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1 **Dike fields as drivers and witnesses of 20th century**
2 **hydrosedimentary changes in highly engineered rivers**

3

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Abstract

5 Many large European and American rivers have been channelized in the 19th century and since
6 then feature Dike Fields (DFs) forming engineered alluvial margins. Drivers and witnesses of
7 contemporary geomorphological and ecosystem changes, these initially aquatic DFs have for
8 the most been filled with fine sediments and become terrestrial. On the Rhône River (France)
9 which has not only been corrected but also equipped with numerous dams (mid-20th century),
10 we studied the terrestrialization (*i.e.*, transformation of aquatic areas in terrestrial ones) in two
11 types of DFs: open fields (groyne fields) and closed fields (groyne fields closed by a
12 longitudinal dike). A classification of spatio-temporal terrestrialization patterns (5 types) has
13 been obtained under GIS thanks to aerial photographs and completed by ground penetrating
14 radar surveys to characterize the sediment structural organization of the deposits. It highlights
15 local specificities (inherited forms) within a generalized trajectory of fluvial disconnection.
16 Studying the evolution of the water lines and riverbed elevation allowed to emphasize the
17 control factors and the associated forcings leading to terrestrialization. During phase 1 (reach
18 only channelized – 1890s to 1970s), it is 47% of the closed fields areas which have been
19 terrestrialized and 16% for open fields. Since the incision is not very pronounced on the reach,
20 it appears to be mainly due to accretionary processes as a result of lower shear stresses within

21 the DFs. The terrestrialization from phase 2 (channelized and bypassed reach – 1970s-2000s)
22 corresponds to 32% of the areas of closed fields and 51% of open fields. A cross-validation
23 between the planimetric approach and a lateral connectivity model shows that dewatering
24 caused by the flow diversion has provoked the emersion of almost the half of the DF extent on
25 the upper – and most impacted – part of the reach (75% of the total terrestrialized area). In
26 terms of fluvial rehabilitation, to understand the DFs trajectories provides new insights to guide
27 future restoration design in line with the societal stakes and the current hydrological conditions.
28 Strategical DF reconnections (removing or lowering dikes) could support the river to gain space
29 and recreate hydrological connectivity gradients favorable to habitat diversity that it is currently
30 unable to create or maintain on its own.

31

Key words:

river engineering; terrestrialization; groyne fields; floodplain; fine sedimentation; lateral
connectivity.

32 1. Introduction

33 Over the past two centuries, the rivers and valleys from Europe and northern hemisphere have
34 undergone an intensification of developments to maximise human control and benefits from
35 fluvial systems. While some of the effects of the engineering developments were intentional
36 and met the objectives of the time in which they were conceived, biophysical adjustments they
37 triggered are now a management issue (Petts and Amoros, 1996; Gregory, 2006).
38 Anthropogenic forcings have altered fundamental hydrologic and sedimentary processes that
39 control eco-morphodynamic and have led to radical landscape and ecological changes (Petts,
40 1987; Dynesius and Nilsson, 1994; Nilsson and Berggren, 2000; Tockner and Stanford 2002;
41 Gregory, 2006). As it is known that water-mediated exchanges (*e.g.*, sediment, organic matter,
42 nutrients, organisms) and flood disturbances are key processes for habitat mosaic
43 diversification and biodiversity (Geerling *et al.*, 2006; Amoros and Wade, 1996), hydrological
44 disconnection (including longitudinal, lateral and vertical dimensions) is considered to be one
45 of the main ecological alterations of river systems (Kondolf *et al.*, 2006; Amoros and Bornette,
46 2002; Ward, 1998)

47 Within this anthropo-complexity, certain infrastructures are widespread on engineered rivers.
48 That is the case of channelization features, a common 19th century corrective intervention
49 aiming to improve navigation conditions but also to gain floodplain space for human activities
50 as well as increasing flood protection (Copeland, 1983; Brookes, 1985; Brooker, 1985;
51 Sukhodolov *et al.*, 2002). Hydraulic infrastructures (classically groynes and longitudinal dikes)
52 have been implanted "in" or "on the edge" of river channels to correct and fix its geometry on
53 sinuous, braided, anabranching or meandering rivers (*e.g.*, Danube, Mississippi, Oder, Piave,
54 Po, Rhine, Rhône). Also, in-channel structures directly limit lateral hydrological connectivity
55 (Geerling *et al.*, 2006; Bravard *et al.*, 1986) and exacerbate overbank fine sedimentation on
56 adjacent floodplain (Citterio and Piégay, 2009; Depret *et al.*, 2017). Dike fields (hereafter, DF)
57 are no exception; they constitute sediment traps which partially or completely terrestrialized
58 during the 20th century. Previous works have studied their impact on flow recirculation

59 (Copeland, 1983; Elawady *et al.*, 2001; McCoy, 2006; Papanicolaou and Fox, 2008), sediment
60 deposition (Sukhodolov *et al.*, 2002; Schwartz and Kozerski, 2003; Savic *et al.*, 2013) as well
61 as on ecological and geomorphological responses (Hudson *et al.* 2008; Buczyńska *et al.*,
62 2018). However, though these engineering structures are mostly present along highly
63 developed reaches, factors controlling DF evolution from aquatic to terrestrial stages are not
64 well explored notably in multi-pressure contexts: for instance, many of the channelized rivers
65 were also developed for hydropower during the mid-20th century boom (Petts, 1984; Petts and
66 Gurnell, 2005; Belletti *et al.*, 2020).

67 At the end, cumulative “natural” and anthropogenic forcings led gradually to the establishment
68 of new terrestrial margins more or less ecologically functional – sometimes considered as
69 impacted systems or novel ecosystem (according to Morse *et al.*, 2014); but which are
70 undoubtedly anthroposystems whose ecological interest must be assessed (Hobbs *et al.* 2006;
71 Morse *et al.* 2014; Thorel *et al.*, 2018). To note that we would prefer the term terrestrialization
72 (*i.e.*, transformation of aquatic areas in terrestrial ones) rather than sedimentation or
73 deposition; aware that alluvial margin formation can be induced by sediment deposition and/or
74 lowering of the water level due to different cascading adjusts.

75 In this context, identifying the factors controlling the DF evolution, quantifying their individual
76 and combined effects is complex. That is why, in an original way on the dike fields, we propose
77 to use a space for time substitution approach (Dépret *et al.*, 2017; Fryirs and Brierley., 2012;
78 Piégay and Schumm, 2003). The underlying strategy is to take into account local variability,
79 while being able to detach from it in order to highlight the main controlling factors of the
80 terrestrialization, and in particular, to understand the effect of the main engineering
81 development phases. In the light of an interdisciplinary geohistorical study combining GIS
82 approaches and Ground Penetrating Radar (GPR) surveys, the dike fields depict the entire
83 20th century fluvial disconnection trajectory, by being both drivers and witnesses of the
84 developments and associated ecosystemic response. Also, while the restoration programs
85 encourage to give back space to river (*e.g.*, with dike dismantling), it is crucial to be able to
86 target the relevant levers and define a pertinent scale for functional rehabilitation so that

87 restoration action can be in adequacy with concrete environmental conditions while
88 compromising with the societal stakes.

89 Our objectives are therefore to characterize (i) the terrestrialization trajectories within dike
90 fields of a highly-regulated river, the Rhône River; (ii) the associate sediment patterns and
91 deposits characteristics within the dike fields and (iii) identify and quantify the underlying
92 processes and control factors.

93 **2. Study area**

94 The Rhône River is an 812km long river that originates in Switzerland at the Furka Glacier
95 (2340 m asl) in the Swiss Alps (canton of Valais). Its watershed covers 98,500 km² of which
96 90,500 km² are located in France. It flows into the Mediterranean Sea with an average annual
97 discharge of 1700 m³/s at the Beaucaire gauging station located directly upstream from the
98 delta (Olivier *et al.*, 2022). During the modern period, the Rhône was a multi-thread river. In
99 many reaches, the river flowed in a fairly wide unvegetated gravel corridor, locally braiding or
100 anabranching. After two last centuries development, the river mainly became a single-thread
101 channel (Tena *et al.*, 2020; Riquier, 2015; Bravard, 2010).

102 We selected the Rhône River to explore such multi-driver contexts of groyne-field
103 terrestrialization because its development history is complex. It can be sequenced in two main
104 phases for which the effects of the developments can be studied. Phase 1 corresponds the
105 19th century chenalization. Corrective hydraulic structures consist in classic groyne fields and
106 – to resist high stream power of the river locally – in specific structures that are more robust.
107 These ones are made up of transverse support dikes (called *tenons* in french). They are used
108 as supports for submersible longitudinal dikes; forming the *Casiers Girardon* (named from the
109 engineer who designed them). Phase 2 corresponds to the massive equipment of the river for
110 hydroelectric production. It consists of 19 dams on the French part of the river that were built
111 between 1948 et 1986 (except for the historical dam of Cusset built in 1898). Sixteen of them
112 are bypassed schemes for which an artificial canal was built next to the river course and diverts

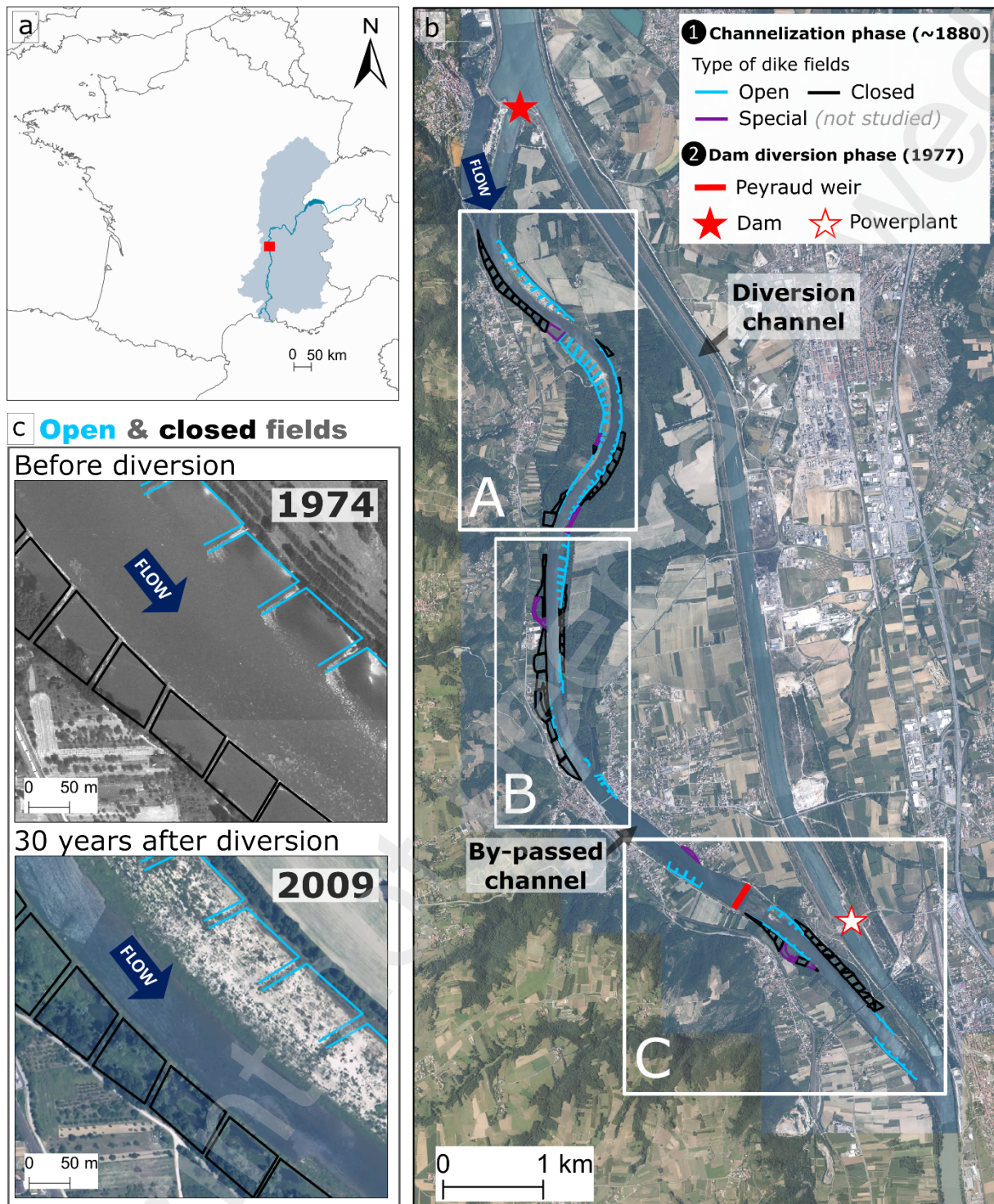
113 most of the bypass flow (management modalities depending on of each dam) supplying a
114 hydropower plant (Annex 1). Following these two phases, the active channel has strongly
115 incised and narrowed (Tena *et al.*, 2020; Parrot, 2015), side channels were disconnected
116 (Dépret *et al.*, 2017; Riquier, 2015; Citterio *and* Piégay., 2009) and corrective hydraulic
117 structures were filled with fine sediments on which riparian vegetation developed (Räpple,
118 2018). Nowadays, the Rhône River is at the heart of rehabilitation projects and so the future
119 of these alluvial margins – between conservation or dike removal – is questioned. Their
120 ecological interest as possible novel ecosystems (Thorel *et al.*, 2018) – in particular that of
121 riparian vegetation (Janssen *et al.*, 2020) – makes debate while a removal operation could be
122 interesting to encourage a greater lateral mobility where it is feasible. Also, the inherited coarse
123 sediments (corresponding to the former river bed below the fine sediment deposits) constitute
124 an interesting alluvial stock for artificial gravel augmentation; to be promoted according to the
125 risk of contamination represented by the overlying reservoir of fine sediments.

126 The studied reach is located in the Middle Rhône at the Péage-de-Roussillon section (PDR),
127 which is one of the bypassed reaches of the river. It is 12.6 km-long and extends from the 50.6
128 River Kilometer (RK) to the 63 RK downstream of the city of Lyon (Figure 1.a & Figure 1.b).

129 This reach historically presented a braided pattern pursued then by a meandering style before
130 the 19th and 20th century human interventions (Bravard *et al.*, 2008b). From the channelization
131 development, it initially features 234 dike fields: 89 Girardon closed dike structures, 126 groyne
132 fields, 19 other specific structures such as former side channel closing dikes (Räpple, 2018).
133 Wide and long on average about 60 m by 130 m, they were cumulatively covering more than
134 108.2 hectares, with a density of 18.6 structures per river kilometer. In this study, we will only
135 refer to classical groyne fields as “open fields”, the second ones as “closed fields” and both as
136 “dike fields”. It will be considered that a dike field unit corresponds to the projected extent of
137 the dikes which compose it (Figure 1.c). At PDR, the mean annual discharge is about 1050
138 m³/s (Ternay gauging station) but since the diversion in 1977, only a minimal flow of 10 to 20
139 m³/s runs through the bypass whereas most of the flow is diverted to a side canal for

140 hydroelectric production. The PDR hydroelectric plant capacity is overrun from 1600 m³/s; in
141 such case, the excess is released in the bypass. Conditioned by this threshold value,
142 modalities of the floodplain hydrological connectivity are stretched between regulated low
143 water conditions and severe erratic flood conditions. As per restoration plans, since 2014, the
144 minimal flow has been increased to 50 and 125 m³/s. Note that in 1979, a weir (*seuil de*
145 *Peyraud*) was implemented in order to preserve some lands from water level modifications
146 caused by the diversion.

147 Despite these heavy engineering developments, PDR remains a site of significant ecological
148 value where many natural protection areas were established such as the National Nature
149 Reserve of *la Platière* (1986), a Sensitive Natural Area zonation (1992), a Natura 2000 site
150 (1992) and a Special Protection Area (Birds Directive, 2006).



151

152 Figure 1 : a. Location of the Rhône River in France and of the studied reach: Péage-de-Roussillon
 153 (PDR); b. Overview of the dike fields (according to their type) in the bypassed reach of PDR and
 154 location of the sub-sectors corresponding to the analysis in Figure 4; b. Overview of open and closed
 155 field terrestrialization evolution before (1974) and 30 years after (2009) the diversion at PDR. Data
 156 source: Photography of 1974, IGN; orthophotography of 2009, BD ORTHO, IGN.

157

158

159 **3. Material & method**

160 To address terrestrialization, a GIS retrospective approach coupled with geophysics surveys
161 was implemented to characterize the margin evolution and sediment deposits features.
162 Inspired by theoretical and experimental sediment deposition patterns of Sukhodolov *et al.*
163 (2002), we propose to rethink them with the GIS and historical data openings so that we obtain
164 the diachronic perspective needed for any trajectory study. Regarding the drivers, the study
165 strives to differentiate the processes underlying terrestrialization; notably with regard to the
166 forcings linked to the water level lowering (incision versus flow diversion). To do this, we
167 propose a multi-source approach using historical data (water line and river bed elevation) and
168 overflow-driven lateral connectivity models (from Džubáková *et al.*, 2014).

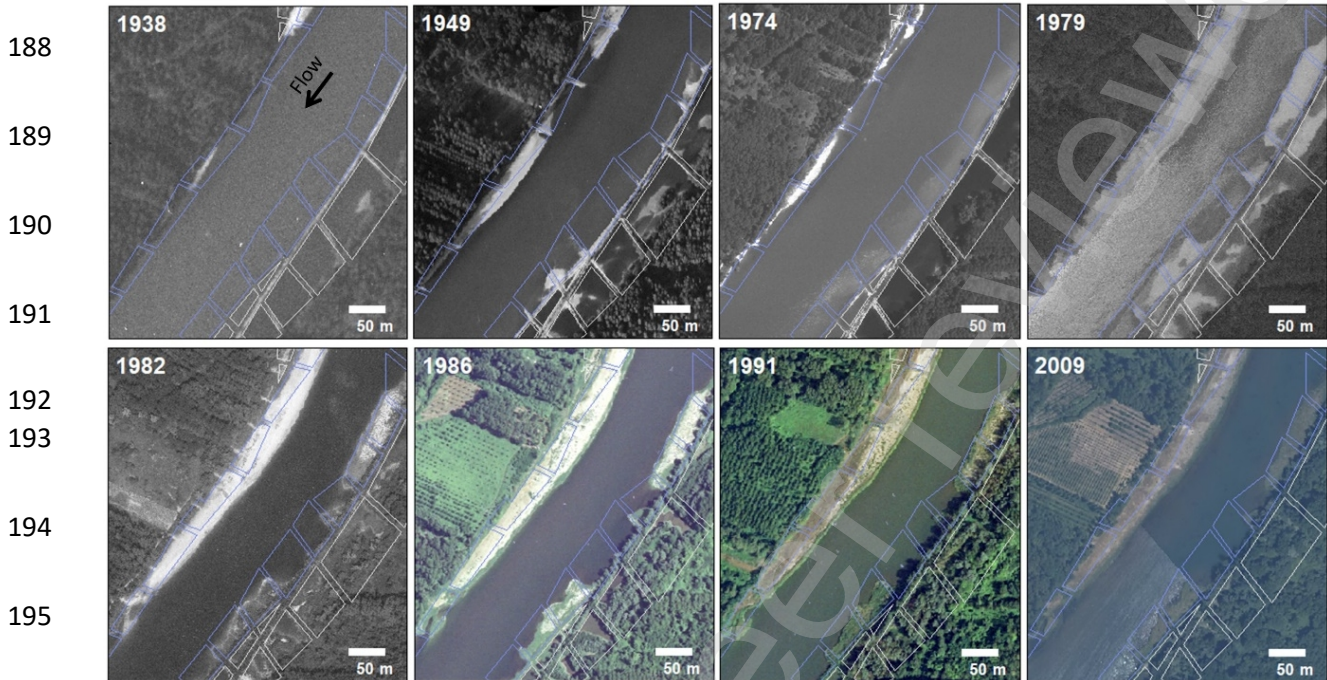
169 **3.1. Planimetric evolution of terrestrialization**

170 Terrestrialization is first assessed by studying the planimetric evolution based on photograph
171 archives georeferenced on GIS as it is now done classically (*e.g.*, Bryant and Gilvear, 1999;
172 Winterbottom, 2000; Gilvear and Bryant, 2003). On the Rhône River, many studies have
173 already used the available map and photographic archives to follow the evolution of the side
174 channels and floodplains but do not focus on the dike field evolution (Riquier *et al.*, 2015; 2017;
175 Dépret *et al.*, 2017; Tena *et al.*, 2020; Arnaud *et al.*, 2021).

176 *3.1.1. Selection of aerial photograph series*

177 The riverscape features were established under GIS (ArcMap™ 10.8) with georeferencing and
178 vectorization processes of aerial images from the National Institute of Geographical and Forest
179 Information data bank (IGN). Nine time series were selected in order to understand the role of
180 each development phase on the terrestrialization processes (Figure 2). They are used to
181 document the post-channelization / pre-diversion evolution of the beginning and the middle of
182 the 20th century (1938, 1949, 1974), the direct impact of diversion (1979), the rapid post-
183 diversion changes (1982 and 1986) and adjustments several decades after diversion (1991,
184 2002, 2009). Their scales vary between 1/15,000 and 1/25,000 for aerial photographs from

185 1938 to 2002. Orthophotographs from 2009 with a 66 cm pixel resolution served as a
186 georeferencing base. All of their detailed characteristics (scale, acquisition technique, colour
187 gradient, river discharge, etc.) are available in Annex 2.



Source: IGN - corresponding dates

196
197 Figure 2: Diachronic photograph series from several dike fields located at RK 55.

198 3.1.2. GIS processing

198 The quality of fit on the DF scale was increased thanks to a specific georeferencing process in
199 which the reach extent is divided by polygons of 2 kilometers long. Subparts of the photographs
200 are georeferenced within these focusing areas all along the dike field succession (10 to 20
201 ground control points evenly distributed). As we concentrate on the DF evolution, dike
202 crossings are used as ground control points as well as nearest infrastructures (bridges,
203 buildings). The associated RMSE vary between 4.1 ± 1.6 m (1938 series) and 2.2 ± 0.9 m
204 (2002 series), indicating that the associated rectification is fairly good-of-fit (cf. Gurnell, 1997;
205 Arnaud *et al.*, 2015).

206 The limits between water and terrestrial areas were then digitized for each date with a scale
207 ranging from 1:500 to 1:1,500 depending on the photograph quality. The photograph series
208 that follow our selection give the information of the deposit stability and prevent from

209 interpretation errors due to the photograph quality variability. Also, the presence of woody
210 riparian vegetation can make this limit unclear when their canopy overhang it. We drew them
211 in an interpretative compromise of a few meters (2 to 10 m) from the edge of vegetation based
212 on the scale relative indication of the existing breaks between tree crowns (Liébault and
213 Piégay, 2002; Depret *et al.*, 2017; Tena *et al.*, 2020). Then, one polygon vector is created per
214 photographs series, corresponding to terrestrial margin at each date. We also used an existing
215 vectorial layer of the dike field implantation based on old maps and aerial photographs
216 produced by Räßle (2018). By intersecting it with the multi-date polygon series, we obtain the
217 in-dike diachronic evolution.

218 3.1.3. *Quantitative and qualitative analysis of terrestrialization processes within the* 219 *dike fields*

220 Very specific dike configurations like half open dike fields (enough similar to wing groynes, *cf.*
221 Przedwojski, 1995) were eliminated from the statistical planimetric study. Also, dike fields
222 which are not directly located next to main channel and ones that display clear anthropogenic
223 modifications (maintenance, engineering intervention, etc.) have been removed from the
224 dataset. That is why we finally selected 193 DFs (85 closed fields and 108 open fields) on the
225 234 inventoried dike structures.

226 Cumulative Terrestrialized Areas (TA) were obtained by summing terrestrialized areas within
227 the DFs over the entire sector according to the specified time window (Eq. 1).

$$228 \text{ Cumulative TA} = \sum \text{mineral or vegetated surface within each dike field} \quad (1)$$

229 On the other hand, the evolutionary trajectories in terms of terrestrialization are examined
230 depending on the percentages specific to each DF. For each date, the percentages of
231 terrestrialization are obtained by the calculation (Eq. 2).

$$232 \text{ TA (\%)} = \frac{\text{mineral or vegetated surface within the dike field}}{\text{extent of the dike field}} \times 100$$

$$233 \quad (2)$$

234 Inspired by the inter-groyne deposition patterns of Sukhodolov *et al.* (2002), the
235 terrestrialization pattern classification is determined with an empirical and expert methodology
236 based on the observation of the planimetric recurrences but also on the evolutionary aspect
237 thanks to the multi-date dataset.

238 **3.2. Characterization of fine sediment deposits within the dike fields**

239 We combined telemetric and geophysical datasets to assess the organization of fine sediment
240 deposits and link it with the planimetric history. Each approach aims to cover different features
241 and scales. We characterise the topography of the alluvial margins (reach scale) using a LiDAR
242 DEM. A GIS model based on the study of fine sediment thickness allows us to better assess
243 the sediment storage within dike fields on two third of the reach length. Subsurface profiles
244 obtained by Ground Penetrating Radar provide information on sedimentary structures within
245 the DFs.

246 *3.2.1. Topographic dataset*

247 For the elevation dataset, we use an airborne LiDAR Digital Elevation Model (DEM) produced
248 in 2010 by the IGN. It has a 2 m resolution and a 0.2 m vertical accuracy. The pulses density
249 is of 1 to 2 per square metre for which a pulse is a 0.4 m diameter disc (IGN, 2010). For each
250 DF, the average elevation was calculated from this DEM on the total extent. For the elevation
251 associated to chronoplanimetric time window, it is calculated on the associate extent within the
252 DFs. The topographic transect were extracted from the LiDAR DEM thanks to the 3D Spatial
253 Analyst tool from ArcMap™ 10.8.

254 *3.2.2. Gravel layer GIS model based on metal rod probing*

255 The dike fields trapped fine sediments that deposited on a layer of coarse sediments (gravel
256 and pebbles; hereafter, gravel layer). Thus, the limit between coarse sediments and fine
257 sediments embodied by the gravel layer not only constitutes a chronological marker but
258 physical evidence of the geomorphological process modifications of the Rhône. To estimate
259 its delimitation, more than 330 sampling points were surveyed between the RK 52 to 58. The

260 depth to gravel - and so the fine sediment thickness of the sub-deposit - was estimated by
261 driving a 1 cm diameter metal rod into the fine sediment deposit until it hits the gravel layer
262 (Tena *et al.*, 2020; Piégay *et al.*, 2008; Dufour *et al.*, 2007). Using this dataset, the gravel layer
263 and fine sediment thicknesses were modelled using a GIS cokriging method (Piégay *et al.*,
264 2015). From this dataset, fine sediment thicknesses within the DFs were extracted according
265 to each date of the planimetric history.

266 3.2.3. Ground penetrating radar subsurface images of the sediment deposits

267 The characterisation of the sediment structure was investigated by Ground Penetrating Radar
268 (GPR). It is a non-invasive geophysical method based on a principle of high frequency
269 electromagnetic energy signal reflection. It provides high resolution images of shallow
270 subsurface structures and is often used in sedimentological studies (Davis and Annan, 1989;
271 Beres and Haeni, 1991; Gawthorpe *et al.*, 1993).

272 We use a GSSI SIR 3000 structure (Geophysical Survey Structure Inc., Salem, USA), with a
273 shielded antenna at a central frequency of 200 MHz in monostatic mode. The compilation and
274 the juxtaposition of the signals recorded during the movement of the radar antenna make it
275 possible to obtain a vertical profile (*i.e.*, radargram). On radargrams, the reflectors correspond
276 to the reflection lines of the signal associated with changes in the ground structure and/or
277 texture. It shows the main sedimentary structures and their interpretation gives an idea of the
278 deposit organization (Vauclin, 2020; Regli *et al.*, 2002; Beres *et al.*, 1999).

279 Three transects running on 380 m were carried out to provide a representative panel of deposit
280 structures according to the chronoplanimetry and DF type (open/closed). Transect GPR T1
281 long of 100 m is oriented West to East and crosses transversally a closed field in a concavity
282 of the left bank (RK 54.625). Transect GPR T2 (d = 140 m) is oriented North to South, parallel
283 to the channel and crosses 3 closed fields lower in the same concavity (RK 55.1). Transect
284 GPR T3 (d = 140 m) is also oriented parallelly to the channel and crosses 3 open fields in a
285 convexity of the right bank (RK 54.1).

286 **3.3. Assessment of terrestrialization due to channel incision**

287 If sedimentary deposition surely contributes to terrestrialization, different hydro-geomorphic
288 processes such as river bed incision or flow diversion can cause a lowering of the water level
289 and also lead to terrestrialization. So, we aim to apprehend the incision phenomenon by
290 monitoring the vertical evolution of the river bed. By monitoring the evolution of the water lines,
291 it is possible to assess the effect of the incision on it (at comparable discharge states) and the
292 impact of the dewatering that followed the diversion flow (total versus residual discharge).

293 *3.3.1. River bed evolution during the 20th century*

294 River bed elevation and in particular incision phenomenon have been studied by Parrot (2015)
295 according to three periods. She established (i) a reference state in 1897, (ii) a “post-
296 channelization – recently diverted” state (1982) and (iii) a current “post-channelization – post-
297 diversion” state (2008). They were extracted from bathymetric transects collected every 500 m
298 at sus-mentioned dates (Topographic Data Base of the Rhône; IGN, 2010).

299 *3.3.2. Water line evolution during the 20th century*

300 To enlighten the early 20th century situation while the channelization has just been realized,
301 we used a 1902 elevation dataset of the water line (WL) at low flow that is known for each RK
302 (from *Fascicule Armand des pentes du Rhône*, 1902). For the post-channelization and pre-
303 diversion WL characterization, two surveys of the waterline made by the *Compagnie Nationale*
304 *du Rhône* (CNR) were available for the post-chenalization/pre-diversion situation (1962) at low
305 flow (260 m³/s) and mean annual flow (1080 m³/s). The first one was used as a comparison to
306 1902 situation and the second one as a reference of average conditions at this time (1080
307 m³/s). For the recent post-diversion situation, the 2010 WL elevation was available in the BDT
308 Rhône. It corresponds to the minimal flow in the bypassed reach (20 m³/s). The states they
309 informed, the comparisons and insights they allow are summarized in table 1.

310

311

312 Table 1: Available data set about the water line evolution on the PDR reach during the 20th century
 313

Date	Source	Development state	Discharge indications	Informed state	Comparisons and insights
1902	<i>Fascicule Armand des pentes du Rhône</i>	Just after channelization	Low water	Reference state at the beginning of the 20 th century	Channelization effect on water line NB: similar discharge conditions
1962	CNR	60 years after channelization, before flow diversion	Low water (260 m ³ /s)	Reference state at low flow conditions at the end of phase 1	
1962	CNR	60 years after channelization, before flow diversion	“Normal” discharge (1080 m ³ /s)	Reference state in average conditions at the end of phase 1	Flow diversion impact on water line in a channelized situation (cumulative impact) NB: discharge conditions are different but representative of the average conditions of each phase
2010	BDT Rhône	More than 100 years after channelization 31 years after flow diversion	Minimum flow Residual discharge (20 m ³ /s)	State in average conditions at the end of phase 2	

314

315 3.3.3. Dike field relative elevation and change in water line position

316 If the water lines change, so does the channel-DF relationship. To evaluate this evolution, we
 317 use a relative elevation (RE) indicator from the DFs to the water line. The dike field RE to the
 318 WL is obtained according to the following calculation (Eq.3):

$$319 \quad \text{Dike field RE (m)} = \frac{\text{dike field elevation averaged on its total extent}}{\text{water line elevation in the cross section}} \quad (3)$$

320 The delta between 1962 (pre-diversion) and 2010 (post-diversion) WL situation constitutes an
 321 indicator of connection changes between the active channel and the alluvial margins. For lack
 322 of a 1962 DEM Lidar, the 1962 dike field relative elevation to water line is also based on the
 323 2010 dike field average elevation. Thus, it is a partial disconnection indicator because it is only
 324 focused on the WL changes and does not include overbank sedimentation effect that would
 325 be taken into account if we would have a DEM for the pre-diversion state.

326 3.4. Assessment of terrestrialization due to water diversion

327 In order to address the contribution of diversion dewatering in terrestrialization, we aimed to
 328 model the submerged surfaces corresponding to a projected active channel in discharge
 329 conditions relative to situation before and after flow diversion. To do this, we use models of

330 overflow-driven lateral connectivity developed by Džubáková *et al.* (2015). They also served
331 the purpose of making the link between residual hydrological connectivity and the up-to-date
332 state of terrestrialization.

333 *3.4.1. Overflow-driven lateral connectivity models and by-products*

334 The hydrological connectivity of alluvial margins was approximated thanks to the overflow-
335 driven lateral connectivity model raster from Džubáková *et al.* (2015). It was developed in
336 MATLAB and C ++ environments involving the sus-mentioned DEM LiDAR (2010), rating
337 curves and flow time series (daily discharge over the 1986-2010 period). Rating curves are
338 used to obtain water levels associated with water discharge. These levels are then projected
339 onto the floodplain by assuming that the water level is homogeneous within the cross section
340 and decreases in the downstream direction. Based on that principle, a model of overflow-driven
341 lateral connectivity was obtained with different attributes: pixel submersion frequency
342 (days/year), critical discharge leading to the pixel submersion, etc. The model developed on
343 the PDR reach only extends from RK 52.5 to RK 60.

344 *3.4.2. Active channel area based on the modelled critical discharge for submersion*

345 We used the model of “critical discharge for pixel submersion” to obtain estimations of the area
346 submerged in conditions that are representative of the average conditions of each
347 development phase (total versus minimal flow). Thereby, we compared the flooding areas for
348 a discharge corresponding to 1050 m³/s (mean annual discharge at the nearest gauging
349 station) and to 20 m³/s (residual discharge during the 1977-2014 period). The difference
350 between the two extents highlights the effect of the dewatering induced by diversion.

351 We also used the 2010 DEM LiDAR to model the submerged area corresponding to 1050 m³/s
352 (*i.e.*, total discharge) because we had no DEM for the pre-diversion reference state. Because
353 the 2010 DEM LiDAR represents the topography including post-diversion sediment deposited,
354 the model could overvalue the water volumes. By this way, it could overestimate the flooding

355 area associated to a 1050 m³/s discharge in pre-diversion situation (with less sediment
356 deposited than on the 2010 situation).

357 *3.4.3. Link between current terrestrialization rate and hydrological connectivity of the DFs*

358 The link between the average flooding frequency of the DFs (hydrological connectivity proxy)
359 and the terrestrialization rate of the DFs was assessed by a Generalized Linear Model (GLMs).
360 Because the percentage of terrestrialized area is a proportion and the flooding indicator a
361 frequency, we used a binomial function link. Employing the glm function of R (version 4.0.3),
362 we detailed the proportion of deviance explained (D^2) that we obtained by using the Dsquared
363 function of the modEVA package. The model is performed on a dataset of 116 dike fields
364 corresponding to the extent of the submersion frequency raster which covers two thirds of the
365 reach (from the dam to the Peyraud weir; cf. Figure 1).

366 **4. Results**

367 **4.1. Terrestrialization processes in space and time**

368 *4.1.1. Cumulative terrestrialized area*

369 The quantitative approach reveals that the cumulated closed field extents cover 38.87 ha of
370 which 47% (18.31 ha) have been terrestrialized during the pre-derivation period, 32% (12.53
371 ha) during the post-derivation period whereas 21% (8.03 ha) of their surface remain aquatic.
372 In open structures that cover 39.3 ha, 16% (6.18 ha) correspond to surfaces terrestrialized
373 during the pre-derivation period, 51% (20 ha) during the post-derivation period whereas 33%
374 (13.12 ha) of their surface have remained aquatic.

375 The general trend towards terrestrialization of alluvial margins including differences in the
376 temporal sequences between the two types of dike fields is highlighted in Figure 3. During
377 phase 1, the phenomenon is already underway in the closed fields while it is very little in the
378 open fields. Indeed, the average percentage of terrestrialized areas (TA) in closed fields
379 reached 26.9% in 1938, *i.e.*, 40 years after their establishment. Between 1938 and 1949, TA

380 increased to 40.4%. Between 1949 and 1979, the phenomenon slowed down: in thirty years,
381 the average TA only increased by 7%. Regarding open dike fields, only 5.9% of their surfaces
382 were terrestrialized in 1938. The average percentage increases to 11.4% and stagnated during
383 the 1949-1979 period.

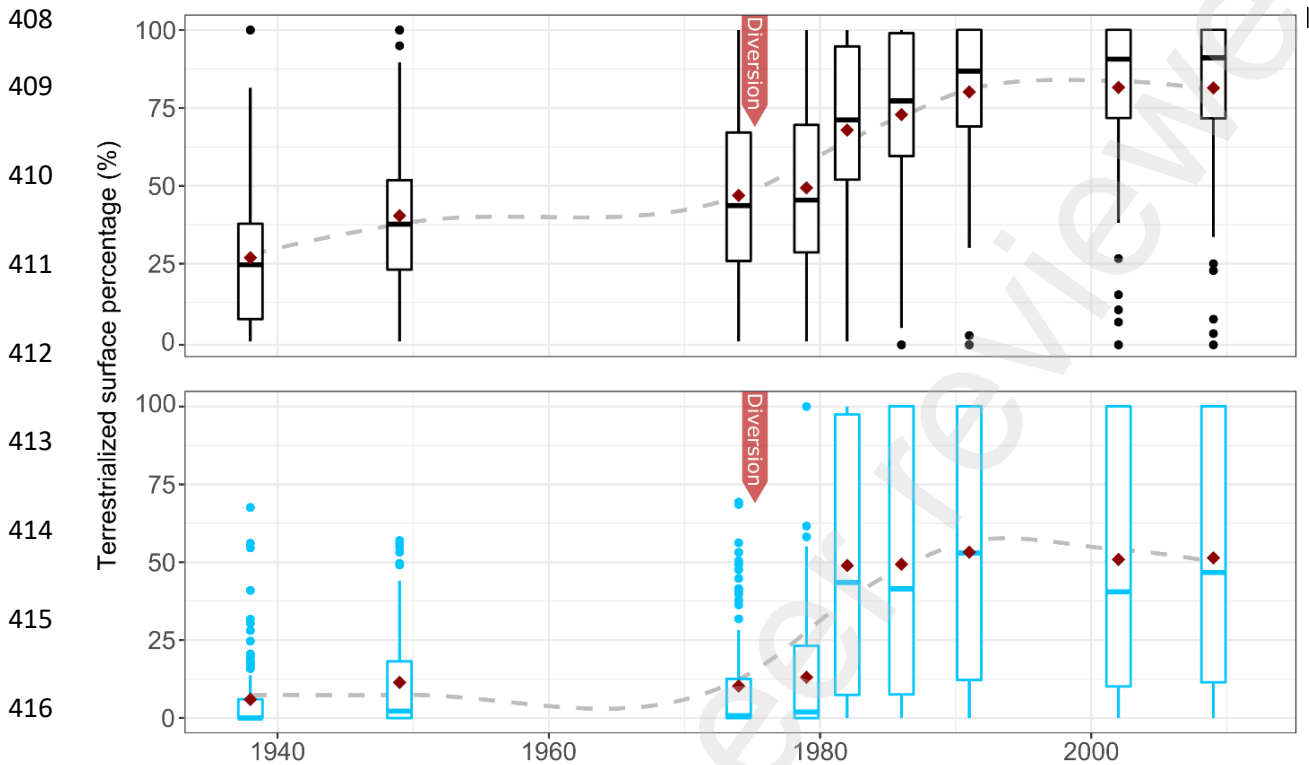
384 During the second phase, the terrestrialization phenomenon gets carried away. In the closed
385 fields, over the period 1979-1982, the average TA had considerably increased from 49.3% to
386 67.9%. After this strong acceleration, terrestrialization slowed down again and the TA
387 stagnated around an average of 81%. In open fields, the average percentage of TA has been
388 multiplied by 4.1 over just a few years going from 12% to 49%. Then, it had stalled around 52%
389 during the 1991-2009 period.

390 These general trends to terrestrialization are accompanied by significant variability due to the
391 specific trajectories of the different types of dike fields. For the closed fields, the interquartile
392 ranges (IQR) of the TA percentages are homogeneous (from 1938 to 1986: IQR ranging from
393 30.5 to 42.8) even if it is possible to note that it decreases between 1986 and 1991
394 ($IQR_{1986}=39.3$; $IQR_{1991}=31$) then stagnates on the later dates ($IQR_{2002}=28.2$, $IQR_{2009}=28.3$). For
395 open fields, the opposite trend is observed. Mainly aquatic before diversion, the interquartile
396 deviations are firstly stretched during the phase 1 (from 1938 to 1979: IQR ranging from 6 to
397 23). After the diversion, the associated IQRs become very pronounced covering at the
398 maximum in 1986 92.4 % of the spectrum and reflecting the variability of open field
399 configurations. We also note that there are many more outliers with higher percentages of TA
400 before diversion for open fields, while the opposite situation is reported in closed fields with
401 fewer outliers characterized by lower TA percentages.

402 *4.1.2. Terrestrialization space-time patterns*

403 The chronoplanimetric analysis clearly show the formation of alluvial margins and the role of
404 each engineering development phase. The maps (Figure 4) provide an overview but also
405 insight into more local trends in the terrestrialization history.

406 Older pre-diversion terrestrialized areas (dark green to light green surfaces) are mostly located
 407 at the back of the closed field. Post-diversion areas (warm colors corresponding to “after



417 Figure 3: Terrestrialization percentage evolution within the dike field extents throughout the 20th
 418 century ($n_{\text{closed fields}} = 85$, $n_{\text{open fields}} = 108$ where closed fields are in black and open fields in blue; red
 419 symbols correspond to the averages)

420 The Figure 4.a shows the planimetric evolution at the scale of a meander. In concavity (right
 421 bank), some closed fields have gradually terrestrialized, which results in shades of green (pre-
 422 diversion terrestrialization) in the back of the structures whereas warm color surfaces are
 423 leaning against them (post-diversion terrestrialization). On the left bank, within the channel
 424 convexity, there are unicolored open fields (light orange corresponding to 1979-1982-time
 425 window) which therefore terrestrialized uniformly and quickly after the diversion.

426 The Figure 4.b depicts the situation upstream of the Peyraud weir. It is first characterized by a
 427 straight which ends on a meander corresponding to the bend of two-thirds of the bypassed
 428 reach. On the right bank, many closed fields have been implanted at the level of and former
 429 side channel and its associated island (*île de Poucharle*). They are marked by first phase

430 terrestrialized areas and remaining aquatic surfaces. On the other hand, the closed fields
431 located in the heat of the concavity are still entirely aquatic. On the left bank, the planimetric
432 dynamics are different depending on local conditions: the open fields located in the convexity
433 upstream of the sub-sector have been partially terrestrialized mainly in phase 2. The
434 southernmost open fields, which are smaller and in a straight section have not been
435 terrestrialized. Closed fields that benefit from the open field protection began to strongly
436 terrestrialize from phase 1 while the others do so more during phase 2.

437 The Figure 4.c displays the situation in the straight section located downstream of the Peyraud
438 weir. On the right bank, in the first row, there are open fields still aquatic. Behind these, closed
439 fields have been built to close a former side channel and are surrounding the associated island.
440 Around this island, the surfaces have mainly terrestrialized during the first phase (green
441 colors). On the left bank, there is a series of open fields that have been more or less
442 terrestrialized during phase 2. The two closed fields protected by a first row of open fields were
443 mainly terrestrialized during phase 1, while the following ones – directly exposed to the channel
444 – were terrestrialized more gradually, with numerous post-diversion patches or still aquatic
445 areas.

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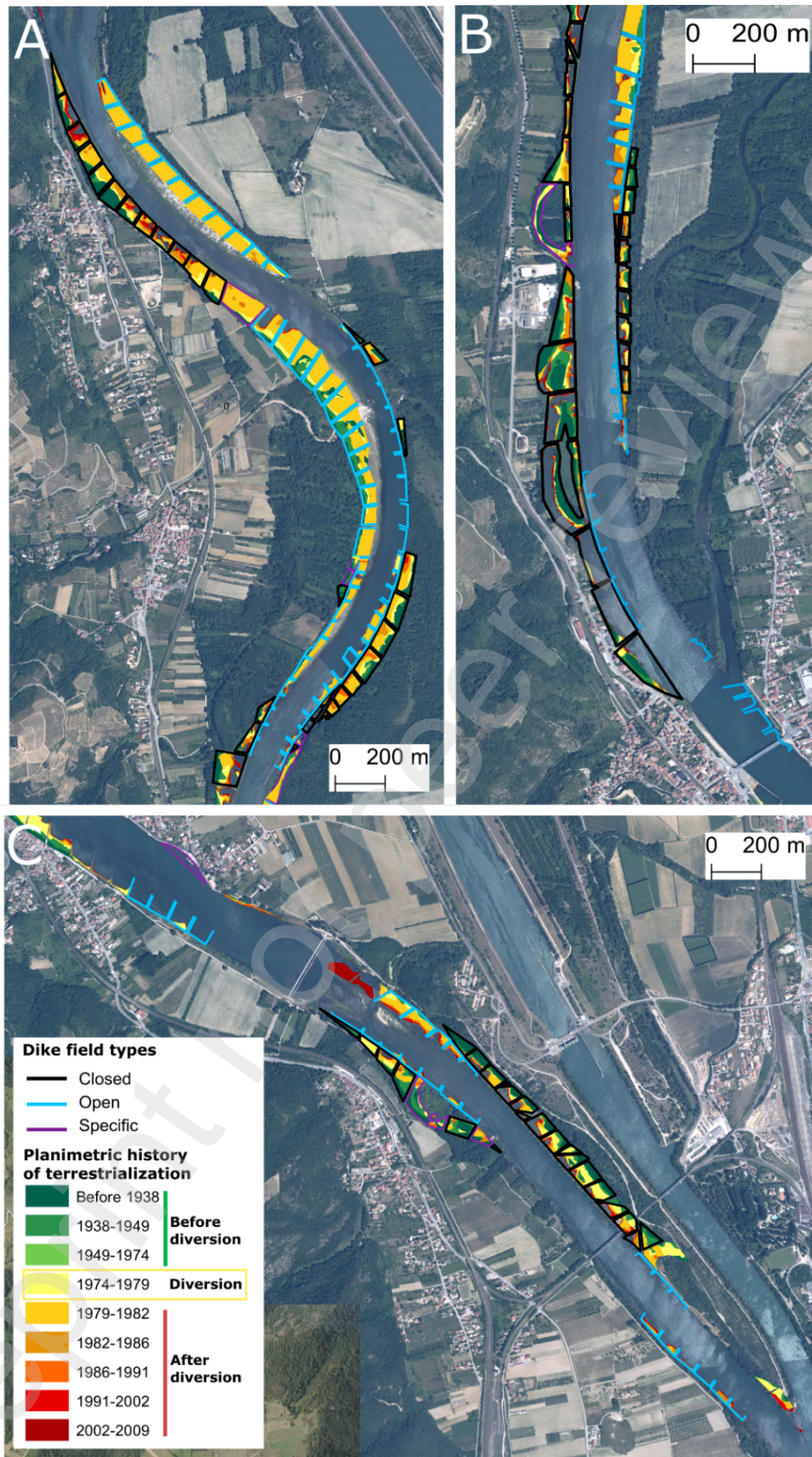


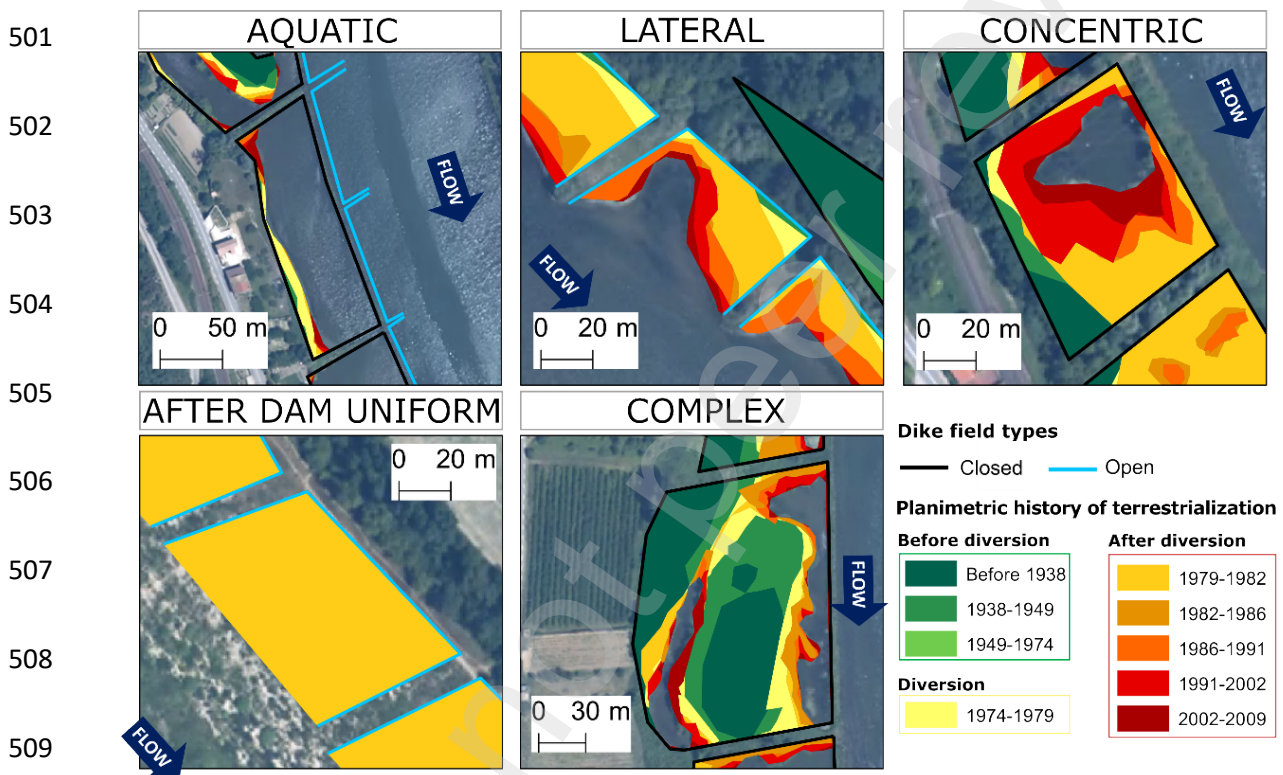
Figure 4: Planimetric patterns of terrestrialization through time within the dike fields of the Péage-de-Roussillon bypassed reach during the 20th century. Sub-sectors a, b and c are localized on Figure 1. (Data source: orthophotography of 2009, BD ORTHO, IGN; planimetric vectors from the dataset presented in section 3.1).

4.2. Chrono-planimetric recurrences and classification of terrestrialization patterns

Although differences were observed according to local conditions and the type of DFs, the chrono-planimetry show many recurrences (Figures 3 and 4). Depending on the prevalence of observed forms, associated periods of terrestrialization and structuring similarities or singularities, five categories of terrestrialization patterns were defined: aquatic, lateral, concentric, after dam strip and complex (Figure 5). The aquatic type is associated with a DF surface that remains unterrestrialized for more than 85% of the DF extent (limit based on natural distribution breaks). Lateral type is characterized by a partially or totally terrestrialized area with multiple successive terrestrialized bands of varying sizes and distributed laterally to the bank or angularly to the transversal dikes. Concentric type is characterized by being highly terrestrialized (~10% of remaining aquatic areas) and the presence of areas with progressive concentric closures that may remain aquatic or end up by gradually terrestrializing. After-dam uniform patterns correspond to uniform patches that terrestrialized consecutively to the diversion (light orange corresponding to 1979-1982 after diversion time window). For the complex group, the DF surface is more or less terrestrialized and shaped according complex forms caused by geomorphological specificities (e.g., presence of former side channels, old islands).

Regarding the percentage of terrestrialization, TA% are significantly different (p -value = $4.04E10^{-6}$) reaching $81.4 \pm 24.5\%$ for closed fields and $51.39 \pm 40\%$ for open fields (Table 2). Out of a total of 85 closed fields, we identified only 2 aquatic patterns (associated TA%: $4.9 \pm 3.3\%$), 18 that are lateral (TA%: $66.1 \pm 31.8\%$), 41 that are concentric (TA%: $85.1 \pm 12.8\%$), 7 are after-dam uniform ones (TA%: 100%), 11 are complex ones (TA%: $84.6 \pm 23.45\%$) (Table 2). Also, 6 closed fields are classified as “already full” which are dike fields with an early filling – at the beginning of the 20th century – for which the absence of information makes it irrelevant to associate them with a pattern. From the first photo archive (1938), they are already strongly or entirely terrestrialized.

494 Out of a total of 108 open fields (Table 2), we identified 22 aquatic patterns (associated TA%:
 495 3.2 ± 5.2 %), 49 are lateral (TA%: 50.4 ± 25.3), 3 are concentric ones (TA%: 89.6 ± 10.7 %),
 496 20 are after-dam uniform ones (TA%: 96.2 ± 17 %) and 14 are complex (TA%: 85.3 ± 26.2 %).
 497 Thus, aquatic patterns are mainly observed in open fields, lateral ones in both types of DFs,
 498 concentric ones mainly in closed fields, after-dam uniforms in both but mainly in open fields.
 499 Finally, the complex patterns which transcribe local specificities are associated with two types
 500 of DFs whose implantation was itself a function of local conditions.



510 Figure 5: Classification of recurrent terrestrialization patterns (Data source: orthophotography of 2009,
 511 BD ORTHO, IGN).

512 Table 2: Pattern occurrences and associated percentages of Terrestrialized Area (TA%) in closed and
 513 open fields.

	Pattern type	Aquatic	Lateral	Concentric	After dam uniform	Complex	Already full	Total
Closed fields	Count (n)	2	18	41	7	11	6	85
	TA% (Average \pm SD)	4.9 ± 3.3	66.1 ± 31.8	85.1 ± 12.8	100	84.6 ± 23.5	100	81.4 ± 24.5
Open fields	Count (n)	30	41	3	20	14	x	108
	TA% (Average \pm SD)	3.2 ± 5.2	50.4 ± 25.3	89.6 ± 10.7	96.2 ± 17	85.3 ± 26.2	x	51.39 ± 40

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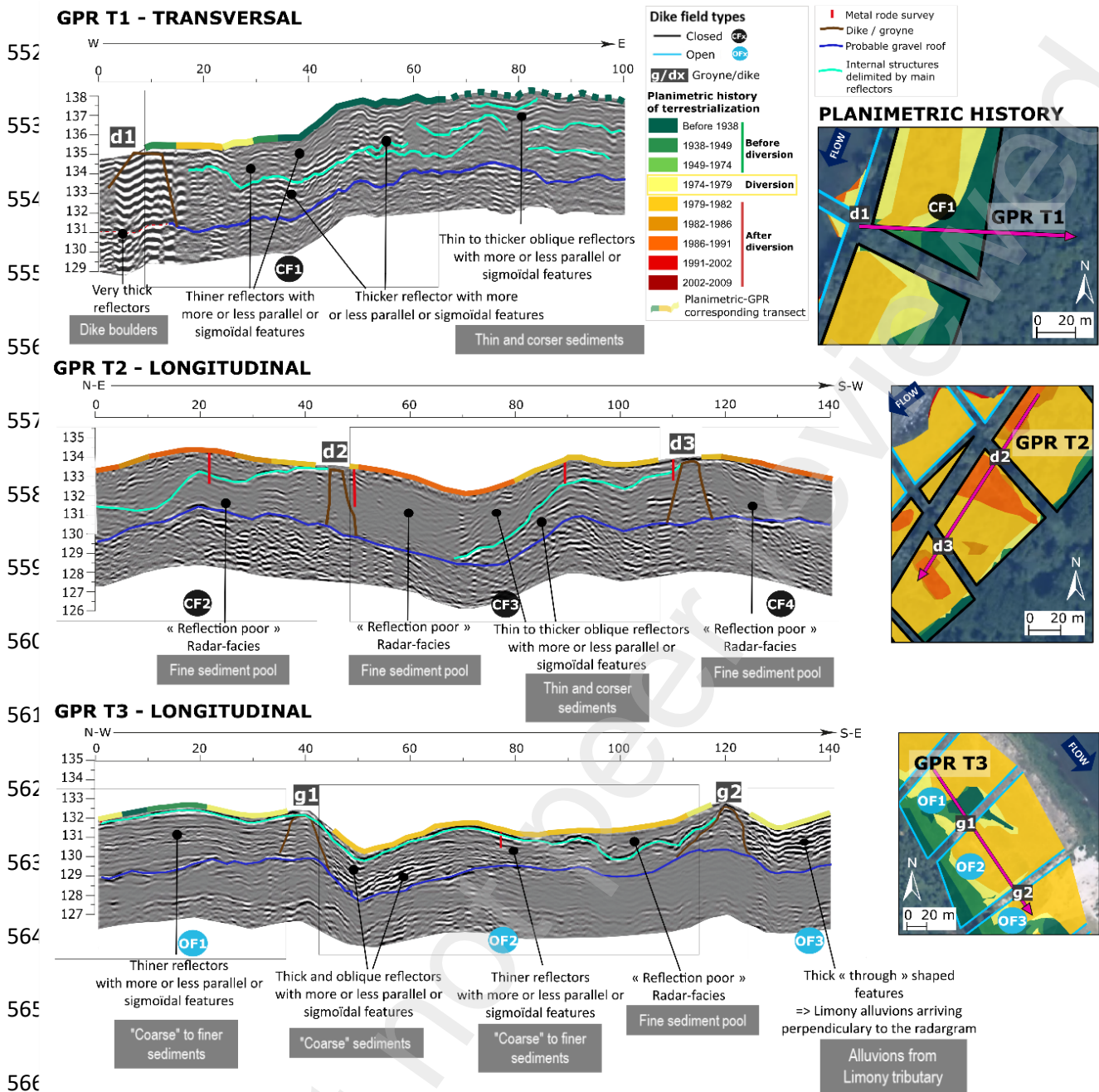
516 **4.3. Architecture of sedimentary deposits in relation to**
517 **terrestrialization patterns**

518 The architecture of the sedimentary deposits was approached by geophysical surveys to
519 corroborate their geohistory and better understand the vertical pattern. On the radargrams
520 (GPR outcomes), feature delimitations are drawn by the variation of the reflectors caused by
521 the changes in texture and density. It is then possible to identify structuring elements such as
522 the dikes or the gravel layer corresponding to the old river bed made up of coarse alluvium
523 (Figure 6). Above the thick reflector interpreted as top of the gravel layer, we observe different
524 structures, with more or less marked reflectors depending on the transects that we wanted to
525 be a representative panel of deposit structures according to the chronoplanimetry and DF type
526 (open/closed).

527 The GPR T1 transect is transverse. It crosses a closed field with a transversal pattern (CF1)
528 and extends over the alluvial floodplain. Between 3 and 4 m, there is a feature corresponding
529 to the longitudinal dike d1. Between 20 and 50 m, the reflectors located below the one
530 highlighted in yellow are thicker and present more or less parallel reflectors with sigmoid
531 patterns. The surface vector refers to the chronoplanimetry that can be observed on the
532 associated map: the levee located between 37 and 42 m is concordant with the change
533 between the pre and post-derivation period. The formerly terrestrialized surfaces (before 1938)
534 are higher than the recent ones (+2.8 to 3.5m).

535 The GPR T2 transect runs along the longitudinal dike of closed fields (CF2, CF3 and CF4)
536 located in two dike fields further downstream from the GPR T1. It crosses d2 and d3, two lateral
537 transverse support dikes. The radarfacies are generally less contrasted than those of the GPR
538 T1, in particular behind the d2 and d3 dikes corresponding to fine sediment pools (between 50
539 to 70 m and 115 to 140 m). Thicker sediments are observed under the reflector highlighted in
540 yellow between 70 and 110 m. All the chronoplanimetry of the transect corresponds to post-
541 derivation time windows. The fine sediment pools are associated with the period 1986-1991.
542 Topographically, there is little variability except at the level of the pool depression (about 1 m).

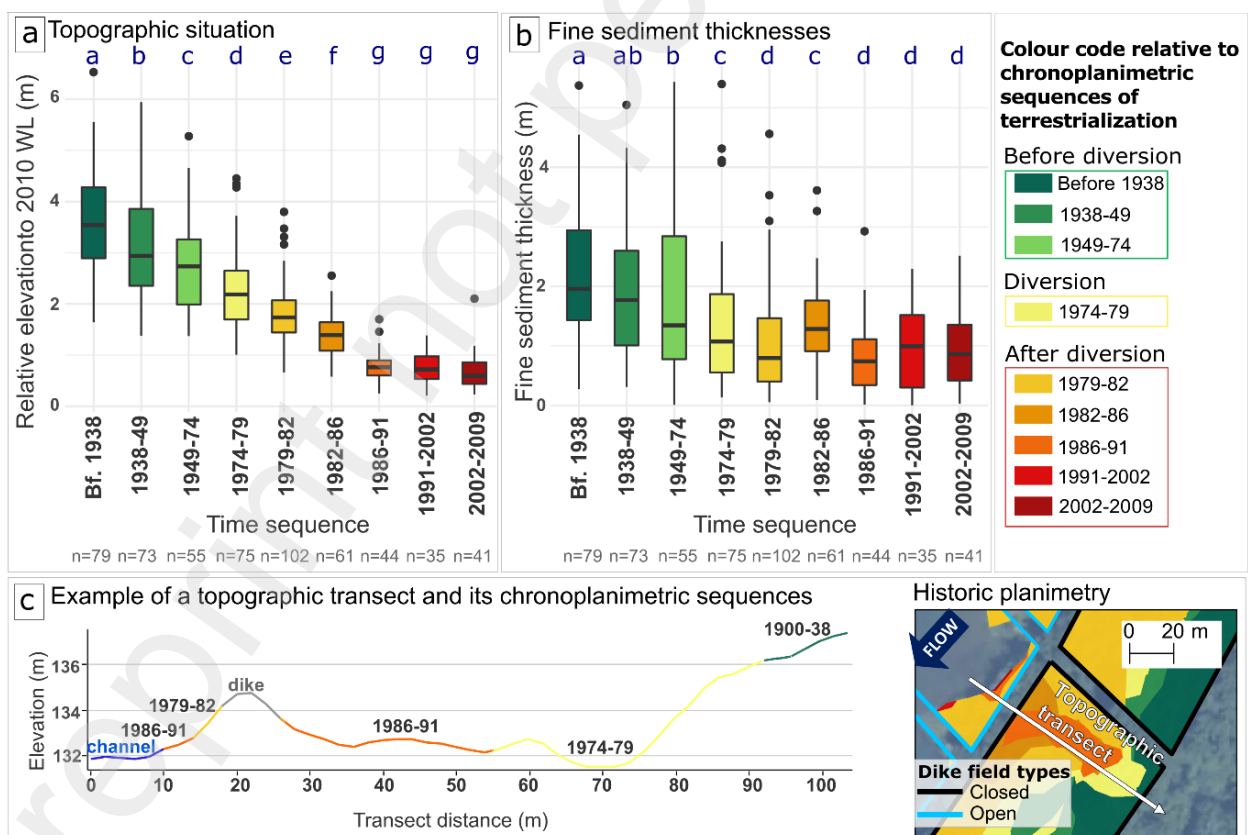
543 The GPR T3 transect covers open fields (OF1, OF2 and OF3) longitudinally to the channel in
544 an area mainly terrestrialized following the diversion (1979-1982). It crosses two groynes noted
545 g1 and g2. The reflectors here are much more contrasted and depict coarser alluviums than in
546 the closed fields. Between 0 and 38 m, the reflectors are rather parallel and thick until meeting
547 g1. After g1, there is a depression between 42 and 58 m which gradually reduced in direction
548 of g2. The reflectors are firstly thick and become thinner as we get closer to g2. Behind g2,
549 there is the beginning of another depression marked there also by underlying deposits with
550 very thick reflectors. Topographically, the variability is moderate on the T3 transect (delta of 2
551 m).



567 Figure 6: Ground Penetrating Radar survey of 3 transects crossing some closed fields (GPR T1 and
 568 GPR T2) and some open fields (GPR T3) and their associated planimetric history at PDR. (Data
 569 source: orthophotography of 2009, BD ORTHO, IGN; planimetric vectors from the dataset presented in
 570 section 3.1).

571 Data of topographic variability and fine sediment thicknesses - according to the periods of
 572 terrestrialization - were extracted from the LiDAR DEM and the thicknesses raster (Figure 7).
 573 The average elevation and fine sediment thickness values associated with each
 574 chronoplanimetric sequence were calculated within the dike fields ($n_{DF} = 135$) on the available
 575 dataset between RK 52 to 58. The elevations specific to the chronoplanimetric sequences

576 show a marked gradient (*cf.* Figure 7.a; Kruskal-Wallis, p -value $< 2.2e-16$) with higher
 577 elevations for the oldest sequences (maximum observed before 1938 = 3.63 ± 1 m) and lower
 578 elevations for the most recent sequences (maximum observed for 2002-2009 = 0.68 ± 0.3 m).
 579 The alluvial margins are stepped according to their geohistory with very distinctive limits (*cf.*
 580 Figure 7.b; Kruskal-Wallis, p -value $< 2.2e-16$). Also, all the Wilcoxon tests show significant
 581 difference of elevation except for the last three chronoplanimetric sequences that are more
 582 homogeneous. The example of topographic cross-section (Figure 7.c) illustrates topographic
 583 variability according to the period of terrestrialization and highlights a levee at the pre/post-
 584 diversion limit of the chronoplanimetric sequences (at 90 m). Greater thicknesses are observed
 585 with chronoplanimetric sequences from the beginning of the 20th century (max before 1938 =
 586 2.21 ± 1.1 m) compared to more recent ones (min for 2002-2009 sequence = 0.91 ± 0.64 m).
 587 However, the 1982-1986 sequence stands out, with significantly greater thicknesses than other
 588 post-diversion chronoplanimetric sequences (1.36 ± 0.7 m; *cf.* Wilcoxon tests on Figure 7.b).



589
 590 Figure 7: a. Topographic situation of the sediment deposits to the 2010 water line according to their
 591 terrestrialization history at PDR. Wilcoxon tests were performed and significant differences (p -value
 592 < 0.05) are specified according to the letter classification; b. Fine sediment thicknesses based on

593 calculations from the MNT Lidar dataset and the gravel roof model at PDR. Wilcoxon tests were
594 performed and significant differences (p-value <0.05) are specified according to the letter
595 classification; c. an example of a transversal transect crossing an open and a closed field at PDR, its
596 associated historic planimetry allowing the observance of before-after diversion heterogeneity. (Data
597 source: orthophotography of 2009, BD ORTHO, IGN; planimetric vectors from the dataset presented in
598 section 3.1). River bed and water line elevations changes caused by engineering developments and
599 associated DF disconnection
600

601 **4.3.1. Phase 1: channelized situation (1900s-1970s)**

602 On the sub-sector between RK 52 and 63, an average river bed incision of -0.92 m is observed
603 on phase 1 with a maximum of -3.41 m at RK 59 (Figure 8.a). A maximum bed incision of -
604 5.64 m is observed at RK 63.5, downstream of the studied sub-sector.

605 The 1902 and 1962 WL at low water evolve according to a regular upstream-downstream
606 gradient. They present rather equivalent slopes even if that of 1962 is slightly more pronounced
607 (1902 WL Slope: 0.0443% and 1962 WL Slope: 0.0475%). The 1962WL at low water is lower
608 than 1902 one, on average by -1.07m with local variations between -0,62 m (RK 50) and -1,79
609 m (RK 59). 1902 exact discharge at low water is unknown whereas one of 1962 is about 260
610 m³/s. So, the differences between them may be attributable to a possible effect of the river bed
611 incision phenomenon but also to a possible sensible discharge variation.

612 The river bed incision and the WL changes are also associated with an active channel
613 narrowing of 44.8 % with an average width (main + side channels) reducing from 360 m to 199
614 m, with 13.7% due to side channel disappearance between 1860 and 1974 (Table 3).

615 Also, at the end of Phase 1, the DF patterns are essentially aquatic, lateral and complex. They
616 are associated with low but variable terrestrialization rates of $28.3 \pm 29.6\%$ (Figure 8.b).
617 Besides, the average relative elevation (RE) of the DFs to the WL is interesting to approach
618 the channel-DF relationship: at the end of Phase 1, the 1962 RE of the DFs according to their
619 pre-diversion terrestrialization percentages (GLM model) is associated with a $D^2 = 0.55$. In this
620 relation, the more physically disconnected the DFs are from the WL, the more terrestrialized
621 they are.

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4.3.2. Phase 2: channelized and bypassed situation (1970s-2000s)

Between RK 52 and 63 of the study sub-sector, the river bed incision did not amplify (-0.13 m on average) during this phase 2 and so the longitudinal profile stabilized. On the other hand, a raising is observed upstream of the dam (max. at RK 50.5 with + 4 m) and a strong incision downstream of the sector when the Rhône is total again (average incision between RK 64 and 68 of -3.2 m and max of -5.1 m).

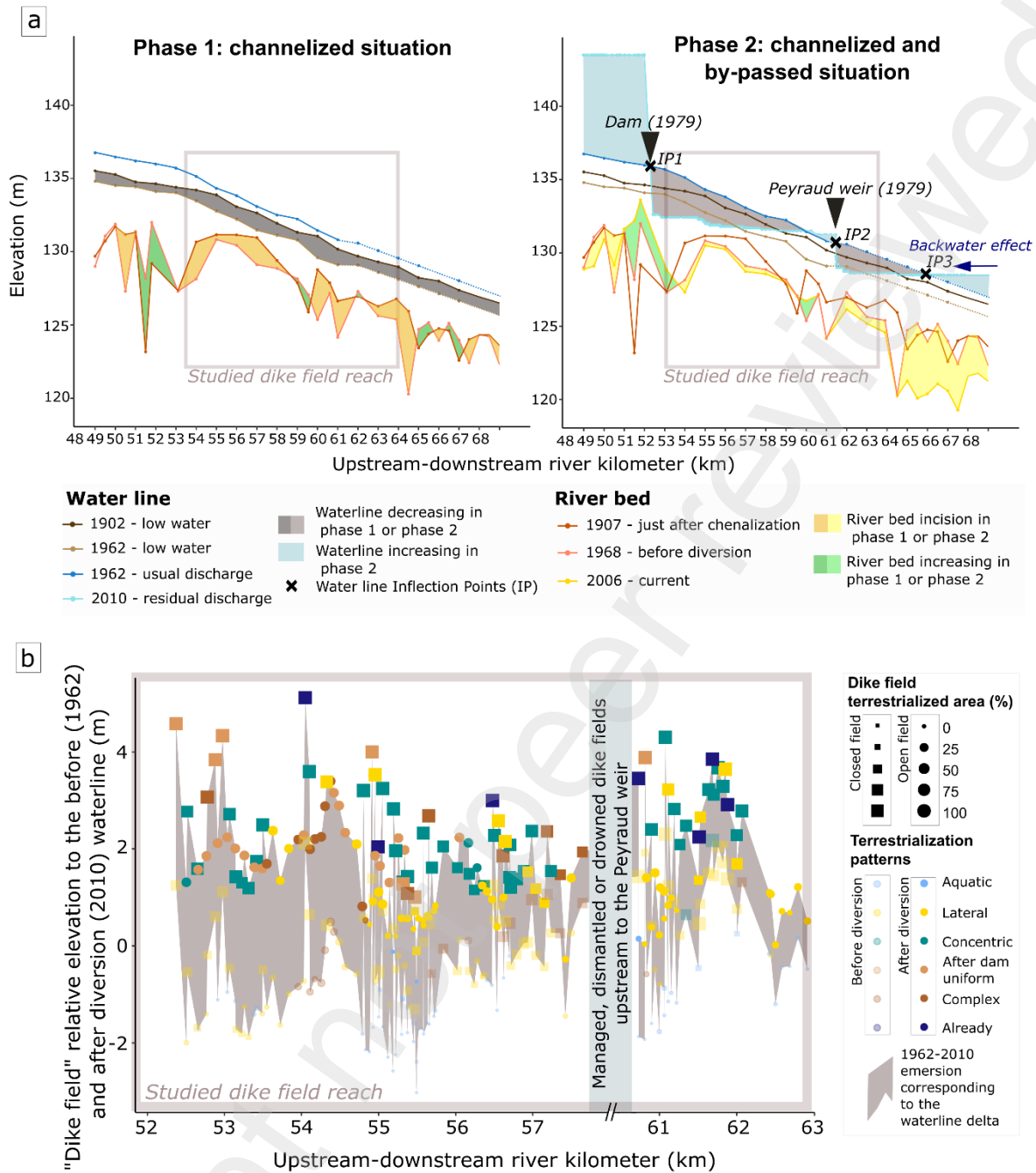
1962 WL with a mean annual flow and 2010 WL with a residual discharge are used to compare the situations in the average conditions before/after the installation of the diversion dam. The 1962 WL with a mean annual flow – just like 1962 WL with low water but higher on average of +1.62 m – evolves in a regular upstream-downstream elevation gradient. Flow diversion does not only cause a lowering of the WL due to the discharge reduction but also some WL slope changes. After a sudden fall at the level of the dam identified as Inflection Point 1 (IP1), the slope of the 2010 WL flattens (2010 WL Slope_{RK51-59}: 0.0165%) until meeting the Peyraud weir (IP 2 on Figure 8.a) where it falls and then flatten again. By comparing the 1962 and 2010 WL, if the two first IP are induced by the presence of the dam and the weir, the IP3 is marked by the fact that the slope is not recovering and the WL stays flat.

These WL changes are associated with an active channel narrowing of 10.4 %, the average width reducing from 199 m to 161 m (between 1974 and 2009). Currently, active channel only represents 45% of its 1860 area (Table 3).

Thus, the change in slope induces a change in the amplitude of the disconnection due to dewatering and the weir effect, by positively (between IP1 and IP3 except at the Peyraud weir location between RK 59 and RK 60.5) or negatively (before IP1, after IP3) incrementing the alluvial margins relative elevation according to the upstream-downstream gradient of the reach (Figure 8.b). The average delta between 1962 and 2010 WL resulted in an average dike field emersion of +2.22 m, with a maximum of +3.34 m at RK 52.4 just after the dam and a minimum of +0.98 at RK 62.9 not far before the IP3. Diversion-caused dewatering resulted by severely disconnecting the closed fields which are located relatively higher and more outside the channel (closed fields: $RE_{WL2010} = 2.34 \pm 1.03$ m, Distance = 13 ± 11 m to the 2000s active

651 channel). In contrast, the opened fields are settled in the channel (open fields: $RE_{WL2010} = 1.23$
652 ± 0.84 m, $D = 8.7 \pm 15$ m to the 2000s active channel but with an asymmetric distribution seeing
653 as median distance = 0 m) and proportionally emerged to the channel narrowing according to
654 location. Indeed, the rate of terrestrialization increase drastically directly after the flow diversion
655 but remain very variable with regard to open fields (*cf.* TA% in open fields with a large
656 distribution after diversion; observable on Figure 4).

657 The 2010 RE according to the post-derivation percentage of the dike fields (GLM model) is
658 associated with a $D^2 = 0.61$. Thus, the more physically disconnected the DFs are from the
659 WL, the more terrestrialized they are.



660

661 Figure 8: a. Upstream-downstream overview of the evolution of the water line and river bed elevation
 662 during phase 1 and phase 2 at PDR. State modalities for the water line survey are: during setting up
 663 the dike fields at low water (1902), before the establishment of the bypass at low and usual discharge
 664 (1962) and for the minimal flow (20m³/s in 2010) State modalities for the river bed survey are: just after
 665 setting up the dike fields (1907), before the diversion (1968) and about 28 years after diversion (2006)
 666 for the river bed survey (based on Parrot *et al.*, 2015); b. Before-after diversion dike field
 667 terrestrialization rates and patterns with regard to the water line change and the occurred emersion
 668 (comparison of the 1962 water line at the normal discharge and the 2010 water line at residual
 669 discharge); Note that for Figure 8.a. and 8.b., the WL 1962 (low and usual discharge) is only available
 670 between RK 48 and 60 and is extrapolated beyond.
 671

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Table 3: Active channel evolution at PDR from 1860 to 2009 (GIS survey)

Parameters	Objects on the PDR reach (11,12 km)	Date		
		1860	1974	2009
Area (ha)	Active channel (with side channels)	400,4	221,2	179,6
	Active channel (without side channel)	311,4	214,6	179,6
Width (m)	Active channel (with side channels)	360	199	161
	Active channel (without side channel)	280	193	161

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4.4. Part of the diversion-caused "dewatering" in the terrestrialization

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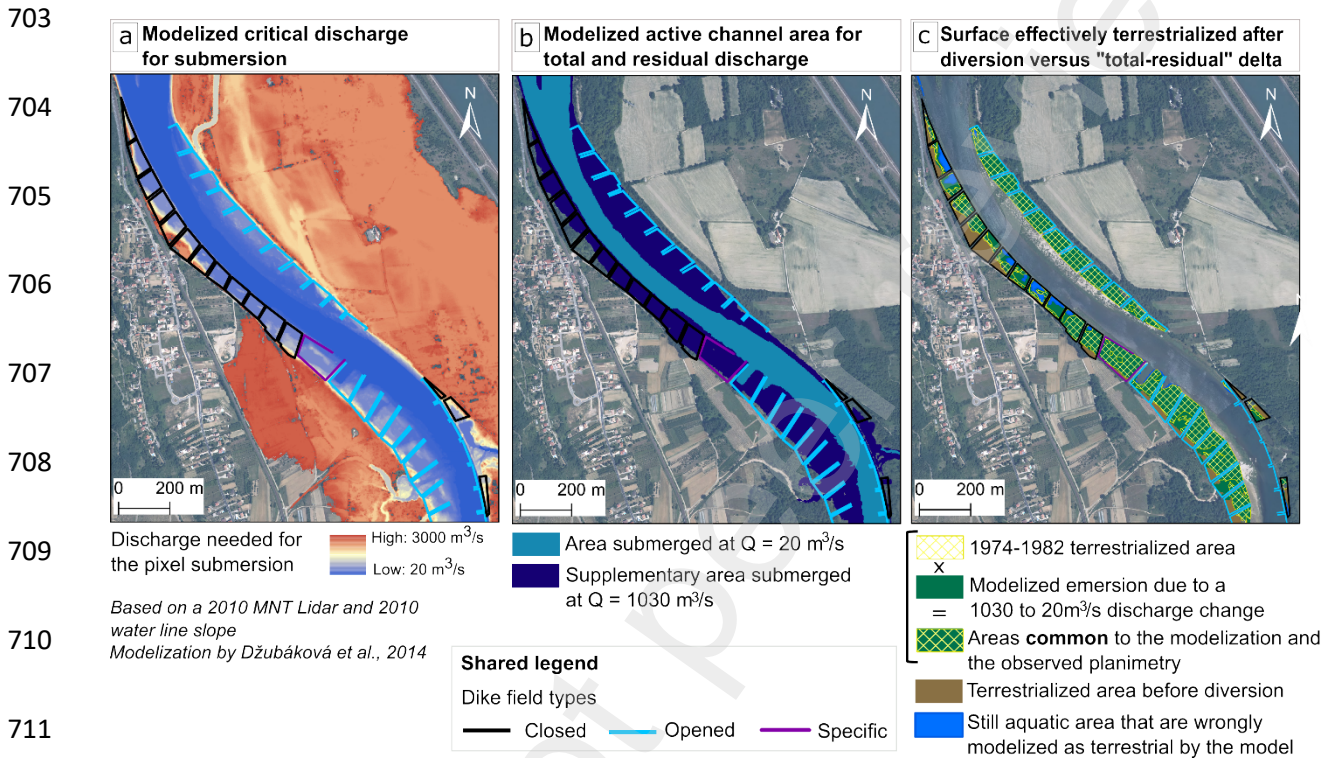
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By inferring discharge-corresponding active channel surfaces from the "critical discharge leading to the pixel submersion" model (Figure 9.a), the active channel narrowing due to the drastic flow reduction was estimated. The difference between the occupied surfaces with the total average water discharge (1030 m³/s) and the occupied surfaces at residual flow (20 m³/s) (Figure 9.b), provide an estimate of the dewatered areas which were compared to the surfaces actually terrestrialized at this period from chronoplanimetric data (Figure 9.c).

In the studied area (8.5 km from RK 52), planimetric outcomes shows that terrestrialized areas directly after the flow diversion (1974-1982 sequence) correspond to 39.5 ha out of a total DF area of 82 ha (*i.e.*, 47% of the total area including terrestrial and aquatic areas). It represents 75% of the total terrestrialized area (1900s-2009) and 80% of the terrestrialized areas during phase 2 (1979-2009). It should be noted that this upstream sub-sector is characterized by a weaker terrestrialization in phase 1 and a much stronger one in phase 2 (*cf.* part 4.1.) than the rest of the reach because of its position along the longitudinal gradient that is more impacted by the flow diversion induced dewatering (Figure 8.a). In exactly the same sector and sample of DFs, the narrowing areas obtained thanks to the "critical discharge" model corresponds to 38.5 ha. The extent intersection of active channel retraction model and the 1974-1982 terrestrialized area amounts to 68% of common surfaces (*cf.* Figure 9.c; green area squared with yellow). This 32% difference may be due to errors in the model or to the fact that it is based on the DEM Lidar of 2010. Thus, the volumes occupied by the sediments deposited during the post-derivation period are not subtracted. This may affect the deployment of water volumes and incorporates an error since they are modeled to deploy on the current topography of the margins instead of the pre-diversion one because of a lack of historical DEM LIDAR. Also, in the phenomenon of terrestrialization, sedimentary deposition processes also

698 participate in the creation of new terrestrial areas, which could involve additional spaces that
 699 are included on the chronoplanimetry of the 1974-1982 sequence and not in the active channel
 700 narrowing model. Also, 3.2 ha have been modeled as terrestrialized when in reality they are
 701 still aquatic. These spaces notably correspond to the aquatic zones of the concentric patterns
 702 (cf. Figure 9.c, blue area).



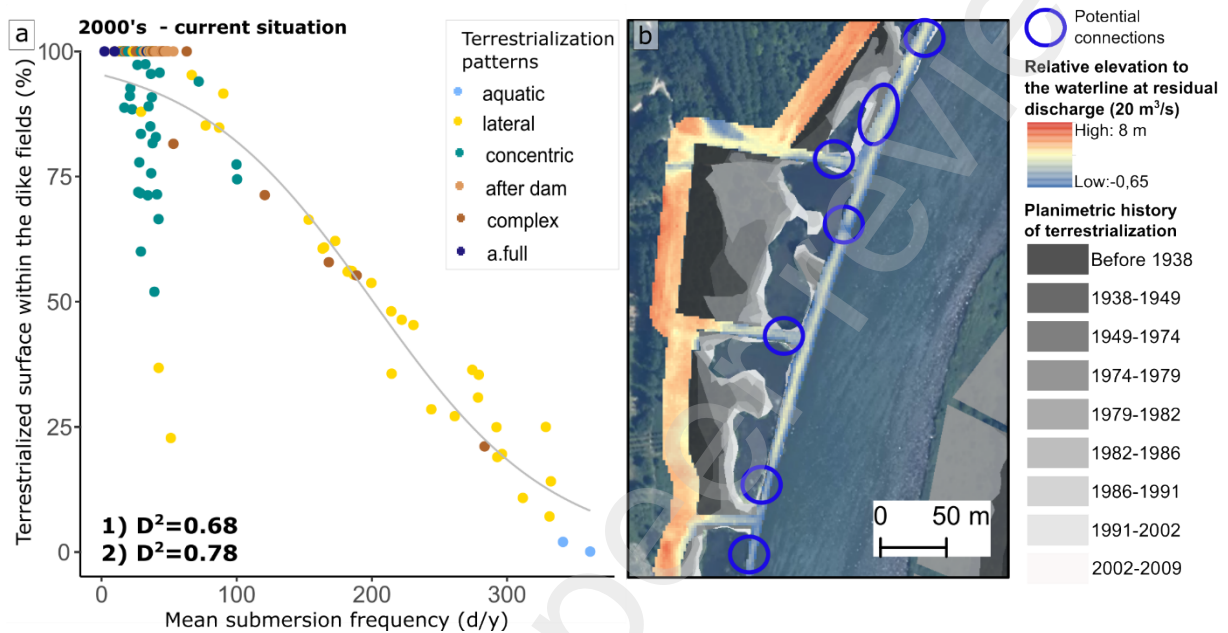
712 Figure 9: a. Modelized critical discharge for submersion of the alluvial margins and floodplain at PDR;
 713 b. Modelized active channel area corresponding to a total average discharge (1030 m³/s) and a
 714 residual discharge (20 m³/s) allowing; c. cross-checking of historical planimetry data and of the
 715 overflow-driven lateral submersion modelling (based on Džubáková *et al.*, 2014).

716 4.5. Current hydrological disconnexion versus local hydrological 717 connectivity hot-spot associate to concentric patterns

718 The average submersion frequency of DFs (Figure 10.a) according to their terrestrialization
 719 percentages in 2009 (GLM model) is associated with a $D^2 = 0.68$. As predictable, the less the
 720 dike fields are hydrologically connected, the more they are terrestrialized. Nevertheless, the
 721 outputs showed that the concentric patterns did not fit the model (cf. Figure 10.a). In this model,
 722 the percentage of terrestrialization associated with this submersion frequency range
 723 overestimates the percentage actually observed for concentric patterns. When we remove the

724 concentric patterns of the dataset, the model reaches a D^2 of 0.78 (Dev =41.4, p-value =
725 $1.237e-10$).

726 Moreover, Minimum dike RE above the channel support this observation by displaying some
727 enough low values with a strong variability (longitudinal dike minimum RE: 1.2 ± 0.7 m) for
728 concentric patterns (Seignemartin, 2020).



729

Figure 10: a. Current terrestrialized area according to mean overflow-driven lateral submersion frequency, associated GLM and highlighted exceptions of the concentric pattern type where D^2 (1) is calculated for the entire dataset, D^2 (2) excludes concentric patterns; b. Low spots, breaches in the dikes corresponding to potential hydrological connection points (based on 2010 Lidar DEM) at the level of closed fields with concentric patterns.

730 5. Discussion

731 5.1. About planform changes on the Rhône River and other highly 732 engineered rivers

733 The assessment of geomorphological evolution based on GIS is often carried out at a larger
734 scale as a part of an overall planform study (Arnaud *et al.*, 2015; Arnaud *et al.*, 2019; Piegay
735 *et al.*, 2019; Tena *et al.*, 2020). By developing a specific georeferencing method consisting in
736 using standardized georeferencing zones associated with recurrent "dike focused" ground
737 control points, the bias due to deformations is reduced and the precision at the dike field scale
738 is increased (low RMSE). The spatial and temporal accuracy of the obtained chronoplanimetry

739 then allows to distinguish several phases of the terrestrialisation phenomenon and patterns
740 within the dike fields.

741 The quantitative data (terrestrialized area and active channel narrowing) show that there is a
742 first “post-channelization” (1900s-1970s) phase with a system that adjusts to these first deep
743 changes. It corresponds to a terrestrialization of their cumulated areas reaching 47% in closed
744 fields and 16% in opened fields. Such a trajectory was already observed at the PDR reach
745 scale: the main and side channels present a surface decrease reaching 40% after the
746 channelization phase (1810-1938 area loss). After the diversion phase, it is a 20% additional
747 loss of surface for the main and side channels, *i.e.*, a total loss of 60% during these two last
748 centuries (Tena *et al.*, 2020). In the dike fields, the second phase (after the dam diversion) is
749 associated with a terrestrialization of 32 % in closed fields and 51% in opened fields of their
750 areas. In total, after the two phasis of engineering developments, these are 79% closed field
751 and 67% of opened field areas that have been terrestrialized. Thus, compared to the previous
752 overall “floodplain” assessment, DF terrestrialization percentages are quite similar or higher.
753 These results are in accordance to those find in the literature. For example, an average
754 channel width narrowing of 60% is observed between 1826 and 1991 on the Danube River
755 which has also been channelized (study reach extent: 10.25 km; Hohensinner *et al.*, 2004).
756 On the Piave River (Italy), that is much engineered with streambank protection structures,
757 hydroelectric dams (study reach extent: 110 km; Surian, 1999) a 58 to 70% active channel
758 narrowing was reported. On the Dordogne river in France (study reach extent: 162 km), the
759 12,2% active channel retraction from 1948 to 2012 was interpreted as combined effects of
760 streambank protection structures, regulation and sediment extractions (Boutault, 2020). At the
761 scale of groyne fields on the Danube River, Savic *et al.* (2013) observed that 40 to 80% of the
762 surfaces were currently filled with fluvial sediment materials. Thus, compared to other rivers
763 and alluvial compartments, the Rhône River DFs – which are a specific and very constrained
764 part of the engineered margins – have recorded a particularly drastic phenomenon of
765 terrestrialization. Nevertheless, surface losses of floodplain aquatic areas are even more

766 drastic in the former side channels of the Rhône River by reaching 90% during the few last
767 decades (Depret et al, 2017).

768 **5.2. Hydromorphologic processes underlying the phase 1: channelized**
769 **situation (1900s-1970s)**

770 Riverbed incision is an expected and commonly observed impact on channelized rivers (e.g.,
771 Wyżga, 2001; Brierley and Fryirs, 2005; Kroes and Hupp, 2010). Indeed, the purpose of the
772 DFs was to cause the channel to retract and concentrate the shear stresses in the center so
773 that it would deepen, thereby increasing the draft and promoting navigation conditions
774 (Girardon, 1883; Fruget, 1992). In this way, during the first phase, the channelization could
775 have definitely influenced the emergence of the surfaces adjacent to the active channel. In the
776 case of PDR, we can observe a channel narrowing and a simplification of channel geometry.
777 Also, the difference between 1902 and 1962 WL at low water shows a slight lowering of 1,07
778 m that can be a little more or less pronounced according to the potential difference of discharge
779 between low water of 1962 – 260 m³/s – and 1902, unknown). Although all these
780 hydromorphologic changes could indicate a riverbed incision (Simon and Rinaldi, 2006;
781 Zawiejska and Wyżga, 2010; Arnaud *et al.*, 2015; Parrot, 2015), PDR remains relatively
782 preserved (average elevation delta between 1897 and 1969 of -0,92 m) in comparison to other
783 sectors of the Rhône River (e.g., Pierre-Bénite reach: -4,05 m), even if it can reach high value
784 locally (max. of the reach: -3.41 m at RK 59). The bypassed reaches experienced an increase
785 in in-channel shear stresses with the channelization, so they experienced a phenomenon of
786 bedload transport leading to reduction and riverbed incision. At the PDR, shear stresses in the
787 channel likely increased with channelization but - in a cascade effect - the available sediment
788 load provided by the upstream channelized portion would offset the potential imbalance
789 between shear stresses and available sediment. This explains the moderate incision. On the
790 other hand, the Pierre-Bénite reach is located in the upstream part of the channelization work
791 and therefore does not benefit from the cascade effect and the associated upstream sediment
792 supply.

793 Also, if shear stresses have increased within the channel, DFs delimit areas where they are
794 reduced. By relying on the types of vegetation in their biogeomorphic function, it is possible to
795 attest of hydro-sedimentary tendencies (Bendix and Hupp, 2000; Corenblit *et al.*, 2009).
796 According to the diachronic photograph series (Figure 2) and previous studies (Seignemartin,
797 2020), sediment deposits located at the back of closed fields are terrestrialized and vegetated
798 since the first photographs (Figure 2: 1938, left bank). They seemed rather stable – slightly
799 increasing – and so, subject to limited scouring processes that remains weak enough to allow
800 development of trees (Figure 2: 1938, 1949 and 1974 series; Figure 3: associated quantitative
801 data). Open fields are for many aquatic but for those who have begun to terrestrialize (*e.g.*, on
802 Figure 2, right bank), the situation is quite similar to that observed on more flooded habitat
803 such as gravel bars (Gilvear and Willby, 2006; Francis *et al.*, 2006). They present open areas
804 that are under fluctuating water levels and stronger erosive processes where pioneer
805 vegetation can be sometimes observed (mainly herbaceous and shrubby layers; Seignemartin,
806 2020). The bareness of these sedimentary deposits or even the presence of pioneer vegetation
807 indicates greater instability and hydrological disturbance than where woody vegetation is able
808 to develop (Malanson, 1993; Corenblit *et al.*, 2009). In this situation, closed and opened fields
809 during the first half of the 20th century seem hydrologically connected to the channel and
810 subject to deposition and erosive processes according to magnitude of flood disturbance. The
811 morphological context (concavity, convexity, rectilinear zone), the density and specificities of
812 the DF – *e.g.*, relative elevation, geometry, type (open field versus closed fields), or the
813 characteristics of the closed field longitudinal dike such as its height, can explain local
814 variations in terrestrialization patterns, in particular by playing on shear stress conditions and
815 hydraulic recirculation patterns (Copeland, 1983; Sukhodolov *et al.*, 2002). The GPR surveys
816 also show that sediment internal structures are much more pronounced in the open fields.
817 Subjects to more shear stresses, they present sediment patterns that are more contrasted
818 (thicker reflectors on the radargrams; Figure 6 - GPR T3) associated with coarser grain size
819 (*e.g.*, case of the plunge pool downstream of groynes that are typical of energy dissipation
820 gradients; Figure 6 - GPR T3). On the contrary, closed fields showed a greater propensity for

821 fine sediment accretion along its distal side, probably due to the longitudinal dike and groynes
822 limiting shear stress.

823 In conclusion, geomorphological and biomorphic trajectories highlight the control factors of the
824 terrestrialization during phase 1. At PDR, although it is possible that the incision had a slight
825 impact – locally more or less pronounced – the terrestrialization seems to be driven by
826 sediment accretion processes due to the limitation of shear stresses in the DFs.

827 **5.3. Hydromorphologic processes underlying the phase 2: channelized** 828 **and bypassed situation (1970s-2000s)**

829 During phase 2, the incision is not amplified on the studied section (average elevation delta
830 between 1969 and 2009 of -0,13 m). Thus, the water level evolutions are almost entirely
831 attributable to the establishment of the bypassed reach in 1977. In this case, the flow reduction
832 in the bypassed reach has probably reduced in-channel shear stress; and mitigate incision
833 tendencies. A similar trend was observed on an old Rhine bypassed section by Arnaud *et al.*
834 (2015). On the other hand, we observe at PDR a phenomenon of pre-dam river bed
835 aggradation (depositional pattern) and post-dam incision (erosional pattern) (Figure 8.a –
836 Phase 2). It is a common morphological adjustment on engineered rivers of the northern
837 hemisphere: the dam reservoir leads to favorable conditions for sedimentary accumulation,
838 while downstream, the constraints caused by the flow, which has become total again, create
839 conditions favorable to incision (Kondolf, 1997; Ibisate *et al.*, 2013).

840 In the bypassed reach, the flow reduction had the direct effect of causing a dewatering leading
841 to the emersion of the channel edge areas. It also leads to a lowering and a change in slope
842 of the WLs, implying that margin emersion is expressed differentially according to the
843 upstream-downstream gradient depending on the angle of the change in slope (Figure 9.a and
844 9.b). To this upstream-downstream pattern is added the effect of the Peyraud weir, creating
845 an inflection point (IP 2 on Figure 9.b) which instigates new gradients at 2/3 of the reach. Its
846 installation in 1979 involved the dismantling and/or submersion of certain structures (*cf.* Figure
847 8.a., RK 59 to 60.5 at the Peyraud weir) which explains the absence of DFs studied at this

848 level. Finally, a backwater effect maintains and prolongs the flattening downstream of the water
849 line. In this case, it is the downstream connection of the bypassed reach with the main channel
850 which is impacted by the next downstream reservoir on the river. This phenomenon is typical
851 of bypassed configurations (Lamouroux *et al.*, 1999).

852 Within the reach, the longitudinal gradient of the water line is therefore marked by the dam, the
853 weir and the backflow effects. Therefore, the channel-alluvial margins connection relationship
854 evolves (in time and space) differently along this gradient. This differential hydrological
855 connection can be an additional explanatory factor for local variability within more global trends
856 of terrestrialization. It is added to the complexity associated to morphological context, density
857 and geometrical characteristics of the DFs that can influence the hydrological connection and
858 shear stress parameters of engineered margins.

859 After the flow diversion (1979), alluvial margins are then under the two-development impact by
860 being corseted and less hydrologically connected because of the regulation. Therefore, the
861 already accreted and/or dewatered surfaces are more inclined to be encroached by terrestrial
862 vegetation that can increase roughness and store fine sediments which will not be remobilized
863 as the erosive processes are reduced under regulated flood conditions. The GPR radargrams
864 testify that there are recent deposits (e.g., upper layers on the radargrams associated with
865 recent chronoplanimetric sequences, Figure 6) with a finer texture than previous deposits. On
866 the Rhône River, it is in line with the literature about overbank fine sediment storage in areas
867 enduring a loss of hydrological connectivity (Citterio and Piégay, 2009; Arnaud *et al.*, 2015;
868 Tena *et al.*, 2020; Vauclin *et al.*, 2020). Also, the roughness due to vegetation encroachment
869 is favorable to increase fine sediment accretion (Arnaud *et al.*, 2015). Indeed, vegetated
870 surfaces (herbaceous, shrubs and trees) evolve from 32.4% in 1974 to 55.2% in 1986 and
871 then stabilized around 61 % on the 1991 and 2009 series (Seignemartin, 2020). This
872 adjustment dynamic during phase 2 – whether in terms of channel narrowing, terrestrialization
873 or vegetation – is typical of post-dam adjustment trajectories. The initial response is intense

874 and followed by a of asymptotic relaxation (Graf, 1977; Surian and Rinaldi, 2003; Petts and
875 Gurnell, 2005; Arnaud *et al.*, 2015).

876 Also, according to Janssen *et al.* (2020), the current tree density in closed fields testifies to
877 rare disturbances spaced out over time: the wooded areas have increased over time and so
878 has the specific diversity. There is in particular the appearance of hardwood species, typical
879 of secondary successions (*e.g.*, *Fraxinus angustifolia*, *Ulmus minor*, *Acer campestre*) which
880 develop in within a riparian forest initially composed of softwood species (*e.g.*, *Populus alba*,
881 *Populus nigra*, *Salix alba*). Gradual disappearance of the recruitment niches of these tree
882 species testify to a hydrologically disconnected alluvial environment. In open fields, the
883 vegetation encroachment of shrubby layers is also more important on post-diversion
884 terrestrialized surfaces (Seignemartin, 2020). These observed vegetation patterns are
885 evidence that alluvial margins are characterized by overall hydrologic disconnection and that
886 only vegetation very close to the channel is representative of riparian habitat (Malanson, 1993;
887 Corenblit *et al.*, 2009; Corenblit *et al.*, 2014). (Malanson, 1993; Corenblit *et al.*, 2009; Corenblit
888 *et al.*, 2014).

889 To the impacts of developments on the studied section are added the pressures and their
890 impacts on the scale of the Rhône watershed (*e.g.*, gravel mining in the active channel until
891 the 1990s). Also, Vázquez-Tarrío *et al.* (2018) showed in particular that a multi-dam series can
892 have a cumulative impact on sediment transfers and geomorphic interaction between
893 successive reaches; which is our case here because the PDR reach corresponds to the second
894 diversion dam of a series of eleven between Lyon and the Mediterranean Sea.

895 **5.4. From deposition patterns to terrestrialization ones:** 896 **correspondences, specificity and contribution of the chronoplanimetric** 897 **approach**

898 A classic reference in the field is the classification of sediment deposition patterns established
899 by Sukhodolov *et al.* (2002) from flume experiments and observations on the Elbe River. Based
900 on the proportion of filling and the deposition forms, their inter-groyne typology presents seven

901 patterns that are also observable in our classification (*cf.* Figure 11 and Table 4). Our aquatic
902 type can refer to the “weak deposition” of Sukhodolov. Lateral patterns gathered many forms
903 found in Sukhodolov typology: “upstream” and “downstream triangle shaped deposition”,
904 “upstream” and “downstream wave shaped deposition”, “uniform partial” and “complete
905 deposition”. Our typology does not segregate them because the approach here tends to break
906 away from local hydraulic controls and enlighten the impact of the main fluvial modifications.
907 Indeed, the objectives of Sukhodolov *et al.* (2002) were to make the link between flow
908 recirculation and sedimentary deposition at one date and a local scale whereas we seek to
909 highlight at the cumulative developments that lead to terrestrialization over a century at a reach
910 scale.

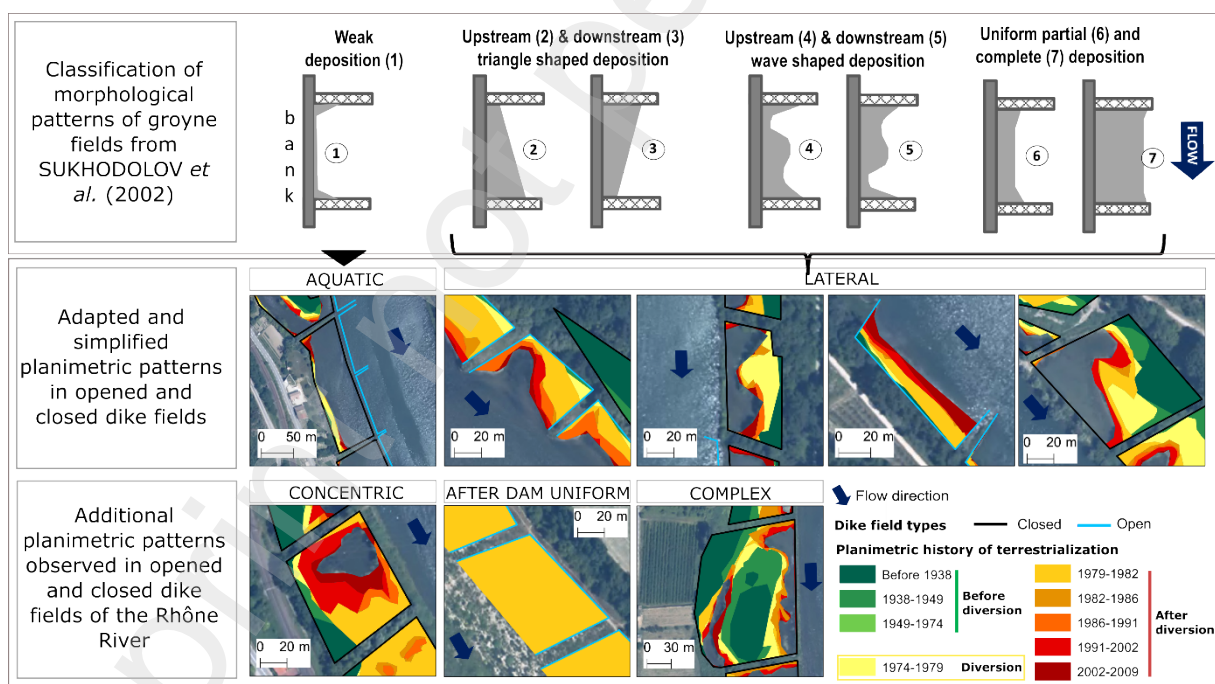
911 In addition to these corresponding patterns, there are additional ones that are related to the
912 Rhône River engineering developments and geomorphological specificities. Indeed, the case
913 of closed fields which presence of the longitudinal submersible dike might complexify the
914 hydrological connection terms and play on scour patterns by involving other parameters (dike
915 height, possible dike breach, etc.). One of the main pattern particularities of closed fields is the
916 recurrence of concentric type that is observed with two current states: semi-aquatic with pool
917 within the concentric shapes or fully terrestrialized. In the semi-aquatic case, the current
918 hydrological connectivity is underestimated by the average submersion frequency of DFs
919 (Figure 9.a). Indeed, that kind of patterns seems to be conditioned by breaches or lower spots
920 in the dike that induce water inlets (Figure 9.b) which instigate circulating flows, scouring
921 patterns with enough shear stress to shape concentric forms and associated water ponds for
922 still aquatic ones (Figure 9.b). For fully terrestrialized one, chronoplanimetries show that they
923 become terrestrial shortly after flow diversion. They are associated with former concentric
924 water pool that fill up with fine sediments (Figure 6 - GPR T2). Uniform type is another
925 additional pattern that retranscribes the direct effect of the flow diversion and its associated
926 dewatering (Figure 8.c).

927 Also, local variability (presence of former side channels, old islands, etc.) is associated with
928 “complex shapes” of which surface is more or less terrestrialized and which patterns evolve

929 according to the initial form implied by the geomorphological specificities (e.g., accretion
 930 around an old island, within former side channels).

931 This GIS approach provides terrestrialization patterns that are diachronic on a very large
 932 sample of DFs. They endow a whole spatio-temporal dimension which provides information on
 933 local particularities but also on the overall transformations of the alluvial margins. After
 934 identifying major changes, it would be possible to focus on intra-class variation of patterns,
 935 notably by studying the DF geometric parameters and hydraulic indicators. GIS produced
 936 datasets could also be computed with existing hydraulic model outcomes (e.g., in Copeland,
 937 1983; Sukhodolov *et al.*, 2002; McCoy, 2006).

938 Moreover, the relevance of a planimetric approach to characterize sedimentary deposits is
 939 validated by the comparison of planimetric patterns with topography (Figure 7.a). It confirms
 940 the methodology but also offers an interesting tool for the chronological characterization of
 941 sedimentary deposits, taking the characterization towards 4D.



942
 943 Figure 11: Comparison of the terrestrialization patterns within the dike fields at PDR and the inter-
 944 groynes deposit patterns of Sukhodolov *et al.* (2002)
 945

946

Table 4 : Classification of terrestrialization patterns and Sukhodolov correspondences

Type	Description	Correspondence to the Sukhodolov classification
Aquatic	The surface of the dike structure is mainly aquatic (aquatic surface > 85% of the dike structure extent).	Weak deposition
Lateral	The surface of the dike structure is partially terrestrialized; laterally to the bank.	Upstream & downstream triangle shaped deposition Upstream & downstream wave shaped deposition Uniform partial and complete deposition
Concentric	The surface of the dike structure is highly terrestrialized. Areas with progressive concentric closures may remain aquatic.	No correspondence Additional pattern observed in closed field
After dam uniform	The surface of the dike structure corresponds to a uniform terrestrialized band caused by the lowering of the water line (after diversion).	No correspondence Additional pattern due to diversion
Complex	The surface of the dike structure is more or less terrestrialized. Stationary variability (presence of former side channels, old islands, original dike configurations, etc.) causes complex forms.	No correspondence Additional pattern due local complexity

948

949 **5.5. Implications for adapted river restoration measures**

950 DF terrestrialization constitutes a logical channel response to the Rhône River hydrological
 951 disconnection. In a distal logic, it first affected the side channels (Citterio and Piégay, 2009;
 952 Riquier *et al.*, 2017), then the distal part of DFs and ended up affecting the DF proximal areas
 953 with different situations according to local shear stress changes and effects of new
 954 infrastructures on longitudinal water level. If the DF could have been thought of as aquatic
 955 functional relays to the side channel (Thorel *et al.* 2018; Franquet, 1999), they lose their
 956 potential as fluvial annexes (refuge habitats) once they have become terrestrial. In contrast,
 957 their primary function is still at work since they continue to constrain the alluvial margins,
 958 impacting alluvial functionality and questioning their future within the framework of ecological
 959 restoration programs (Räpple, 2018; Thorel *et al.*, 2018).

960 At the level of the connected dike fields, the zones of privileged hydrological connection allow
 961 the maintenance of aquatic and concentric patterns making these dike fields which come
 962 closest to the concept of “novel ecosystem” (Morse *et al.*, 2014). These features present hydro-
 963 sedimentary dynamics that seem to be the most in a new equilibrium under current functional
 964 conditions since these allow them to preserve a semi-aquatic character; all consideration kept
 965 of an incision context and forecasting of water discharge decrease. At the level of concentric
 966 patterns that are fully terrestrialized, there are residual pits inherited from before-dam erosive
 967 dynamics, then filled with fine sediments (Figure 6 - GPR A). Thereby, these pools are

968 representative of a high connectivity which allows water inputs with enough smooth erosive
969 processes to maintain fine sediment deposits but no longer sufficient to maintain aquatic pools.
970 They draw attention to the fact that there is a hydrological connectivity threshold that could be
971 assessed. Currently restoration programs are on a bimodal restoration strategy between DF
972 conservation or dismantling. It would be interesting to elaborate a further adaptive strategy
973 aiming to recreate hydrological connectivity gradients favorable to a mosaic of semi-aquatic
974 habitats. It would imply a dike field reconnection model – inspired by the effective side channel
975 reconnection strategies (Riquier *et al.*, 2017) – via lowering or removing certain dikes in order
976 to maintain ecotones that have a high potential for biological diversity and ecological
977 functioning (Risser, 1990; Naiman and Décamps, 1997; Ward *et al.* 1999). A work of
978 modulation of instream flow in the bypassed could also make possible to recreate the
979 necessary hydrological connections.

980 These operational prospects are to be considered taking into account overall trajectories, in
981 particular the potential effect of climate change on environmental and socio-economic
982 systems. It would notably impact magnitude and timing of streamflow (Beniston, 2012;
983 Beniston and Stoffel, 2014; Clarvis *et al.*, 2014; Rahman *et al.*, 2015). Flow regulation is under
984 control in the bypassed sections and might be impacted by management changes, notably
985 with a potential increase of extreme events (Beniston and Stoffel, 2014). Already impacted by
986 by-pass dam and pumping, water table sinking and retraction has caused less hydromorphic
987 conditions that have affected riparian vegetation development and community composition
988 (Dufour, 2007). The non-bypassed parts but also the intake channels could be subject to
989 streamflow reduction. In this case, a potential retraction of the water table could lead to gradual
990 dewatering and an alteration of groundwater-alluvial areas interactions; exacerbating even
991 more the floodplain hydrological disconnection at a larger scale.

992 This approach also provides sediment diagnosis useful in the framework of restoration
993 programs. For example, at PDR in a sub-sample of 147 DFs defined for restoration purposes,
994 volumes of 675,000 m³ of fine sediment overlaying 723,500 m³ of coarse sediment are

995 estimated, spread over a cumulated area of 77.1 ha. Allowing a 4D characterization of the
996 alluvial margins, this cross-validation (geohistory-geophysics) could guide the sanitary
997 assessment by prioritizing the sampling of terrestrialized areas where the chronology of
998 contaminant flow peaks is concomitant with (Seignemartin *et al.*, 2022).

999 **6. Conclusion**

1000 Updating the study of infrastructure "sediment deposition", intra-dike field terrestrialization
1001 patterns by GIS shed light on the prevalence of engineering developments in their evolutionary
1002 trajectories by controlling hydrosedimentary and vegetation processes within the dike fields
1003 and in the main river channel.

1004 The Rhône River chenalization transformed the multi-thread channel into a single channel,
1005 marked by a shear stress concentration in the main stem with more or less incision (*e.g.*, low
1006 at PDR compared to other bypassed Rhône River reaches, cf. Parrot, 2015) and the set-up of
1007 new semi-aquatic engineered alluvial margins. The DFs have then experienced a first stage of
1008 partial terrestrialization which may be due to a sedimentation along the distal edge of DFs due
1009 to shear stress reduction. The second phase initiated by the flow diversion participates directly
1010 to the margin terrestrialization: cross-checking of models underlines that diversion-induced
1011 dewatering has provoked the emersion of almost the half of the DF extent on the upper part of
1012 the studied reach (75% of the total terrestrialized area). It also modifies drastically the
1013 hydrological connectivity of the floodplain. So, the margins are even less hydrologically
1014 connected and therefore more inclined to vegetation encroachment, roughness increase and
1015 fine sediment deposits which will not be remobilized (erosive processes reduced under
1016 regulated flood flows). This is even more exacerbated by peak flow magnitude and recurrence
1017 decrease following derivation, reducing shear stress in the DFs.

1018 The DF terrestrialization is ending up telling the story of a drastic disconnection of the Rhône
1019 River from its riparian ecosystem, become a rarely "flooded" plain. Indeed, it constitutes an
1020 expected extension to the phenomenon of hydrological disconnection of the Rhône River
1021 which, in a distal logic, first affected the side channel and progressively the DFs, then that get

1022 carried away with the second development phase and ended up by affecting the proximal
1023 channel margins. Therefore, it led to an area reduction of side channels, a loss of semi-aquatic
1024 features and therefore their ecotone and refuge habitat functionalities. Concerning the
1025 rehabilitation masterplans, a dike field reconnection in line with hydrological reality (a
1026 strategical dike removal or lowering) could support the river in recreating gradients of
1027 hydrological connectivity that it is no longer capable of creating or maintaining on its own. In
1028 this context of profound modifications of rivers to the point that we qualified them of
1029 "anthropocene rivers", it is essential to assess the evolutionary trajectories of these anthropo-
1030 ecosystems in order to target ecosystemic dysfunctions and lost functionalities with a view to
1031 proposing some functional(ity) rehabilitation measures adapted the hydro-sedimentary reality
1032 of river systems.

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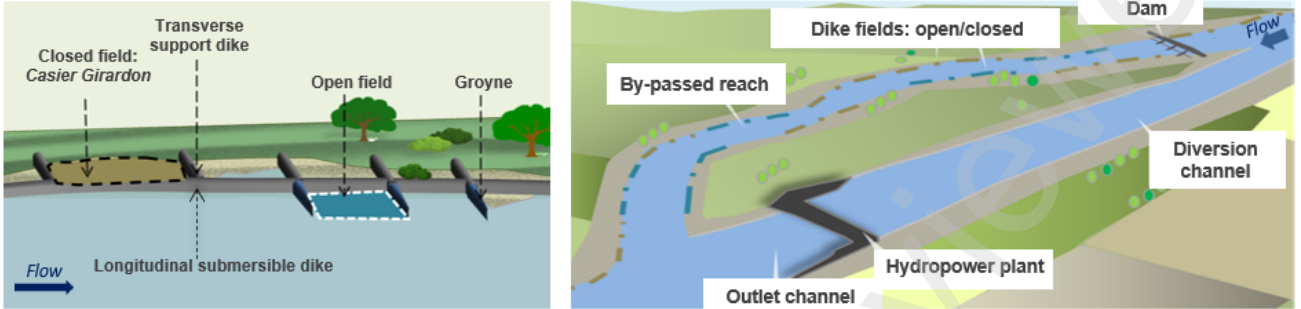
1339

9. Supplementary material

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Annex 1: engineering interventions (phase 1 and 2) and associated features on the Rhône River

① [1880-1900] Dike field setting for channelization ② [>1950/1970] Diversion dam installations



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Annex 2: characteristics of the photograph series

Year	Source	Date	Scale or resolution*	Photo type	Color type	Mean discharge (m ³ /s) **	Mission ID
1938	IGN	17/08/1938	1/24172	Argentic	B&W	877	C3410-0221_1938
1949	IGN	01/10/1949	1/16673	Argentic	B&W	342	C3031-0551_1949
1974	IGN	26/07/1974	1/18577	Argentic	B&W	510	C3033-0201_1974
1979	IGN	20/06/1979	1/17515	Argentic	B&W	1140	C2934-0041_1979
1982	IGN	09/07/1982	1/14202	Argentic	B&W	810	C3329-0031_1982
1986	IGN	25/06/1986	1/20718	Argentic	Color	882	C2928-0012_1986
1991	IGN	16/07/1991	1/17665	Argentic	Color	731	C91SAA2002_1991
2002	IGN	20/05/2002	1/25306	Argentic	Color	1200	CP02000012_2002
2009	IGN	04/06/2009	66 cm	Numeric	Color	634	CP09000262_FD38F80

*the scale varies slightly from one shot to another in the same campaign

**mean discharge levels at Ternay gauging station – non-bypassed part

1343