test, $p < 0.05$). For bedrock sections, the limit is located at kp 84.5 (Figure
556 3F). Upstream, the mean length of bedrock sections and the distance between two consecutive
557 sections are 5.6 and 62 bankfull widths, respectively. Downstream, they are 9.6 and 23.4
558 bankfull widths.

559 Examined at the cross-section scale, the influence of specific stream power on the
560 manifestation of erosion appears to be absent; in the absence of lateral constraints and when
561 both banks are considered, the mean specific stream power is 22.7 W m^{-2} and 22.3 W m^{-2} for
562 cross-sections with and without erosion, respectively (Mann-Whitney test, $p = 0.83$; Figure
563 7A). Focusing on concavities alone, the mean stream power is 22.8 W m^{-2} and 21.7 W m^{-2}
564 (Mann-Whitney test, $p = 0.1$; Figure 7A). Conversely, local curvature probably exerts a
565 significant influence since they are 1.8 times higher on cross-sections with erosion when both
566 banks are considered and 1.6 times higher when considering concave banks alone (Mann-
567 Whitney test, $p < 0.000001$; Figure 7A). Finally, for cross-sections subjected to erosion, no
568 correlation was detected between the normalized retreat rate on the one hand, and the specific
569 stream power or the local curvature on the other hand (Figure 7B).

570



571
 572 Figure 7 – Comparison of specific stream power for a discharge not exceeded 99% of the time
 573 and of curvature between eroded and non-eroded unconstrained cross-sections (A). Relation
 574 between the normalized annual retreat rate and the specific stream power for a discharge not
 575 exceeded 99% of the time and the curvature of eroded cross-sections (B).

576
 577 Lateral constraints play a major role in the expression of lateral erosion. Indeed, there
 578 was a statistically significant difference in erosion between constrained and unconstrained
 579 banks (Chi-square test, $p < 0.00001$; Table 2); 67% of cross-sections with erosion are located
 580 where constraints are absent, while 60% of cross-sections without erosion are located where
 581 constraints are present. Furthermore, 72% of cross-sections subjected to lateral constraints

582 escape erosion, and the proportion drops to 46% for cross-sections not influenced by lateral
 583 constraints. If we consider only concave banks, the role of constraints appears even more
 584 significant since 83% of eroded cross-sections are located where constraints are absent and
 585 90% of cross-sections subjected to lateral constraints escape erosion.

586

587 Table 2 – Presence-absence of lateral constraints and lateral erosion on cross-sections spaced
 588 50 m apart. Statistical differences were determined using the Chi-square test.

	Lateral constraints	No lateral constraints	<i>p</i> -value
Right or left bank			
Erosion	260	524	<0,00001
No erosion	656	442	
Concave banks			
Erosion	79	717	<0,00001
No erosion	703	383	

589

590

591 **4.5 Preservation and restoration of lateral mobility: priority elements**

592 The developed logistic regression models provide a relatively good explanation of the
 593 concave bank retreat rates between 1959 and 2016 on sections prioritized for preservation of
 594 lateral mobility (Table 3 ; Figure 8). Just over 50% of the variance in retreat rates is explained
 595 by the maximum specific stream power and the mean local curvature along the sections, with
 596 both variables playing a significant role (Table 3). The equations for the prediction of the
 597 maximum (Eq.1) and the mean (Eq.2) retreat rates are:

598 Logit (Maximum annual normalized retreat rates) =
 599 $-4.107 + 0.02562 \times \text{maximum specific stream power} + 3728 \times \text{mean curvature}$
 600 (Eq.1)

601
 602 Logit (Mean annual normalized retreat rates) =
 603 $-5.279 + 0.03772 \times \text{maximum specific stream power} + 4784 \times \text{mean curvature}$
 604 (Eq.2)

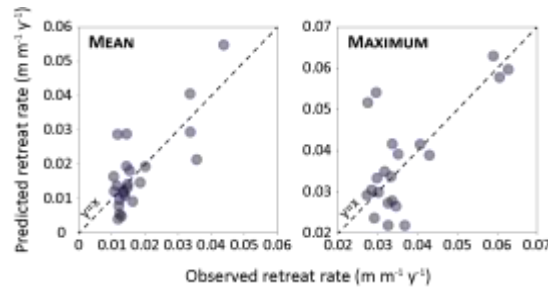
605
 606
 607 Table 3 – Logistic (logit) regression coefficients explaining the maximum annual normalized
 608 retreat rates ($\text{m m}^{-1} \text{ year}^{-1}$) and the mean annual normalized retreat rates ($\text{m m}^{-1} \text{ year}^{-1}$) as a
 609 function of maximum specific stream power (W m^{-2}) and mean curvature ($\text{rad m}^{-1} \text{ m}^{-1}$) ($R^2 =$
 610 Coefficient of determination).

	Coefficient	Standard error	t	p-value	Pseudo-R ² (Cox and Snell)
Logit (Maximum annual normalized retreat rates)					
Interception	-4.107	0.1678	-24.48	***	
1959 maximum specific stream power	0.02564	0.005298	4.84	***	0.53
1959 mean curvature	3728	1602	2.33	*	
Logit (Mean annual normalized retreat rates)					
Interception	-5.279	0.2499	-21.13	***	
1959 maximum specific stream power	0.03772	0.007577	4.98	***	0.52

611

612 p -values *** = 0, * = 0.01, . = 0.05.

613

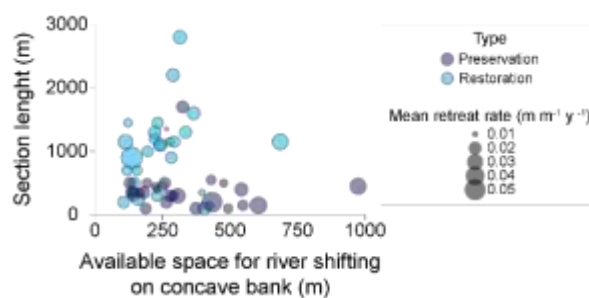


614

615 Figure 8 – Relations between predicted and observed retreat rates for concave banks between
 616 1959 and 2016 along unconstrained sections identified as a priority for preservation of lateral
 617 mobility.

618

619 If the preservation and restoration sections have similar predicted retreat rate values,
 620 they show a clear difference in the length and the space available for river shifting, with
 621 preservation sections significantly having shorter length but larger space for river shifting
 622 (Figure 9).



623

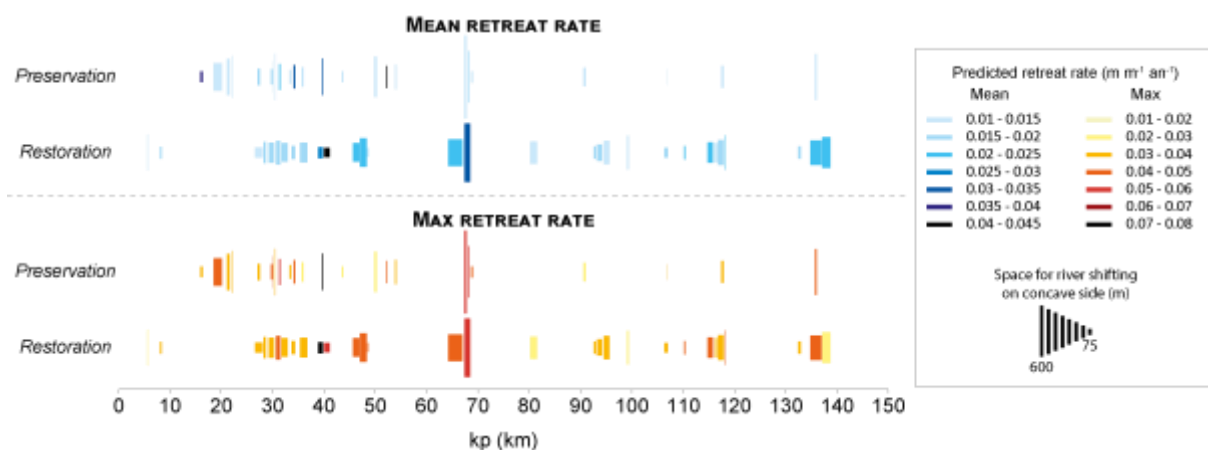
624 Figure 9– Length versus available space for river shifting on the concave side, and predicted
 625 mean concave retreat rates along sections identified as a priority for preservation or
 626 restoration of lateral mobility.

627

628 Twenty-four sections of the river are of particular interest in terms of preserving
 629 lateral mobility (Figure 10). They extend over a total length of 9.3 km (6.3% of the length of
 630 the study reach). Most are located upstream, between kp 15.9 and 69 (20 sections out of 24
 631 and 84.3% of the total length of the sections), consistent with the decrease in erosive activity
 632 identified downstream of kp 70 (Figure 10).

633 After elimination of sections of less interest from the point of view of restoring river
 634 lateral dynamics, 30 sections remain from the initial 112, extending over 69.2 km, 45.9% of
 635 which have bank protection (Figure 10). These 30 sections represent a total length of 28.6 km,
 636 or 19.7% of the length of the study reach, and bank protection occupies 11.3 km, namely
 637 39.3% of the total length of the 30 sections. Compared with the conservation sections, the
 638 restoration sections are more evenly distributed along the study area (Figure 10), but there is
 639 also a high concentration of these restoration sections upstream; 12 of the 30 restoration
 640 sections are located between kp 26.6 and 48.6, over 20 km (15.1% of the study reach length).
 641 Moreover, these 12 sections represent 76.9% of the total length of the restoration sections.

642



643
 644 Figure 10 – Localization and characteristics of sections identified as a priority for
 645 preservation or restoration of lateral mobility. The predicted retreat rates were computed from
 646 equations in Table 3, with 2016 values for specific stream power and curvature.

647

648

649 **5. Discussion**

650 **5.1 Performance of logistic regression models**

651 The logistic regression models developed for reaches of high interest for preserving or
652 restoring lateral mobility explain slightly more than 50% of the variance in the maximum or
653 mean lateral erosion between 1959 and 2016 (Pseudo-R² in Table 3). Other controlling factors
654 not considered here (maximum specific power in 1959 and mean curvature in 1959) should,
655 therefore, be considered. They were not included in the model due to insufficient data. The
656 first such controlling factor is heterogeneity of bank strength, driven by bank height and
657 morphology, the type of vegetation covering banks (e.g. Ielpi and Lapôtre, 2020; Horton et
658 al., 2017; Micheli and Kirchner, 2002; Micheli et al., 2004; Piégay et al., 2003), and the spatial
659 heterogeneity of the alluvial infill material (e.g., Bogoni et al., 2017; Constantine et al., 2009;
660 Fisk, 1944, 1947; Güneralp and Rhoads, 2011; Motta et al., 2012). The second controlling
661 factor is the spatial variability in the bedload supply, a major driver of lateral mobility in
662 meandering streams (Ahmed et al., 2019; Constantine et al., 2014; Donovan et al., 2021;
663 Dunne et al., 2010; Rollet and Piégay, 2013). The third controlling factor is the bed material
664 D₅₀, theoretically conversely correlated with bank retreat (Bledsoe and Watson, 2001; Richard
665 et al., 2005). The fourth controlling factor is the effect of lateral constraints on contiguous
666 river sections devoid of such constraints, where bank erosion can be inhibited/prevented or,
667 conversely, promoted. The fifth controlling factor is gravel mining in the riverbed that can
668 increase lateral erosion by destabilizing banks (Schumm et al., 1984; Simon, 1989; Simon and
669 Rinaldi, 2006; Watson et al., 2002), and the presence of undetected blocks of former bank
670 protection located in the riverbed that can conversely slow bank retreat (Dépret et al., 2017).

671 Compared with similar analyses that attempted to explain and/or predict lateral erosion
672 of meandering rivers computed from sequential aerial photographs through statistical

673 modelling at decadal or multi-decadal scales, the percentage of explained variance in the
674 current study can be considered more satisfactory. For example, in four reaches of the Rio
675 Grande River, U.S., Richard et al. (2005) obtained coefficients of determination (R^2) between
676 0.43 and 0.93 explaining absolute migration rates with parameters representing flow energy
677 used alone (either the mobility index of Bledsoe and Watson [2001], channel forming-
678 discharge, total stream power, or specific stream power) or in combination with a planform
679 index. For 18 sites located in British Columbia and Alberta, Canada, Nandon and Hickin
680 (1986) explained 70% of the variance of the volume of laterally eroded sediment from the
681 outer banks using river size and grain size at the bank toe. In a regional analysis of migration
682 rates of single-thread rivers mainly located in the Rhône River basin, France, Alber and
683 Piégay (2017) explained 45% of the variability in migration rates using total stream power.

684 From a predictive and, thus, an operational point of view, one of the main drawbacks
685 of the proposed models is that they cannot take into account the role of future hydrological
686 variability, and, thus, the effects of ongoing climate change (Buffin-Bélanger et al., 2015).
687 Long-term predictive values of retreat rates estimated through the logistic regression models
688 could therefore be largely under- or overestimated depending on flood regime evolution. The
689 only study dealing with evolution of the flood regime in the Loire Basin according to different
690 climate change scenarios focused on maximum annual daily discharge with a 10-year return
691 period (Moatar et al., 2010a, 2010b). Because of a too high level of uncertainty, it is
692 impossible to predict future changes. Nevertheless, it is worth mentioning because lateral
693 erosion on the Cher River is mainly controlled by low-magnitude events (Dépret et al., 2015),
694 hence any changes in the occurrence frequency and/or duration of such common floods could
695 strongly affect lateral mobility.

696

697 **5.2 The issue of self-maintenance of river course migration**

698 In this study, reaches with a significant shifting potential for preservation or
699 restoration were located and prioritized (Figure 10). However, self-maintenance of mobility
700 was not considered, even though it is a key influencer of the success of restoration operations
701 (Kondolf, 2011). Self-maintenance is mainly dependent on sufficient bedload mobility and
702 supply (Ahmed et al., 2019; Constantine et al., 2014; Donovan et al., 2021; Dunne et al.,
703 2010). This supply, whether from upstream or from local reinjection resulting from bank
704 erosion, promotes point bar fattening, which then increases tractive forces toward the opposite
705 concave banks, ultimately sustaining lateral erosion processes (Dietrich and Smith, 1983,
706 1984; Dietrich et al., 1979; Legleiter et al., 2011). Local reinjection of coarse sediment
707 following bank erosion is considered a major driver of lateral instability (Braudrick et al.,
708 2009). This material is indeed partly redistributed onto the immediate downstream point bar
709 (Pyrce and Ashmore, 2003a, 2003b, 2005), the development of which promotes lateral
710 erosion on the opposite bank as previously explained. This creates a negative feedback loop,
711 with bed migration maintained from near to far in the downstream direction. A reduction in
712 coarse alluvial stock should thus be associated with a weakening of lateral erosive dynamics.

713 It was found that the Cher River could be separated into two sub-reaches with very
714 distinct profiles in terms of the abundance of bars and alluvial riffles (Figure 3F). Whereas
715 upstream of kp 73, bars and alluvial riffles are very frequent, they become very scarce
716 downstream in favor of rocky riffles and bedrock reaches (Figure 3F). If we consider that this
717 dichotomy reflects a marked difference in available bed-material load, and, thus, in bedload,
718 and knowing that the specific stream power and curvature are not higher downstream (Figure
719 3C), it would be expected that the self-maintenance of the lateral erosion processes should be
720 much more limited along the downstream sub-reach. This hypothesis would be confirmed, on
721 the one hand, by retreat rates and the percentage of eroded river length from 1959 to 2016 that
722 were significantly higher upstream of about kp 70 (Figure 3A and Figure 3B), and on the

723 other hand, by the percentage of river length with lateral constraints that does not increase
724 downstream (Figure 3E). Following this reasoning, restoration of lateral mobility by
725 removing bank protection would be less suitable on the downstream sub-reach.

726 This assumed lack of bedload in the downstream sub-reach could be the result of
727 excessive sediment mining in the riverbed from the 1960s to the 1980s (Dépret, 2014; Dépret
728 et al., 2021). However, these sediment extractions also were very significant in the upstream
729 sub-reach (Dépret, 2014). This explanation must, therefore, be at least partially rejected. The
730 lower availability of coarse sediment downstream could, thus, be due to inheritance, and be
731 explained by the decrease in the size and volume of coarse alluvium downstream. There is
732 evidence to support this postulation. First, the percentage of particles larger than 5 mm
733 (roughly the subsurface D_{50} (Dépret, 2014) in the alluvial infilling decreases significantly
734 from upstream to downstream. Above 40% between Montluçon and the Aumance junction
735 (from kp 0 to kp 37.1), it is ~25% at Saint-Amand-Montrond (kp 61.4), 15% at Châteauneuf-
736 sur-Cher (kp 88.85), 10% at Saint-Florent-sur-Cher (kp 108.8), and 5% at Brinay (kp 136.4),
737 slightly upstream of Vierzon (Figure 1) (BRGM-CETE de Lyon, 1979; Debrand-Passard et
738 al., 1977b; Turland et al., 1989c). A report on the survey of potential sand and gravel deposits
739 in the alluvial infill in the Cher River valley from Saint-Amand-Montrond also mentions a
740 fining of gravel between Saint-Amand-Montrond and Vierzon (kp 61.4 and 145.7) (Bos and
741 Trautmann, 1970). A similar downstream trend would apply to the thickness of coarse
742 sediment. The findings of another study aimed at identifying deposits of exploitable
743 aggregates in the alluvial plain of the Cher (CETE of Rouen, 1972) provide information in
744 particular, on the average thickness of coarse alluvium between La Perche (kp 45.55) and
745 Saint-Florent-sur-Cher (kp 108.8). Referred to as ‘gravelly sands’, their thickness would be
746 4.2 m between kp 45.55 and 55, 4.1 m between kp 55 and 69, 3.6 m between kp 69 and 87,
747 and 2.3 m between kp 87 and 105.2. These data tend to confirm the existence of a relatively

748 limited coarse alluvial stock in the downstream sub-reach. For this reason, riverbed mining
749 could have had a greater impact here than in the upstream sub-reach. More broadly, this
750 reduced stock of coarse sediment limits the reinjection of coarse sediments into the riverbed
751 following bank erosion, with a consequent limited capacity for self-maintenance of lateral bed
752 instability compared to the upstream sub-reach.

753 On the Cher River, the mechanisms for self-maintenance of bed migration dynamics
754 also are most likely partially impeded due to livestock access to the riverbed. Along the study
755 area, most of the proximal alluvial plain surface is devoted to sheep or cattle grazing. This has
756 the effect of inhibiting or even preventing the development of vegetation on convex bars. Yet,
757 such vegetation encroachment processes promote concave bank erosion (Bywater-Reyes et
758 al., 2018; Zen and Perona, 2020). Thus, free access of livestock to the river likely diminishes
759 lateral mobility of the Cher River.

760 Finally, regarding the removal of bank protections, one of the main uncertainties
761 regarding the morphological evolution of sections relies on the sustainability of erosive
762 activity. Such management actions would imply bed widening, and thus a likely decrease in
763 specific stream power that could in turn lead to a decrease in the potential for lateral erosion.

764

765 **5.3 Lateral constraints, sediment connectivity and lateral mobility**

766 The mean and median length of constrained and unconstrained concave bank reaches
767 were calculated to be 224–150 m and 255–150 m, respectively, hence decadal-scale bedload
768 displacement velocities would be between 30 and 300 m per decade (Dépret et al., 2021). This
769 means that coarse sediment connectivity between successive unconstrained reaches would
770 likely be very limited, if not absent, at the decadal or even multi-decadal scale. This also
771 implies that at this timescale, sediment reinjected into the bed by lateral erosion in a given
772 unconstrained reach would not be deposited along the unconstrained reach immediately

773 downstream, and, would, therefore contribute little or nothing to the downstream maintenance
774 of lateral dynamics. Furthermore, whereas lateral constraints, particularly bank protection,
775 obviously prevent lateral erosion on reaches along which they are present, they would also
776 indirectly limit the intensity of lateral erosion on reaches along which they are absent by
777 reducing the sediment supply.

778

779 **5.4 Prospects for improving the ecological status of the Cher River**

780 Along the study reach, the ecological status of the river according to the WFD
781 reference is considered poor upstream of the confluence with the Aumance River and
782 moderate downstream (<https://qualite-riviere.lesagencesdeleau.fr/>; Figure 1). However, the
783 WFD requires that good ecological status be reached. In the context of general coarse
784 sediment starvation in rivers, resulting in damaged ecological functioning, river restoration
785 strategies aimed at increasing the coarse sediment supply either by gravel augmentation or
786 through re-establishing space for channel shifting are becoming more popular (e.g., Arnaud et
787 al., 2017; Bravard et al., 1999; Biron et al., 2014; Gaeuman, 2012; Kondolf, 2011;
788 Rheinheimer and Yarnell, 2017; Rinaldi et al., 2011, Staenzel et al., 2020; Williams et al.,
789 2020). Such actions promote longitudinal and cross-wise topographic as well as grain size
790 heterogeneity, both of which increase the diversity of habitat, particularly aquatic habitat
791 (Gaeuman, 2012; Yarnell et al., 2006; Hauer et al., 2018; Staenzel et al., 2020). Moreover,
792 shifting riverscape mosaic processes caused by lateral mobility of rivers facilitates riparian
793 succession associated with pulse disturbance (e.g., Diaz-Redondo et al., 2018; Gonzalez del
794 Tanago et al., 2021; Hauer et al., 2016; Stanford et al., 2005; Tockner et al., 2010).

795 If it is assumed that the unsatisfactory ecological status of the Cher River is at least
796 partly the result of the strong direct anthropogenic constraints exerted on the lateral mobility
797 of the river, no improvement in ecological status is likely to be achieved without restoration

798 of this mobility. However, it has been revealed that such restoration only concerns a relatively
799 limited number of sections (Figure 10). Furthermore, the low bedload velocity (Section 5.3)
800 indicates that most of the coarse sediment re-injected in the riverbed by lateral erosion would
801 remain at a decadal scale in close proximity to the eroded banks. This implies that only a local
802 increase in the heterogeneity of aquatic and riparian habitat could be achieved through such
803 injections. The effects of management actions aimed at restoring lateral mobility would, thus,
804 be spatially limited. Therefore, questions remain to what extent such local diversification
805 could impact the biodiversity of constrained sections located upstream and downstream of
806 restored sections. With this in mind, there appears to be little possibility of achieving good
807 ecological status along the entire length of the river through removal of bank protection.
808 Furthermore, uncertainty remains on the timescale needed for the morphological effects of the
809 removal of protections to be felt. Because the erosive process is relatively slow it could take
810 several years, or even longer, before these actions achieve the desired effect. Such a time-
811 scale does not comply with the needs of managers to obtain ecological improvements in the
812 short term. Due to these spatial and temporal limitations, it might be more productive to
813 implement a combination of rip-rap removal with a series of gravel augmentations close to
814 each other.

815

816 5.5 Applicability and reproducibility of the method for meandering gravel-bed rivers

817 The main principles guiding our methodological approach involve some key elements
818 of previous work through which are identified and delineated the alluvial plain, the historical
819 trajectory of the river course, the zone potentially prone to lateral erosion in the near future
820 (upcoming decades), as well as SEIs in order to preserve an erodible corridor in the alluvial
821 plain (e.g., Malavoi et al., 1998; Piégay et al., 1997, 2005; Biron et al., 2014). However, our
822 methodological framework differs from these previous studies; in addition to enabling the

823 detection of river sections along which bank erosion, and thus an erodible corridor, could be
824 preserved, it also focuses on whether and where lateral mobility could be restored. The
825 different steps of the method, replicable regardless of the energy of meandering gravel-bed
826 rivers, are (1) assessment of bed mobility over recent decades; (2) identification of the lateral
827 constraints (natural and anthropogenic) to lateral mobility and SEIs in the floodplain; (3)
828 quantification and location of their effects on the available space for river shifting; (4)
829 determination of the relationship (through regression) between retreat rates and their
830 controlling factors along river sections without constraints; (5) delimitation of sections where
831 lateral constraints could be removed; (6) application of the regression developed in step 4 to
832 reaches identified in step 5; (7) prioritisation of preservation and restoration sections
833 according to a combination of criteria defined in accordance with river managers (i.e.,
834 predicted retreat rates, length of river sections, and width of the remaining space for river
835 shifting).

836 This approach, when applied alongside information on bedload transport and
837 availability, could facilitate defining the most suitable and sustainable restoration actions in
838 terms of sediment budgeting and sediment exchanges between the river and its floodplain.
839 Along any river corridor, three management options are available and can be combined
840 depending on the intensity of constraints and SEIs, and the potential of the river for lateral
841 mobility: removal of constraints, gravel augmentation, and combining these two. While all
842 three options are suitable in the case of sediment starvation, and thus enable the enhancement
843 of aquatic habitats (e.g., Chardon et al., 2021; Mörtl and De Cesare, 2021), removal of lateral
844 constraints is the only measure that simultaneously promotes the improvement of riparian
845 habitats (e.g., Larsen et al., 2006). For this reason, removal of lateral constraints is thus a
846 relevant management action regardless the existence of any sediment deficit. More broadly,
847 such removal is also directly related to other issues since it can promote, for instance, a local

848 and downstream reduction in flood hazard by increasing water storage in the floodplain
849 during high-flow periods (Arnaud-Fassetta et al., 2009; Benito and Vázquez-Tarrío, 2022).
850 Finally, the robustness of our approach could be enhanced by integrating into the erodible
851 corridor different flooding zones as proposed by Biron et al. (2014) in their definition of
852 freedom space, since the ecological integrity of rivers is also governed by maintenance of the
853 surface and subsurface hydrological connectivity between riverbed and floodplain (Amoros
854 and Bornette, 2002).

855

856 **6. Conclusions**

857 The results of the current study allowed the very strong fragmentation of the Cher
858 River to be highlighted and quantified. Most of the river is laterally constrained due to the
859 presence of anthropogenic structures such as bank protection, former gravel pits in the alluvial
860 plain, bridges, and weirs. Today, the Cher River is composed of a string of constrained and
861 unconstrained reaches, and its available space for channel shifting has been strongly reduced.
862 Because of the fluvial engineering works and anthropogenic legacies, most of the potential for
863 lateral movement of the riverbed, and, therefore, diversification of the riparian and aquatic
864 habitat, has been lost. Due 1) to the very low proportion of the river length with lateral
865 mobility that could be preserved or restored, such restoration can only be done by removal of
866 bank protection where possible, 2) to the very likely local effects of restoration of the lateral
867 mobility, and assuming that the unsatisfactory ecological status of the Cher River is at least
868 partly the result of the strong, direct anthropogenic constraints exerted on the lateral mobility
869 of the river, the probability that a good ecological status can be achieved along the entire river
870 length by removal of bank protection is very low. For these different reasons, implementation
871 of rip-rap removal combined with a series of gravel augmentations close to each other could
872 help toward achieving good ecological status along the entire length of the Cher River.

873 This research has expanded the understanding of how the morpho-sedimentary
874 functioning of a low-energy, gravel-bed river can be impaired by current and past direct
875 anthropogenic constraints, and how to determine the river's recovery potential. However,
876 characterizing the factors controlling the diversity of biotopes and biocenoses through the
877 hydrosedimentary dynamics of such rivers remains challenging. On these rivers, and unlike
878 high-energy rivers, morphogenic processes occur at a relatively reduced intensity and at
879 moderate velocities. For this reason, the effects of direct anthropogenic constraints on the
880 degree of habitat heterogeneity and biodiversity may be much less pronounced than for high-
881 energy rivers. Conversely, the morpho-sedimentary response time of the system to the
882 removal of these constraints could be relatively long. The links between alteration of
883 hydrosedimentary dynamics and biotope degradation, therefore, require further clarification.

884

885

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893

894

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