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# Dike Fields as Drivers and Witnesses of 20th Century Hydrosedimentary Changes in Highly Engineered Rivers

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1 **Dike fields as drivers and witnesses of 20<sup>th</sup> 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 19<sup>th</sup> 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-20<sup>th</sup> 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 19<sup>th</sup> 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 20<sup>th</sup> 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 km<sup>2</sup> of which  
96 90,500 km<sup>2</sup> are located in France. It flows into the Mediterranean Sea with an average annual  
97 discharge of 1700 m<sup>3</sup>/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 19<sup>th</sup> 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.

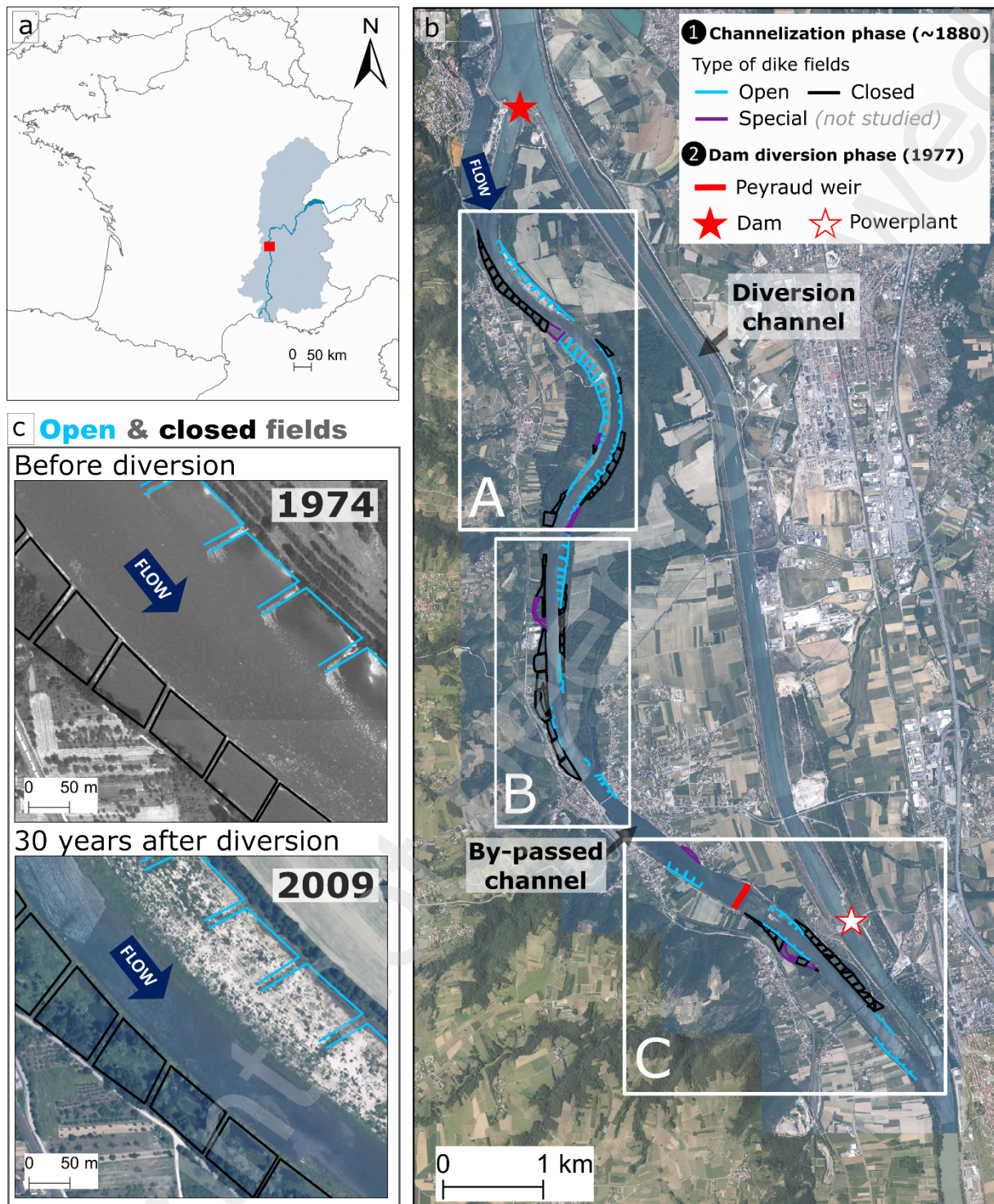
126 The studied reach is located in the Middle Rhône at the Péage-de-Roussillon section (PDR),  
127 which is one of the bypassed reaches of the river. It is 12.6 km-long and extends from the 50.6  
128 River Kilometer (RK) to the 63 RK downstream of the city of Lyon (Figure 1.a & Figure 1.b).

129 This reach historically presented a braided pattern pursued then by a meandering style before  
130 the 19<sup>th</sup> and 20<sup>th</sup> 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 m<sup>3</sup>/s (Ternay gauging station) but since the diversion in 1977, only a minimal flow of 10 to 20  
139 m<sup>3</sup>/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 m<sup>3</sup>/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 m<sup>3</sup>/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).

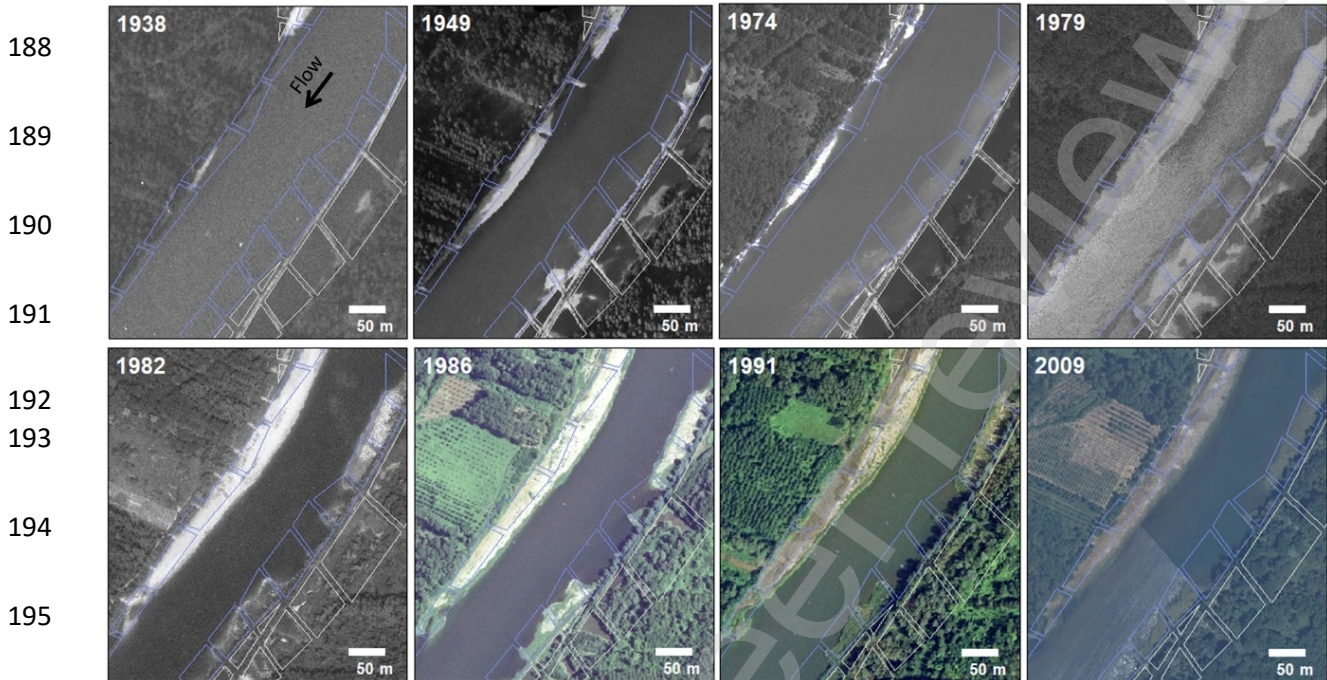
#### 169        **3.1.        Planimetric evolution of terrestrialization**

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 20<sup>th</sup> 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.

### 197 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  $4.1 \pm 1.6$  m (1938 series) and  $2.2 \pm 0.9$  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 20<sup>th</sup> 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 m<sup>3</sup>/s) and mean annual flow (1080 m<sup>3</sup>/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        m<sup>3</sup>/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 m<sup>3</sup>/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 20<sup>th</sup> 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 <sup>th</sup> century	Channelization effect on water line NB: similar discharge conditions
1962	CNR	60 years after channelization, before flow diversion	Low water (260 m <sup>3</sup> /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 <sup>3</sup> /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 <sup>3</sup> /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 
$$\text{Dike field RE (m)} = \frac{\text{dike field elevation averaged on its total extent}}{\text{water line elevation in the cross section}} \quad (3)$$

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 m<sup>3</sup>/s (mean annual discharge at the nearest gauging  
349 station) and to 20 m<sup>3</sup>/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 m<sup>3</sup>/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 m<sup>3</sup>/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.

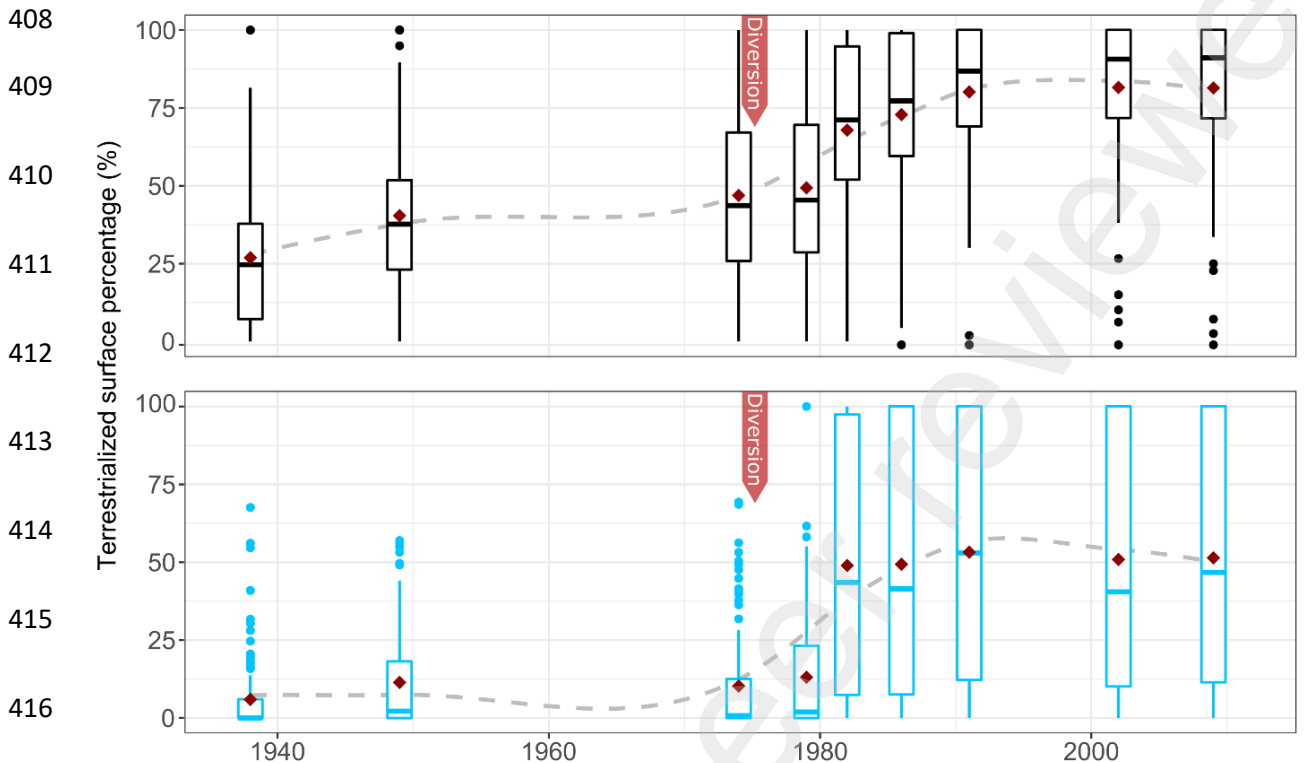
384 During the second phase, the terrestrialization phenomenon gets carried away. In the closed  
385 fields, over the period 1979-1982, the average TA had considerably increased from 49.3% to  
386 67.9%. After this strong acceleration, terrestrialization slowed down again and the TA  
387 stagnated 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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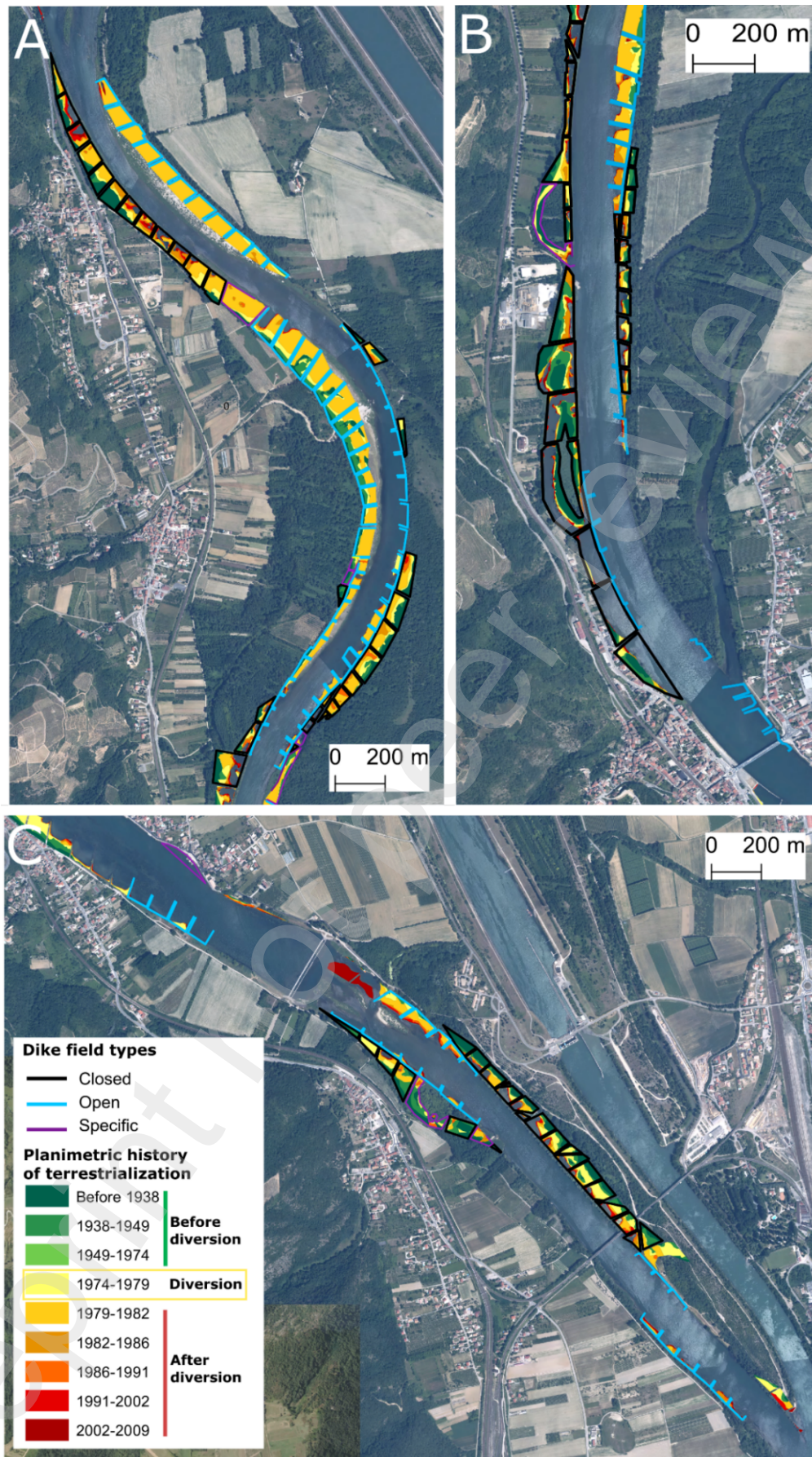


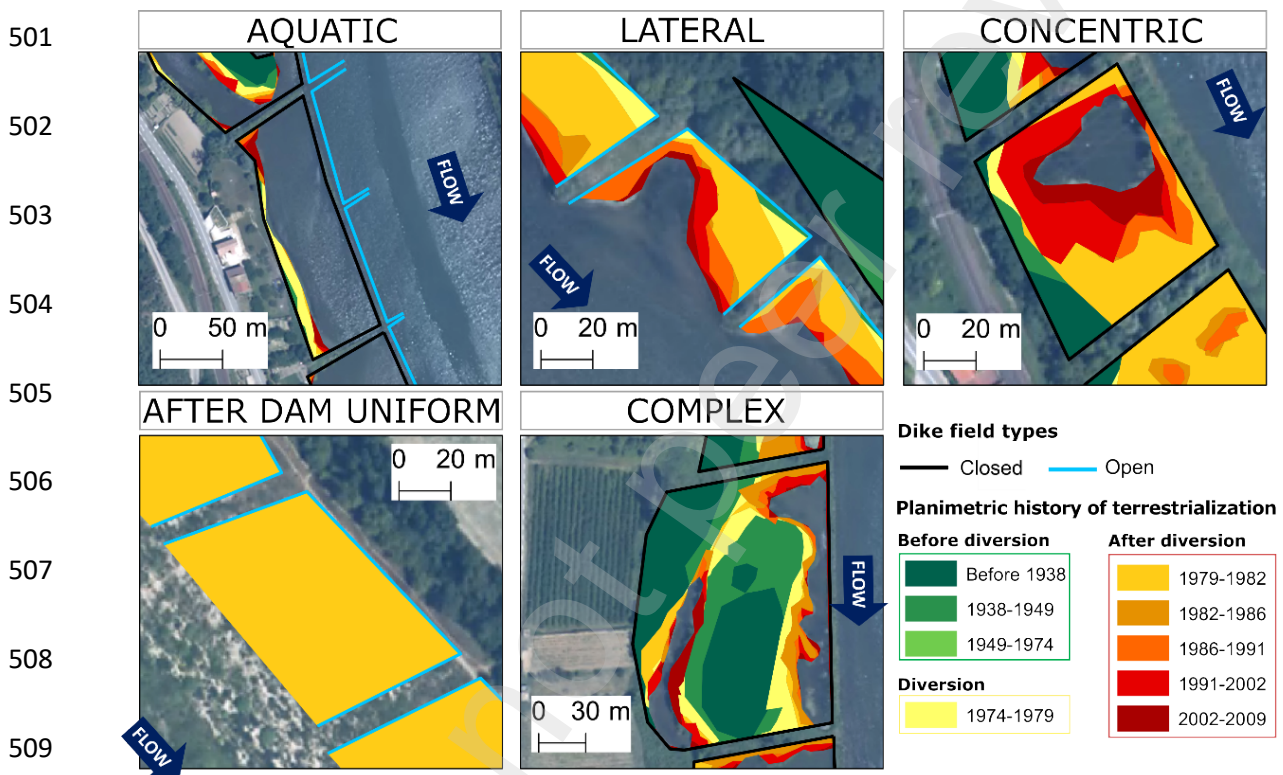
Figure 4: Planimetric patterns of terrestrialization through time within the dike fields of the Péage-de-Roussillon bypassed reach during the 20th century. Sub-sectors a, b and c are localized on Figure 1. (Data source: orthophotography of 2009, BD ORTHO, IGN; planimetric vectors from the dataset presented 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 20<sup>th</sup> 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  $3.2 \pm 5.2$  %), 49 are lateral (TA%:  $50.4 \pm 25.3$ ), 3 are concentric ones (TA%:  $89.6 \pm 10.7$ %),  
 496 20 are after-dam uniform ones (TA%:  $96.2 \pm 17$ %) and 14 are complex (TA%:  $85.3 \pm 26.2$ %).  
 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)	$4.9 \pm 3.3$	$66.1 \pm 31.8$	$85.1 \pm 12.8$	100	$84.6 \pm 23.5$	100	$81.4 \pm 24.5$
Open fields	Count (n)	30	41	3	20	14	x	108
	TA% (Average $\pm$ SD)	$3.2 \pm 5.2$	$50.4 \pm 25.3$	$89.6 \pm 10.7$	$96.2 \pm 17$	$85.3 \pm 26.2$	x	$51.39 \pm 40$

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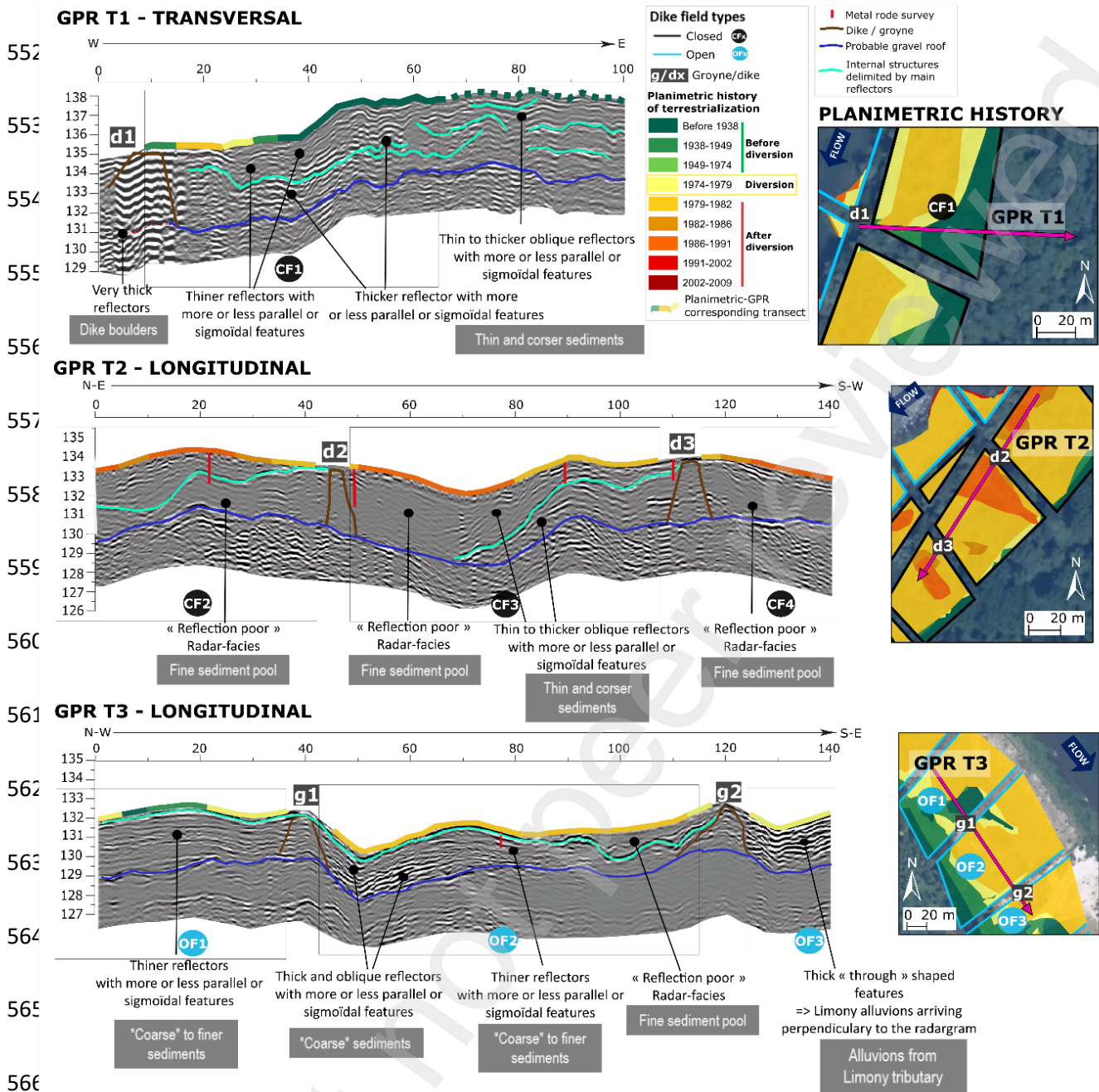
516 **4.3. Architecture of sedimentary deposits in relation to**  
517 **terrestrialization patterns**

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).

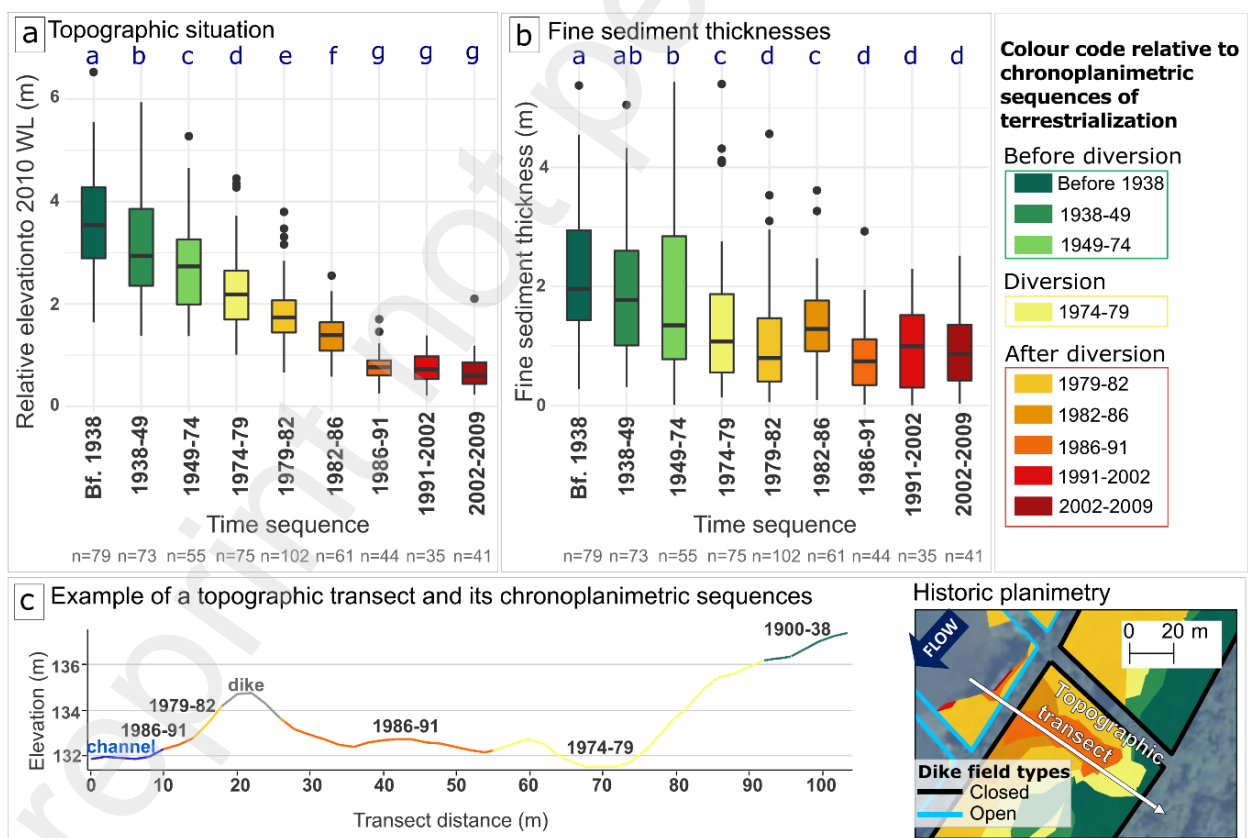
543 The GPR T3 transect covers open fields (OF1, OF2 and OF3) longitudinally to the channel in  
544 an area mainly terrestrialized following the diversion (1979-1982). It crosses two groynes noted  
545 g1 and g2. The reflectors here are much more contrasted and depict coarser alluviums than in  
546 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 =  $3.63 \pm 1$  m) and lower  
 578 elevations for the most recent sequences (maximum observed for 2002-2009 =  $0.68 \pm 0.3$  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 20<sup>th</sup> century (max before 1938 =  
 586  $2.21 \pm 1.1$  m) compared to more recent ones (min for 2002-2009 sequence =  $0.91 \pm 0.64$  m).  
 587 However, the 1982-1986 sequence stands out, with significantly greater thicknesses than other  
 588 post-diversion chronoplanimetric sequences ( $1.36 \pm 0.7$ 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  
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#### 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 m<sup>3</sup>/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).

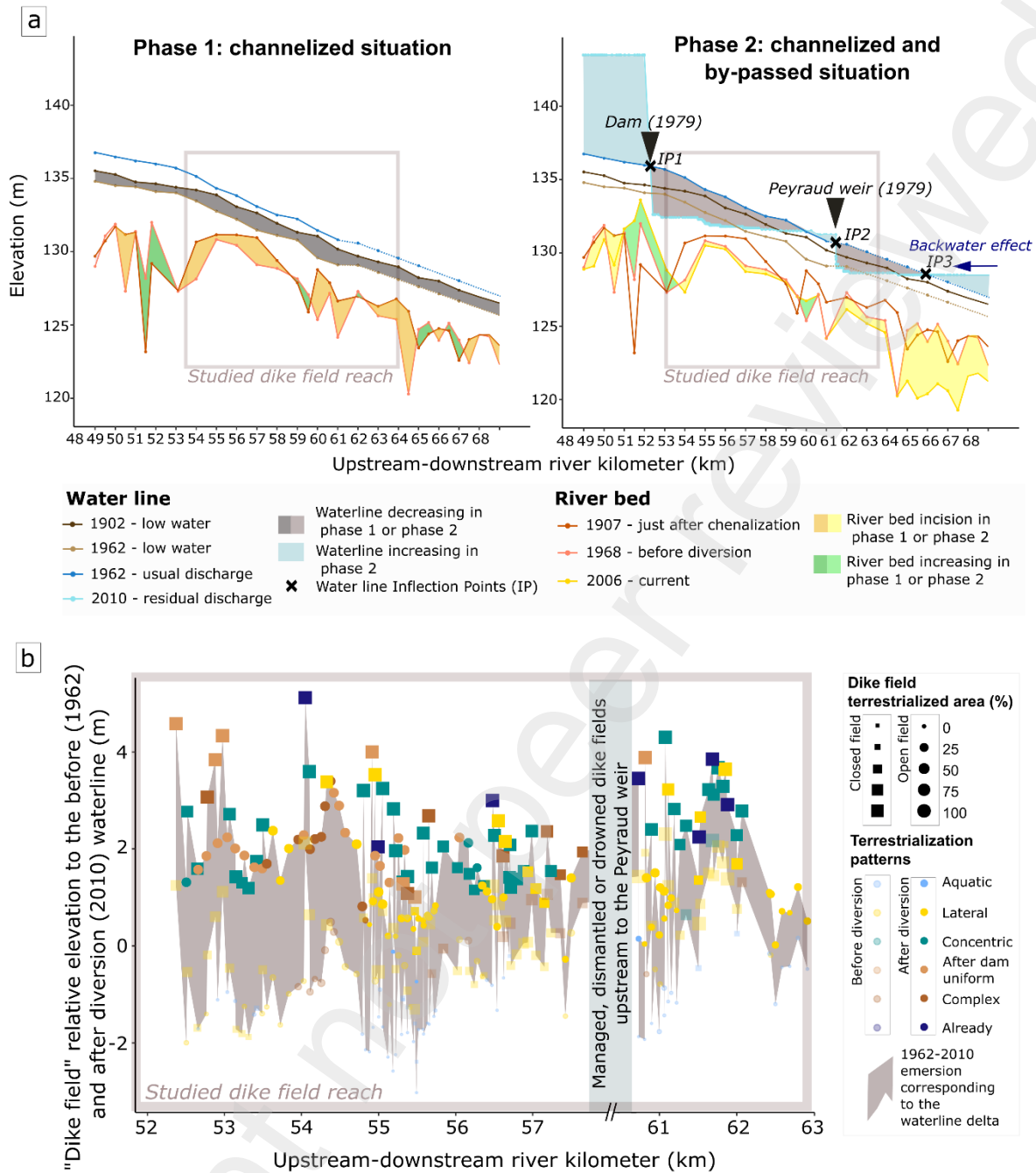
1962 WL with a mean annual flow and 2010 WL with a residual discharge are used to compare the situations in the average conditions before/after the installation of the diversion dam. The 1962 WL with a mean annual flow – just like 1962 WL with low water but higher on average of +1.62 m – evolves in a 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<sub>RK51-59</sub>: 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 =  $13 \pm 11$  m to the 2000s active

651 channel). In contrast, the opened fields are settled in the channel (open fields:  $RE_{WL2010} = 1.23$   
652  $\pm 0.84$  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.



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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 (20m<sup>3</sup>/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.

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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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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 m<sup>3</sup>/s) and the occupied surfaces at residual flow (20 m<sup>3</sup>/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).

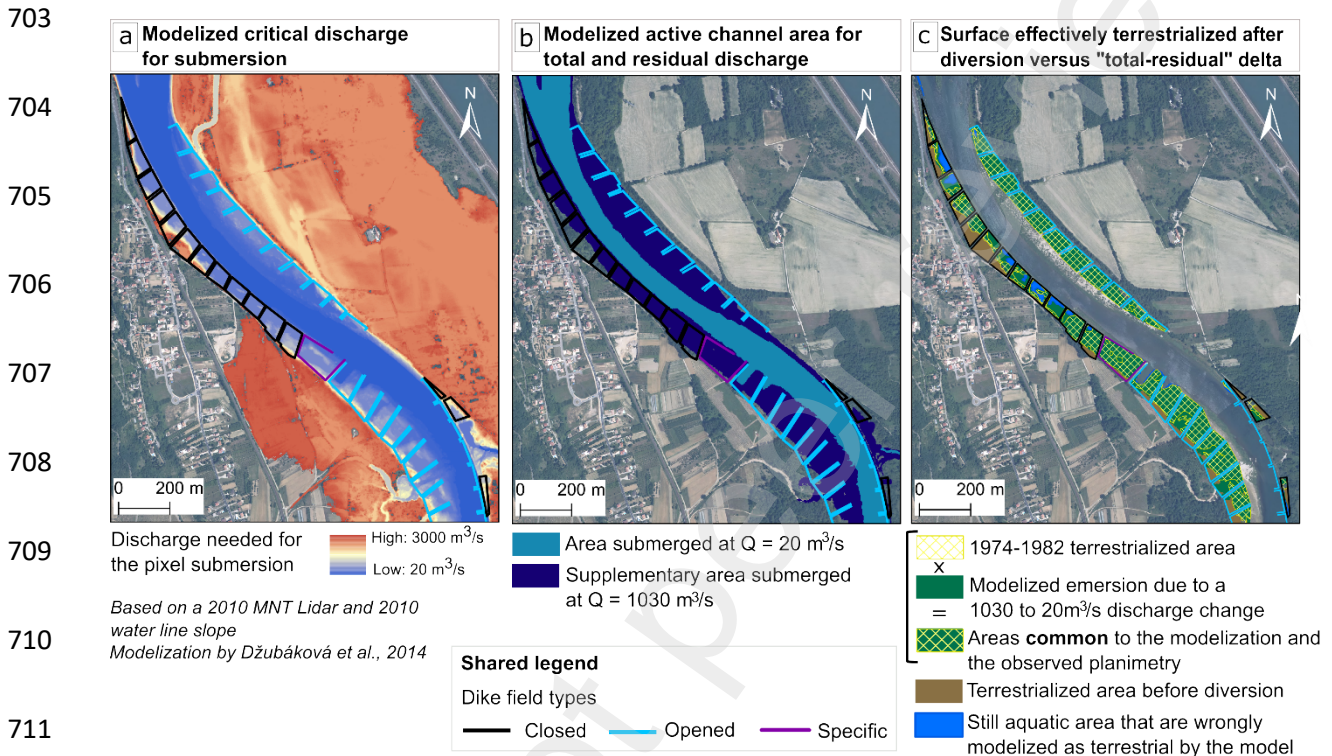


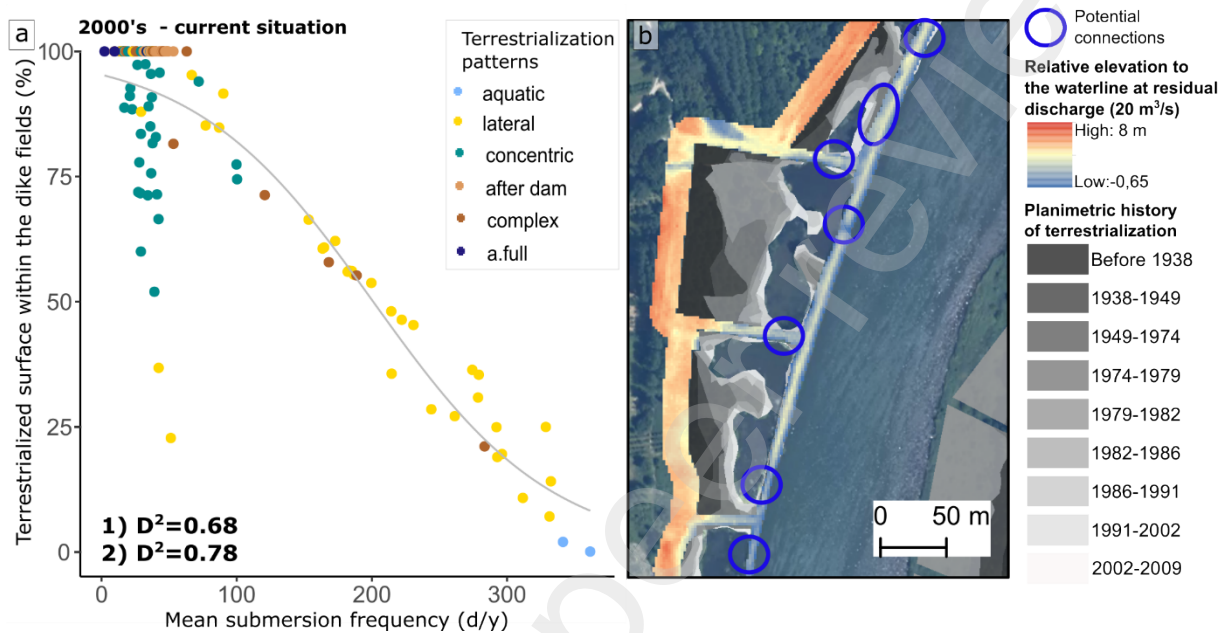
Figure 9: a. Modelized critical discharge for submersion of the alluvial margins and floodplain at PDR;  
 b. Modelized active channel area corresponding to a total average discharge (1030 m<sup>3</sup>/s) and a  
 residual discharge (20 m<sup>3</sup>/s) allowing; c. cross-checking of historical planimetry data and of the  
 overflow-driven lateral submersion modelling (based on Džubáková *et al.*, 2014).

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

The average submersion frequency of DFs (Figure 10.a) according to their terrestrialization percentages in 2009 (GLM model) is associated with a  $D^2 = 0.68$ . As predictable, the less the dike fields are hydrologically connected, the more they are terrestrialized. Nevertheless, the outputs showed that the concentric patterns did not fit the model (cf. Figure 10.a). In this model, the percentage of terrestrialization associated with this submersion frequency range 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:  $1.2 \pm 0.7$  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 m<sup>3</sup>/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 20<sup>th</sup> 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.

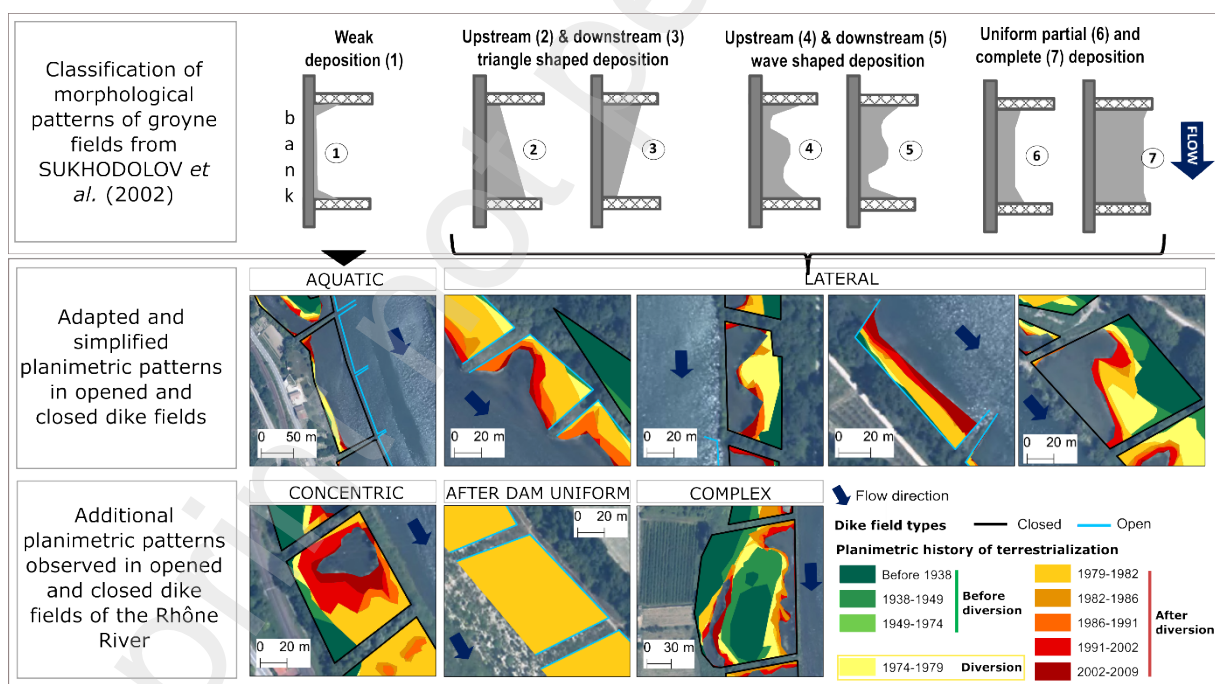
911 In addition to these corresponding patterns, there are additional ones that are related to the  
912 Rhône River engineering developments and geomorphological specificities. Indeed, the case  
913 of closed fields which presence of the longitudinal submersible dike might complexify the  
914 hydrological 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 m<sup>3</sup> of fine sediment overlaying 723,500 m<sup>3</sup> 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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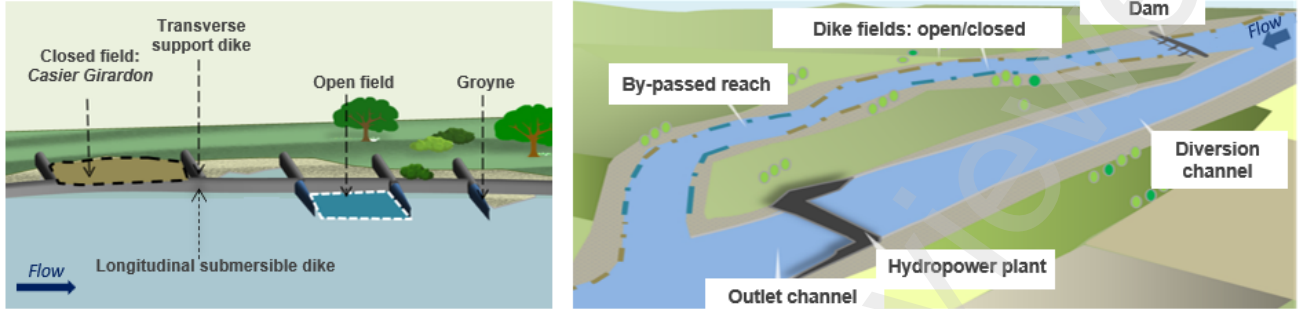
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## 9. Supplementary material

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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 <sup>3</sup> /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

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