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4 Legacy sediments in a European context: the example of 5 infrastructure-induced sediments on the Rhône River 6

7 **Sophia Vauclin^{1*} • Brice Mourier¹ • Hervé Piégay² • Thierry Winiarski¹**

8 ¹Université de Lyon, UMR5023 Laboratoire d'Ecologie des Hydrosystèmes Naturels et Anthropisés,
9 Université (LEHNA) - ENTPE, 3, rue Maurice Audin, 69518 Vaulx-en-Velin, France

10 ²Université de Lyon, UMR 5600 Environnement Ville et Société (EVS) - ENS, 15 parvis René Descartes,
11 69342 Lyon Cedex 7 Lyon, France

12 * [Sophia Vauclin : sophia.vauclin@developpement-durable.gouv.fr](mailto:sophia.vauclin@developpement-durable.gouv.fr)

13

14 **Abstract:**

15 The concept of legacy sediments (LS) as sediments periodically produced by anthropogenic
16 disturbances has been introduced in the early 2010s and has been increasingly used since then,
17 primarily in the USA. It is a key concept to characterize river corridors health and design relevant
18 restoration schemes. Surprisingly, examples of legacy sediments in European rivers remain scarce in
19 the literature, despite the long history of human influences in this part of the world. In this viewpoint
20 paper, we argue that while land-use changes within upstream basins seem to be mostly responsible for
21 legacy sedimentation along downstream river sections in New World countries like the USA or Australia,
22 reach-scale engineering is the main driver of legacy sedimentation along large Alpine European rivers
23 during the Anthropocene era. We give an example of LS induced by navigation infrastructures (groynes
24 and lateral training walls) present along the Rhône River downstream of Lyon (France), and assume
25 that analogous LS might exist in most engineered rivers. Those infrastructure-induced sediments differ
26 from the classic examples of American LS in terms of formation mechanisms and characteristics, which
27 leads us to suggest a broadened definition of legacy sediments in order to make the concept more
28 applicable to the European context.

29 **Introduction:**

30 The consequences of anthropogenic landscape modifications in river catchments have been of
31 increasing concern in the last few decades (Magiligan, 1992; Brooks and Brierley, 1997; Lang et al.,

32 2003, Surian et Rinaldi, 2003; Dotterweich, 2008; Macklin et Lewin, 2008; Williams et al., 2014; Poepl
33 et al., 2017). In the process, the idea of anthropogenic sediments emerged and has been progressively
34 conceptualized under the term of “legacy sediment” (LS). The expression was introduced by Novotny
35 (2004) to describe copper contaminated sediments and was then applied to a variety of context without
36 a clear definition. James (2013) first suggested a precise characterization of LS, mainly based on studies
37 about historical floodplain sediments in the eastern USA (Magiligan, 1992; Brooks and Brierley, 1997;
38 Peck et al., 2007; Walter et Merritts, 2008; Merritts et al., 2011). He defines legacy sediments as deposits
39 generated episodically by human disturbances in a watershed. Said disturbances, however, only
40 comprise of land-use changes such as deforestation, agriculture development or mining upstream from
41 the observed river corridor. This definition is particularly suited to the context of the New World territories
42 (The USA, Australia, New-Zealand, etc.) that underwent drastic land-use changes following the
43 colonization by European settlers. James (2013) acknowledges that his definition can also apply to
44 European geomorphology, but mostly related to older land-use changes such as pre-historic gullying
45 (Dotterweich, 2005; Vanwalleghen et al., 2006; Dotterweich, 2008). The term “legacy sediment” is
46 actually rarely used in this context, being often restricted to Anthropocene era although this can be fully
47 discussed and questioned.

48 Wohl (2015) suggested another definition of legacy sediments as “those for which the location, volume
49 and/or presence of contaminants result from past [i.e. not only the Anthropocene] and contemporary
50 human activities”. They can derive from three processes: reduced sedimentation, enhanced
51 sedimentation and contaminated sedimentation. This characterization is broader than James’s in the
52 sense that such legacy effects can be caused by various disturbances besides upstream land-use
53 changes e.g. dam building, flow regulation, channelization, removal of obstacles within a channel, etc.
54 It is therefore more suited to the Anthropocene European context. Nevertheless, the concept of legacy
55 sediment –with either definition- has hardly been applied to European rivers yet, even though most have
56 a long history of human influences and have been especially impacted by anthropogenic activities from
57 the 19th century onwards, following the industrial revolution. Nowadays, one of the major and persistent
58 forcing on European rivers are infrastructures –including large upstream reservoirs, but also flood-
59 protection walls, groynes and other devices meant to facilitate navigation, run-of-river dams, weirs, etc.
60 According to Grill et al. (2019), only 33% of mid-sized rivers (500-1000 km) and 12% of long rivers
61 (>1000km) are free flowing (i.e. connectivity status index $\geq 95\%$) in Europe. While the consequences of

62 such river manipulations have often been studied in terms of main channel adjustment (e.g., incision,
63 narrowing, armouring, stabilization: Surian and Rinaldi, 2003 ; Zawiejska and Wyżga, 2010 ; Arnaud et
64 al., 2015 ; Habersack et al., 2016 ; Downs et Piégay, 2019; Vázquez-Tarrío et al., 2019), their potential
65 role in creating new floodplain features due to legacy sedimentation has been less investigated, and
66 the characteristics of these sediments have rarely been studied.

67 Legacy sediments contribute to artificially modifying watercourses morphology and geochemistry and
68 are thus a threat to the proper functioning and resilience of river systems. The potential remobilization
69 of contaminated legacy sediments, for example, is a major ecological and health hazard in many rivers
70 over the world (Dennis et al., 2009; Martin, 2015; Niemitz et al., 2013; Nováková et al., 2015; Pavlowsky
71 et al., 2017; Clement et al., 2017; Rothenberger et al., 2017). Moreover, significant volumes of legacy
72 sediments stored in the floodplains and river margins may cause unbalanced sediment budgets and
73 flood management issues (Lecce et Pavlowsky, 2001; Knox, 2006; Richardson et al., 2014; Royall and
74 Kennedy, 2016) as well as loss of connectivity between the river and the floodplain, which is a critical
75 issue for river ecological and geomorphological health (Fryirs, 2013, Wohl, 2017; Fuller and Death,
76 2018). Finally, identifying the consequences of human activities on river corridor morphologies and
77 functioning is essential to implement relevant restoration schemes (Wohl et al., 2005; Walter and
78 Merritts, 2008; Eschbach et al., 2018).

79 Through the example of legacy sediments induced by navigation infrastructures on the Rhône River, we
80 aim to determine how they compare to the widely described legacy sediments in the eastern USA, how
81 well they conform to the existing concepts of legacy sediments and how these concepts can be adapted
82 or broadened to include legacy sediments produced in a European Anthropocene context.

83

84 1. Main anthropogenic drivers of change in river systems in the New World and in 85 Europe: a comparison in the Anthropocene period

86 The concept of legacy sediment originates from the USA, where the awareness around post-colonial
87 sedimentation started in the 1940s, way before the term “legacy sediment” was formally introduced.
88 Legacy sediments were then referred to as “modern sediment” or “post-settlement alluvium” (Happ et
89 al., 1940, Knox, 1972; Dearman and James, 2019). Multiple examples of such deposits were described
90 in the USA, mostly in the Mid-Atlantic region (Walter and Merritts, 2008; Merritts et al., 2011; Hupp et
91 al., 2013; Donovan et al., 2015, Johnson et al., 2018). As a result, both their characteristics and their

92 formation mechanism are well-documented. Legacy sediments in the USA are typically recognizable as
93 an important accumulation of fine sediments (up to 5 m high) on both sides of rivers, forming floodplain
94 levels, even terraces that are mostly disconnected from the main channel (Walter et Merritts, 2008;
95 Webb-Sullivan et Evans, 2014; Johnson et al., 2018). There is a consensus that such deposits were
96 formed following European settlement in the 17th century: the subsequent development of intensive
97 agricultural practices led to accelerated upland erosion, generating an unnaturally large amount of
98 sediments that settled in valleys and caused the watercourses to aggrade. After the sediment loads
99 returned to normal, channels incised back to their original level, creating the disconnection with the
100 newly aggraded floodplains. This mechanism is often referred to as an aggradation-degradation episode
101 (ADE) (James and Lecce, 2013; James, 2013). An additional driver according to some authors (Walter
102 and Merritts, 2008; Merritts et al., 2011) are milldams: ubiquitous in the Eastern USA from the 17th
103 century onward, they interrupt sediment transport and may therefore have further promoted sediment
104 storage in valley-bottoms.

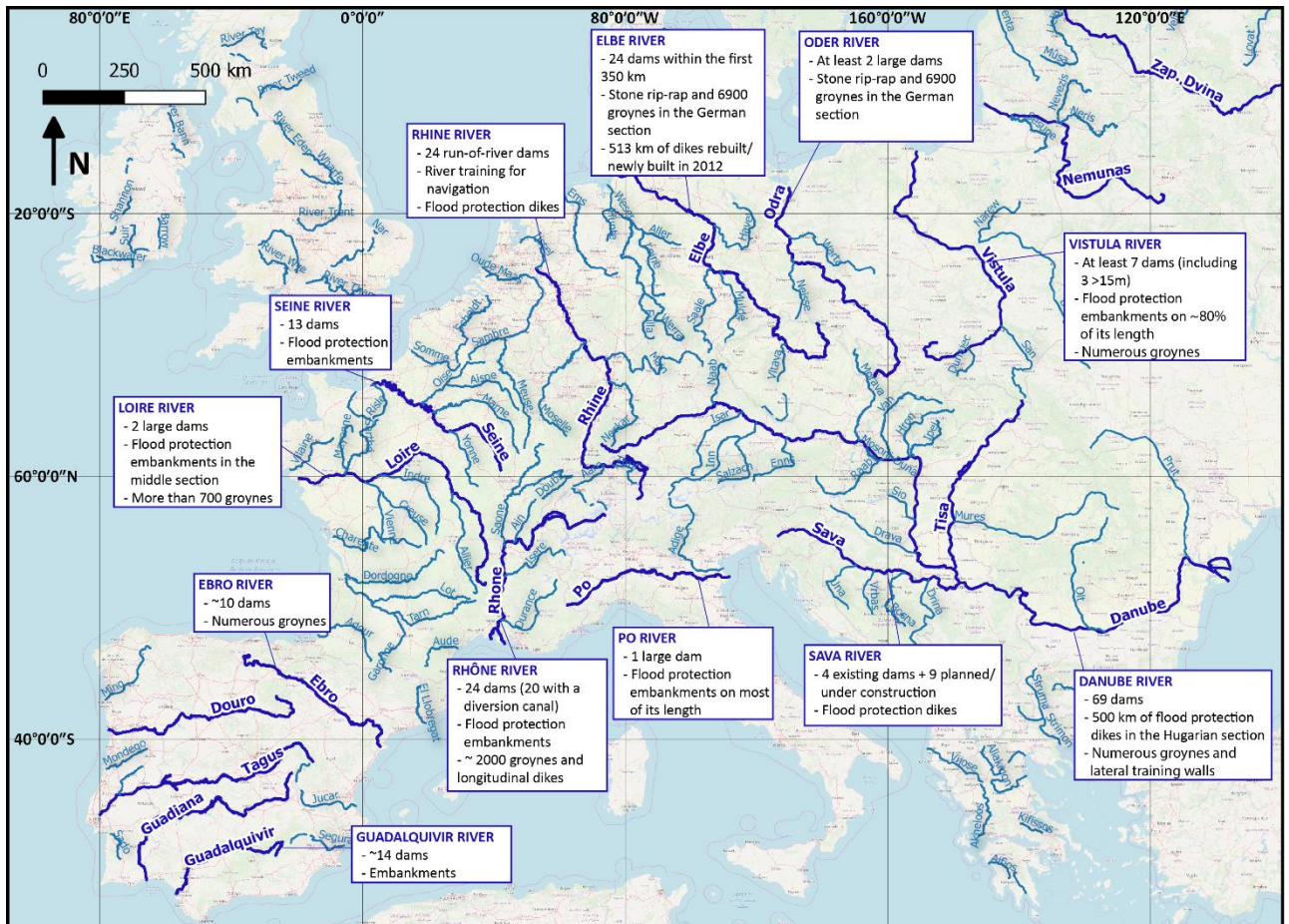
105 Land-use changes following colonization appears as the major anthropogenic disturbance in the USA:
106 as pointed out in James (2013), pre-colonial land surfaces were relatively stable, making the
107 superimposition of large volumes of post-settlement legacy sediments even more outstanding. Similar
108 observations have been made in other settled countries such as Australia (Brooks and Brierley, 1997;
109 Rustomji et Pietsch, 2007; Davies et al., 2018) or New-Zealand (Richardson et al., 2014; Fuller et al.,
110 2015): in lands that were little impacted by their native population, massive and drastic land-use change
111 in the catchment following the European settlement is indisputably the main driver of legacy
112 sedimentation.

113 This cause-effect pattern is not so straightforward in lands that sustained continuous anthropogenic
114 impacts over thousands of millennia such as Europe. Agricultural development in Europe, for example,
115 happened gradually over the span of 7500 years with many periods of expansion and regression
116 (Dotterweich, 2008; Houben, 2008; Dotterweich et al., 2012; Dotterweich, 2013), and so did agriculture-
117 related modifications of rivers and floodplains (Hoffmann et al., 2007; Macklin et al., 2010; Brown et al.,
118 2018). Multiple examples of sedimentation related to land-use changes (mainly agricultural
119 development) dating back from the Iron Age, Gallo-Roman or Middle Age periods have been observed
120 (Dotterweich, 2005; Lespez et al., 2008; Brown, 2009; Macklin et al., 2010; Lespez et al., 2015). This
121 phenomenon might be the closest equivalent to the land-use induced legacy sediments in the New

122 World countries. However, it is mainly apparent in lowland catchments where geomorphic modifications
123 are slow and therefore allowed landforms inherited from the Neolithic to be preserved. It is rarely
124 observed in mountainous river basins (except on main branches such as the Isère or the Rhône),
125 presumably because the high-energy of those actively shifting rivers tends to reshape the floodplain
126 landforms overtime, erasing anthropogenic legacies from the Neolithic. A possible example of legacy
127 sedimentation in highland catchments is the increase in coarse sediment loads in Alpine Rivers during
128 the Little Ice Age (LIA): this phenomenon supposedly derives from both climatic changes (e.g. increased
129 runoffs) and high sensitivity of the basins to erosion due to intense clearing of hillslopes for grazing and
130 exploitation of wood resources (Mather et al., 1999; Delile et al., 2016; Mensing et al., 2016; Bebi et al.,
131 2017). Following this period of increased sediment supply, the upstream alpine basins underwent a
132 rapid decline of agricultural practices associated with afforestation that coincided with the end of the
133 LIA, which led to a strong decline in sediment inflow to the downstream floodplains (Mather et al., 1999;
134 Liebault et Piégay 2002; Liébault et al., 2005; Bebi et al., 2017; Marchese et al., 2017). While these
135 successive legacy effects must have impacted downstream catchments as well, studies generally focus
136 on the local consequences in the small-scale upstream basins. A few instances of other contemporary
137 legacy sedimentation related to land-use changes (agriculture, afforestation or deforestation, mining,
138 etc.) have been documented, but still in small to medium-sized catchments (Piégay et al., 2004; Dalton
139 et al., 2014; Buchty-Lemke et al., 2015).

140 At a larger scale, however, river manipulation arguably represents the most significant perturbation that
141 recently impacted major European watercourses, along with contamination. Two types of river
142 engineering associated with distinct time period can generally be distinguished: most infrastructures
143 related to flood protection and facilitation of navigation (embankments, dikes, groynes, locks) were
144 implemented in the 18th and 19th century, while infrastructures for hydroelectricity production (reservoirs,
145 run-of-river dams and flow diversions) were mainly built during the 20th century (Habersack and Piegay,
146 2007). Construction periods may vary depending on regional or national development disparities: the
147 first major engineering works in the Netherlands were carried out on the Rhine River in the early 1700s
148 (Yossef, 2002); on the Oder River in Poland, weirs and groynes were built on a large scale from 1741
149 to 1896 (Buczyńska et al., 2018); in Hungary, flood-control dykes and groynes were built on the Middle
150 Danube between 1871 and 1914 (Gupta, 2008) and groynes on the Loire River in France were built in
151 the beginning of the 20th century (Barraud et al., 2013). Regarding hydropower, the first European plant

152 was built in 1893 in Serbia (Marković, 2012), and the number of facilities then grew exponentially over
153 Western Europe during the next century. Even though their period of development is mostly over,
154 engineering works remain ubiquitous on European rivers (figure 1 and table S1). It is thus surprising that
155 the concept of legacy sedimentation related to river infrastructures is so underused, although a number
156 of studies do address geomorphological and sedimentation issues related to engineering (Bravard et
157 al., 1999; Surian et Rinaldi, 2003; Provansal et al., 2010; Provansal et al., 2014; Poepl et al., 2015;
158 Habersack et al., 2016; Arnaud et al., 2019; Tena et al., 2020) –and especially large reservoirs (Kondolf,
159 1997; Grant, 2012; Kondolf et al., 2014; Heckmann et al., 2017; Piqué et al., 2017) without referring to
160 the concept of legacy sedimentation. Throughout the rest of the paper, we will focus exclusively on river
161 training infrastructures (e.g. dikes, groynes, weirs) and run-of-river dams as those engineering works
162 may be present all along the river corridor and have been far less studied. Sedimentation processes
163 related to large upstream reservoirs are also critical for river corridors morphology (Teal, 2011; Liro et
164 al., 2019) and would certainly benefit from the legacy sedimentation perspective, but this topic would
165 require a paper in its own right.



166
 167 Figure 1: A non-exhaustive overview of the engineering works on the largest European rivers. Source: OpenStreetMap, see
 168 table S1 in supplementary material

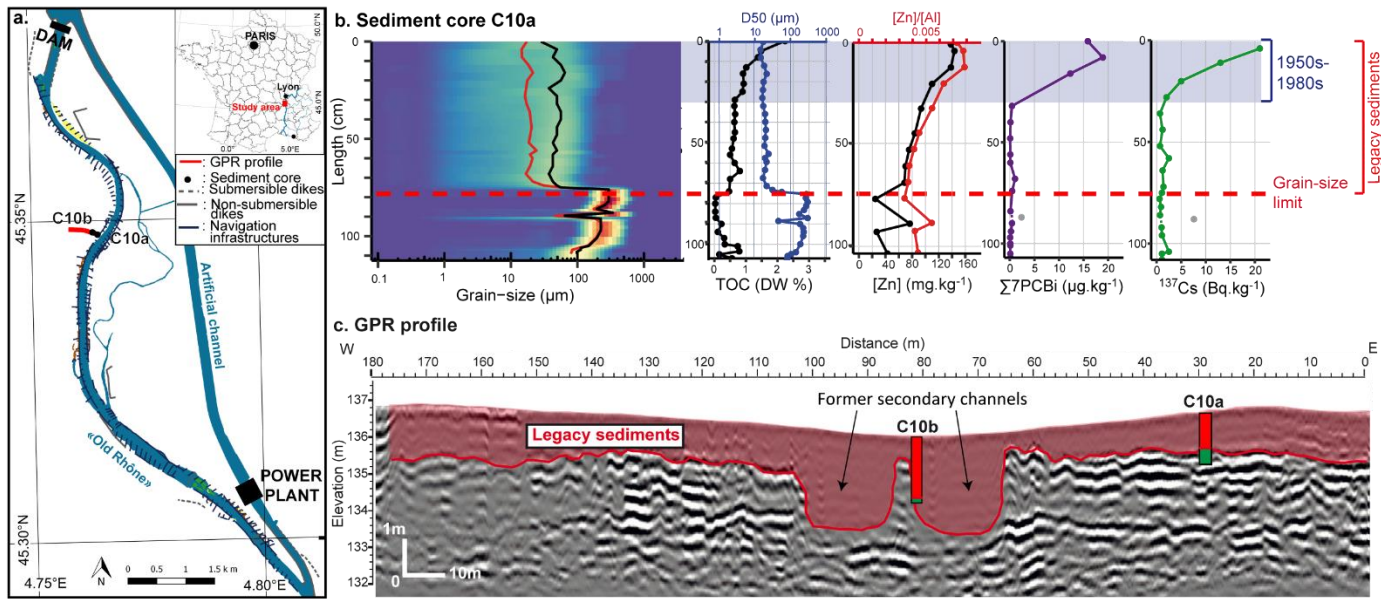
169 2. Infrastructure-induced legacy sedimentation: an example from the Rhône River
 170 (France)

171 In order to illustrate the relevance of applying the concept of legacy sediment in European rivers, an
 172 example from the Rhône River in France is briefly presented.

173 The Rhône is an 8th order 812 km long river that runs from the Furka Glacier in Switzerland to the
 174 Mediterranean Sea; it is the 2nd longest river in France and the first in terms of mean annual discharge
 175 (Olivier et al., 2009). It is a highly engineered watercourse, with numerous dikes and groynes installed
 176 to channelize the river in the second half of the 19th century, and 19 dams along its French course built
 177 between 1948 and 1984 (figure 1 and table S1). Those infrastructures have impacted the river in many
 178 ways: increased slope and transport capacity, reduced sediment load, channel armoring, narrowing and
 179 incision, increased trapping efficiency, etc. (Petit et al., 1996; Bravard et al., 1999; Arnaud-Fassetta,
 180 2003; Parrot, 2015). The study area in this example is located 50 km downstream from the urban area
 181 of Lyon (figure 2.a). It has undergone two periods of engineering and is therefore particularly relevant
 182 to potentially identify infrastructure-induced legacy sediments. Between 1840 and 1880, infrastructures

183 to channelize the river and facilitate navigation were implemented (mainly lateral training walls and
184 groynes). In 1977, the reach was restructured for hydropower production: a canal equipped with a lock
185 and a power plant was dug out and a run-of-river dam was added on the old channel to bypass most of
186 the discharge of the Rhône in the newly built canal (figure 2.a).

187 After analysis of the study area evolution since the 1800s, Ground Penetrating Radar (GPR) surveys
188 and six sediment cores were recovered from the floodplain. The sediment cores were strategically
189 positioned on the GPR profile so that they would cross interesting sediment structures identified on the
190 surveys. Multiple analyses were performed on the cores: grain-size, Total Organic Carbon, metallic
191 elements and PCBs quantification, and ^{137}Cs dating. The comprehensive results are available in Vauclin
192 et al. (2019), and a few key results are also presented in figure 2.b. This multi-criteria investigation
193 allowed to identify a distinctive top layer in five out of the six cores, composed of fine ($D_{50} < 100 \mu\text{m}$),
194 homogeneous sediments that cover an unusually wide range of grain-sizes (figure 2.b). This layer is
195 also contaminated by anthropogenic substances and can be dated by ^{137}Cs trends. Based on the cores
196 dating, we concluded that these singular floodplain deposits result from the implementation of the
197 navigation infrastructures built on the Rhône River at the end of the 19th century: they can be described
198 as infrastructure-induced legacy sediments. We also found out that the hydroelectric development
199 implemented in the area in 1977 caused sedimentation on the river floodplain to stop altogether,
200 meaning that the LS deposited in a restricted time-period -comprised between the 1850s and the 1970s
201 in this site (Vauclin et al., 2019). Finally, by positioning the sediment cores on the Ground Penetrating
202 Radar surveys (figure 2.c), we established that there is a consistent layer of infrastructure-induced LS
203 deposited along the study area.



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Figure 2: a. Study area of Péage-de-Roussillon on the Rhône River (France) with engineering works highlighted; b. An example of multi-criteria characterization of a sediment core allowing the identification of a layer of legacy sediments: (from left to right) grain-size, PCBs concentration and ^{137}Cs activity; c. Ground Penetrating Radar (GPR) survey of a transect of the study area, with corresponding sediment cores positioned.

209

Regarding the mechanism responsible for the deposition of these legacy sediments, our assumption is that the implementation of the navigation infrastructures (i) fixed the river morphology, allowing overbank sedimentation to take place continuously while floodplain sediments used to be reworked regularly under the previous braided configuration, and (ii) induced a partial loss of connectivity between the floodplain and the main channel so that fine sediments kept settling but medium/coarse sediments could not be transported overbank anymore. The decrease in floodplain/channel connectivity can also be linked to river narrowing (40% loss of the active channel surface) and incision (up to 2.5 m) following the implementation of the engineering works (Parrot, 2015; Tena et al., 2020), which might have lessened overbank flows frequency and magnitude. Additionally, engineering works might have acted as a buffer, trapping the coarse sediments before they reach the banks and slowing down the overbank flows, which allowed fine sediment deposition by decantation and/or uniform suspension (Dépret et al., 2017).

220

Additional findings from two other study areas on the Rhône River (Vauclin et al., 2019) show that legacy sediments related to the implementation of navigation infrastructures in the 19th century can be identified along the entire river corridor. We believe that infrastructure-induced legacy sediments might also be present along most engineered rivers in Europe, although further studies would be needed to ascertain it.

223

224

225 3. A conceptual comparison between synchronous legacy sedimentation events:
226 land-use related sedimentation in the USA and infrastructure-induced
227 sedimentation in the Rhône River.
228

229 The infrastructure-induced sediments characterized on the Rhône River have been described as legacy
230 sediments on the sole basis that their deposition was influenced by anthropogenic modification of the
231 river. It appears now interesting to assess how this type of deposit fits in the pre-existing definitions of
232 legacy sediments and how they compare to the widely described legacy sediments in the eastern USA.

233 Legacy sediments production as defined by James (2013) is induced by catchment management: it is
234 primarily driven by human activities that took place at a large scale in the upstream river catchment–
235 essentially land-use changes (figure 3). The main cause for legacy sedimentation being human-induced
236 erosion, a key notion to the concept is that there are sources (hillslopes) that produce LS and sinks or
237 storage zones (mainly valley bottoms) where they deposit temporarily or more permanently. As a result,
238 LS in the USA are systematically characterized by substantially accelerated rates of sedimentation due
239 to intensification of uphill erosion (Knox, 2006; Walter et Merritts, 2008; James, 2013;). Wohl (2015) also
240 highlighted sedimentation rates –either enhanced or reduced- as a key criterion to identify LS.

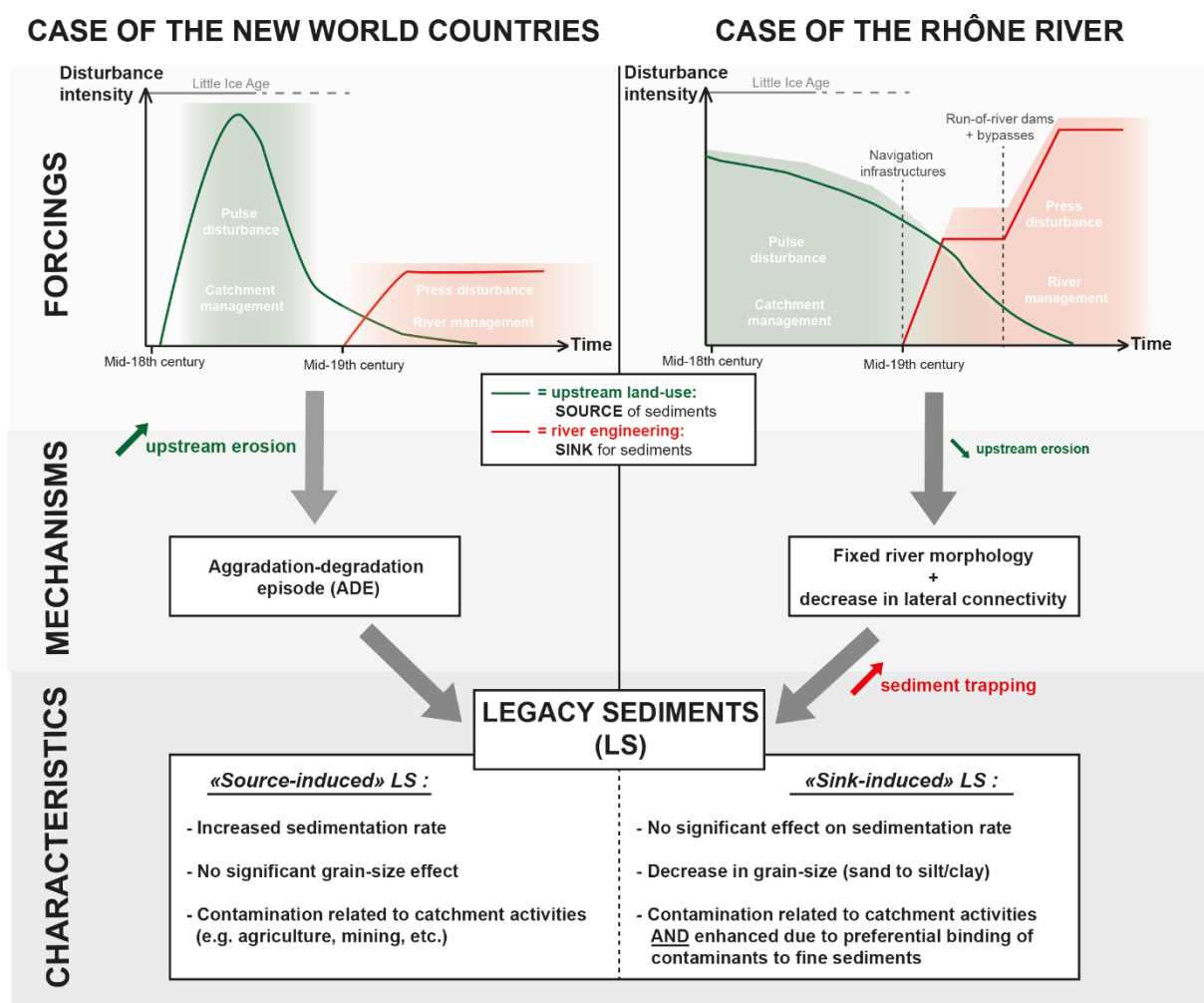
241 Meanwhile, infrastructure-induced legacy sediments in the Rhône River are a consequence of river
242 management rather than catchment alterations (figure 3). The beginning of the legacy sedimentation
243 episode coincides with the end of the Little Ice Age (around 1850) during which coarse sediment
244 deposition induced by climate and upstream land-use decline was observed in the Rhône River
245 catchment: it takes place in a context of overall decreasing sedimentation rates (Liébault and Piégay,
246 2002; Piégay et al., 2004; Citterio and Piégay, 2009, García-Ruiz and Lana-Renault, 2011). Values of
247 sediment accumulation rates in the studied LS are average for a European watercourse or slightly
248 reduced (Vauclin et al., 2019, Tena et al., 2020), but given the overall decrease in sediment load that
249 characterizes the time period, this finding actually shows that infrastructure-induced LS were produced
250 by trapping of fine sediments, resulting in sedimentation rates that are standard but still higher than if
251 there were no river training structures. The key difference with the LS defined by James (2013) is that
252 infrastructure-induced LS were not “generated” from upstream increased erosion but merely trapped in
253 river margins following the implementation of navigation infrastructures that fixed the river morphology
254 and allowed continuous deposition without remobilization of the sediments. Continuing with the “source
255 and sink” analogy, there is no specific source of sediment for infrastructure-induced LS (the decrease

256 in upstream sediment inflow mentioned earlier can be considered as a source effect but it does not
257 generate sediments, on the contrary) but the engineering works did transform the floodplain in a sink for
258 fine sediments. However, sedimentation rates are not as elevated as for American LS and therefore
259 cannot be used as a defining characteristic for infrastructure-induced LS.

260 According to James (2013), periodicity -i.e. the fact that anthropogenic sediments should be considered
261 as LS only if they settle during a restricted time-period and in correlation with a clearly identified human
262 disturbance- is also a requirement for legacy sediments. In the case of the USA legacy sediments, it is
263 especially relevant as the disturbance from which LS derive (upstream land-use changes) is episodic
264 (“pulse” disturbance as defined in Brunsden and Thornes, 1979; Rykiel, 1985; Lake, 2003; Piégay et al.,
265 2018), and therefore so is the settlement of LS (figure 3). In the case of the Rhône River LS, the
266 anthropogenic disturbance is sustained in time (“press” disturbance as defined in Brunsden and
267 Thornes, 1979; Rykiel, 1985; Lake, 2003; Piégay et al., 2018) as most infrastructures will not likely be
268 removed in the near future (figure 3). However, the LS still deposited in a restricted time period -between
269 the 1850s and the implementation of the hydroelectric bypass (1977 in the example presented in section
270 2)- as a second engineering phase caused a near-total loss of lateral connectivity and the interruption
271 of floodplain sedimentation. Even without this secondary disturbance, legacy sedimentation would have
272 likely decreased overtime as the floodplain aggraded, and then stopped once the floodplain could not
273 be overflowed anymore. Infrastructure-induced LS in the Rhône River therefore do qualify as episodic,
274 although for slightly different reasons than the American legacy sediments.

275 American LS can often be identified visually as they tend to form high terraces disconnected from the
276 channel. That is not the case of the infrastructure-induced LS on the Rhône River that form a relatively
277 thin layer (up to 1 m observed in Vauclin et al., 2019 and up to 2.5 m according to Tena et al., 2020)
278 that does not always stand out in comparison to the channel level. Regarding sedimentological
279 characteristics, besides important sedimentation rates, American LS can sometimes also be
280 distinguished from earlier alluvium by lower organic carbon contents (Weitzman et al., 2014; Johnson
281 et al., 2018; Dearman and James, 2019), lower bulk density and lower stratification (Dearman and
282 James, 2019). The grain-size, however, can be similar in both sediment units (Dearman and James,
283 2019) and therefore cannot be used as a discerning criterion. Meanwhile, LS on the Rhône River were
284 formed by preferential deposition of the fine fraction: smaller and homogeneous grain-size constitutes
285 the main criterion to differentiate LS from the underlying sediments. Contrary to the American LS, the

286 organic carbon content was found to be slightly higher in the infrastructure-induced LS than in the
 287 underlying sediments (Vauclin et al., 2019), although this is likely due to terrestrialization and vegetation
 288 development on the LS. An additional criterion to characterize LS might be the contaminants repartition.
 289 Metallic elements tend to be more retained in infrastructure-induced LS (due to a matrix effect)
 290 compared to earlier alluvium, and the early trend of PCBs contamination is recorded in the top part of
 291 the LS exclusively. Besides, American LS are often characterized by important levels of metallic
 292 contaminants or excess nutrients (Niemitz et al., 2013, Pavlowsky et al., 2017).



293

294 *Figure 3: A comparison of the forcings, mechanisms and resulting characteristics of legacy sediments in the New World*
 295 *countries and on the Rhône River*

296 These considerations lead us to suggest criteria -inspired from previous works (James, 2013; Wohl,
297 2015) and with additional findings from this study- to formally identify legacy sediments, whether in
298 Europe or in the New World countries. Legacy sediments should:

- 299 - Result from human disturbance of the river corridor (e.g. pulse of sediment due to upland
300 grazing and erosion, increased trapping efficiency from river training structures, etc.),
- 301 - Be associated with a restricted time-period related to the human disturbance,
- 302 - Display significant modifications of their characteristics due to the human-induced change in
303 sedimentation processes; the affected characteristics may be of various types: accumulation
304 rates, typology (grain-size, density, organic carbon content, magnetic susceptibility, macro-
305 remains, etc.), contamination, etc.

306 Conclusion:

307 In this viewpoint paper, we highlighted the concept of infrastructure-induced legacy sediments from an
308 example on the Rhône River (France) and found out that they differ from the widely described post-
309 settlement sediments from the New World countries in terms of causes, genesis and discriminating
310 characteristics. Due to the ubiquity of engineering works along European large rivers, we believe that
311 such deposits are widely spread in Europe and require further investigation on other major rivers. While
312 this paper focused on the European context, the topic of infrastructure-induced LS is also relevant in
313 most watercourses around the world, as few catchments remain pristine from anthropogenic
314 manipulation (Grill et al., 2019). Even in the USA, Australia and New-Zealand, where the most obvious
315 legacy is related to land-use changes, investigating potential legacy effects due to river training might
316 prove useful for a comprehensive assessment of human impacts on river corridors (e.g. Smith and
317 Winkley, 1996; Remo et al, 2009; Remo et al., 2018) and the definition of pertinent restoration
318 guidelines. Additionally, legacy sedimentation related to large dams remains understudied all over the
319 world. In particular, sedimentation processes upstream reservoirs that result in subaerial deltas(or
320 artificial riparian zones) seems to qualify as legacy sedimentation and constitute an important
321 sedimentological, geomorphological and ecological challenge (Teal, 2011; Tang et al., 2014; Volke et
322 al., 2015; Tang et al., 2016; Liro, 2019).

323 A growing number of river restoration projects are being implemented –mainly in industrialized countries-
324 in an attempt to mitigate the effects of human activities and river training on hydrosystems. In the USA,
325 more than 37 000 restoration programs were identified between 1990 and 2003, with a total cost

326 exceeding \$17 billion (Bernhardt et al., 2005). In Europe, the Water Framework Directive (WFD, 2000)
327 set the achievement of a good ecological status as a legal requirement, with hydromorphological
328 characteristics recognized as key factors to reach this objective. Numerous restoration projects were
329 instigated as a consequence: for example, more than 500 restoration schemes have already been
330 implemented in France between 2013 and 2018, while over 2000 schemes have been carried out in
331 Denmark (Brown et al., 2018). On the Rhône River, a major restoration program was launched in 1998
332 (Lamouroux et al., 2015) with variable results from bioassessments conducted on the rehabilitated
333 reaches (Dolédéc et al., 2015). In that context, investigating infrastructure-induced legacy sediments is
334 essential to define relevant reference conditions that can be used as a goal for an efficient restoration
335 (Wohl, 2018).

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