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1 Efficiency and sustainability of gravel augmentation to restore large regulated rivers: insights  
2 from three experiments on the Rhine River (France/Germany)

3

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## 11 **Highlights**

- 12 • Erosion of stockpile deposits (SDs) is highly dependent on local hydraulic conditions  
13 and sediment grain size
- 14 • A high channel morphological diversity downstream of gravel augmentations (GAs)  
15 increases their positive effects in terms of habitat improvement
- 16 • The effects of GAs are transitory due to the downstream transfer of the sediment  
17 wave in the absence of an upstream sediment supply
- 18 • The feedback from the 3 experiments allows us to formulate operational guidelines  
19 and management scenario fostering the efficiency and sustainability of GA operations

20

## 21 **Abbreviations**

- 22 • Cross-section diversity index: CSD
- 23 • Gravel augmentation: GA
- 24 • Kilometric Point: KP

2

- 25 • Maximal Velocity Ratio: MVR
- 26 • Regierungspräsidium Freiburg: RPF
- 27 • Stockpile Deposit: SD
- 28 • Suitability Index Ratio: SIR

29

### 30 **Abstract**

31 Over the last two centuries, rivers were strongly regulated, inducing notable sediment  
32 starvation and flow reduction. This regulation altered aquatic habitats, biocenosis and  
33 ecosystem services. Gravel augmentation (GA) is increasingly promoted to restore bedload  
34 transport, rejuvenate bed sediments and diversify aquatic and riverine habitats. However,  
35 practical questions remain in terms of efficiency and sustainability. The objective of this  
36 study is to provide feedback from three GA experiments conducted along the Rhine River  
37 downstream of the Kembs dam (France/Germany). The restored sites were monitored over a  
38 time period from 1 to 7 years according to the sites so that the stockpile deposits (SDs) and  
39 channel responses were compared to highlight the strengths and limitations of such  
40 experiments. The monitoring was based on topo-bathymetry, bedload tracking and grain size  
41 surveys. Two-dimensional hydraulic modeling was also performed to link the SD erosional  
42 patterns to critical flow conditions. We show that (i) SD erosion is dependent on the grain  
43 size of the introduced sediments and the local flow velocities, (ii) sediment dispersion  
44 occurred mostly along the thalweg and increased over time, with a progressive decrease in  
45 the virtual velocities, (iii) bathymetric simplification and bed grain-size fining were observed  
46 when the downstream sediment diffusion began, but (iv) at mid-term (~ 5 years) local  
47 channel diversifications occurred due to the fragmentation of the sediment waves with  
48 deposition occurring preferentially on riffles, and (v) new sediment starvation conditions

49 appeared when the sediment waves travelled downstream in the absence of an upstream  
50 sediment supply. The results allow us to propose operational recommendations and  
51 management scenario to improve both the efficiency and the sustainability of GAs  
52 conducted in large regulated rivers.

53 Key-words: Gravel augmentation, Restoration, Large rivers, Geomorphic monitoring,  
54 Feedbacks, Operational guidelines

## 55 **1. Introduction**

56 Numerous large rivers have been strongly affected by regulation (Kondolf et al., 2014).  
57 Damming is one of the most common infrastructures affecting both water and sediment  
58 fluxes, and it often generates sediment starvation below the dams (Kondolf 1997; Wheaton  
59 et al., 2004; Petts and Gurnell 2005; Magilligan and Nislow 2005). These conditions cause  
60 severe and irreversible geomorphic alterations, such as bed incision, bed armoring and  
61 active channel narrowing, which disturb both aquatic and riverine habitats and impair  
62 ecosystem services (Kondolf, 1997; Cooper et al., 2017). Moreover, dams accumulate  
63 sediments, reducing the reservoir capacities and their life span (Kondolf et al., 2014).  
64 Several management strategies were tested to improve the transparency of dams and  
65 partially restore downstream bedload transport. These strategies include permanent  
66 remediation solutions, such as sediment bypass and sediment pass-through (Sumi et al.,  
67 2004). Mechanical excavation of reservoirs and downstream sediment releases have also  
68 been used (Kondolf et al., 2014). Dams are also removed, as in the USA where 1,100 dams  
69 have been removed in small to moderate watersheds (10 to 1000 km<sup>2</sup>) since the 1970s (Foley  
70 et al., 2017). Alternative measures consist of mitigating sediment starvation below dams,  
71 e.g., by reactivating bank erosion after removing riprap protection (Staentzel et al., 2018a),

72 reactivating old side channels, remobilizing sediments stored in floodplains (Landon, 2008;  
73 Thorel et al., 2018), and implementing gravel augmentations (GAs) (Kondolf et al., 2014; Ock  
74 et al., 2013).

75 GA is becoming a common practice because it provides rapid geomorphic improvement by  
76 diversifying bedforms, grain size, and flow conditions (Wheaton et al., 2004.a). First, GAs  
77 were conducted in the USA during the 1960s in the form of an ambitious program for fish  
78 spawning rehabilitation along 13 dammed rivers in California (Kondolf and Matthews, 1991;  
79 Pasternack et al., 2004). In some cases, the GAs were combined with the mechanical  
80 creation of in-channel geomorphic features, such as riffles (Pasternack et al., 2004; Ock et  
81 al., 2015). Between 1968 and 2000, 316,000 m<sup>3</sup> of sediments were introduced for a total  
82 cost of \$3,000,000 (Rollet 2007). More recently, GAs were also implemented below 15  
83 Japanese dams (Sumi et al., 2004; Ock et al., 2013). In Europe, the first GAs were realized in  
84 1978 on the Rhine River below the Iffezheim dam (yearly mean volume of 170,000 m<sup>3</sup>) to  
85 counteract bed incision and maintain a stable water level for navigation (CHR, 2009). GAs  
86 were also employed on gravel-bed alpine rivers (Brousse et al., 2018; Heckmann et al.,  
87 2017), boulder-bed steep reaches (Downs et al., 2016) and large regulated rivers (Schälchli  
88 et al., 2010; Klösch, 2011; Arnaud et al., 2017). Ock et al. (2013) noted several strategies  
89 employed to inject sediment into rivers as in-channel bed stockpile, high-flow stockpile,  
90 point bar stockpile and high-flow direct injection.

91 The restoration of fluvial macroforms by GA improves river ecological quality and  
92 functionalities. For example, Ock et al. (2015) showed on the Trinity River that in-channel bar  
93 development following GA enhanced hyporheic fluxes. Zeug et al. (2013) showed on the  
94 Lower American River that both salmon and trout populations increased following GA due to

95 an increase in spawning areas. Staentzel et al. (2018b) showed that the taxonomic richness  
96 of macroinvertebrates increased after a GA experimental operation on the Rhine.

97 Geomorphic assessment of GA is generally carried out over short-term periods (1 to 3 years)  
98 and usually focuses on channel topo-bathymetric changes and sediment mobility (Table 1).

99 Grain size diversification and fining are expected, but the results are infrequent because  
100 measuring underwater grain size is still challenging. On the other hand, field studies and  
101 modeling approaches evaluating the critical conditions for eroding the stockpile deposit (SD)  
102 are needed to improve such restoration practices. Numerical modeling studies have shown  
103 that various geomorphic responses can be obtained depending on the SD geometric  
104 configuration (Battisacco et al., 2016; Juez et al., 2016). This was recently validated in the  
105 field by Stähly et al. (2019). To optimize the channel response to GA, additional insights into  
106 channel grain size, SD location and geometry and local hydraulic conditions are needed.

107 Implementing a GA operation is not risk-free. Gaeuman et al., 2017 presented three  
108 different modes of sediment pulses which are dispersion, translation/dispersion and  
109 fragmentation.

110 In case of sediment translation, large amounts of sediment may travel quickly and impact  
111 navigable reaches downstream of the bypassed reaches. Moreover, bedload transport  
112 reactivation may destabilize the armor layer (Koll et al., 2010) and bank protections (Arnaud  
113 et al., 2017). The proper hydrological functioning of floodplain excavations along incised  
114 rivers for flood retention purposes may also be disturbed by bed elevation changes.

115 The aim of this paper is to present a comparative analysis of three GAs based on short/mid-  
116 term (from 2009 to 2017) geomorphic monitoring conducted on a bypassed reach of the  
117 Rhine River downstream of the Kembs dam (France/Germany). The objectives are to (i)  
118 define the best hydraulic conditions to erode, and therefore remobilize rapidly, the SD, (ii)

119 evaluate channel responses in terms of sediment mobility, morphodynamics and bed grain  
 120 size as well as the corresponding temporal scales of these evolutions, (iii) perform a risk  
 121 analysis to avoid any negative impacts on human and management issues such as bed  
 122 incision, navigation and flood retention, to consolidate some preliminary results of Arnaud et  
 123 al. (2017), and (iv) provide some operational guidelines and management scenario for  
 124 enhancing efficiency and sustainability of GA-based restorations of large rivers.

Authors	Monitoring framework					Hydraulic modeling	Monitored compartments				
	Before/ after protocol	No impacted /impacted protocol	Reach length monitored (m)	Number of post- GA surveys	Duration (year)	Flow conditions for SD erosion	Bedload mobility	Channel topography/ bathymetry	Grain size	Groundwater exchanges	Flow conditions
Rempel and Church 2009	•		~ 2500	3	3			•	•		
Klößch, 2011		•	1110	3	1		•	•		•	
Gaeuman, 2013	•		560	1 to 4	4		•	•			
Gaeuman, 2014	•		>1000	1	1	• <sup>(1)</sup>		•			
Ock et al., 2015	•		~ 2000	1	2				•		
Downs et al., 2016		•	>250	2	1		•				
Arnaud et al., 2017	•			4	4		•	•			
Gaeuman et al., 2017	•		>1000	4	1		•	•	•		
Heckmann et al., 2017	•		~ 2000	2	7			•			
Stähly et al., 2019	•		~ 300	1	< 1		•			•	
This study	•		5000 to 12000	1 to 5	1-7	•	•	•			

125 Table 1: Characteristics of some GA monitoring sites. <sup>(1)</sup> corresponds to a predictive model

126 (SRH-2D) to design SDs.

## 127 2. Materials and methods

### 128 2.1 Study sites

129 The Rhine River is the third largest river in Europe, with a drainage basin of 185 000 km<sup>2</sup> and  
 130 a river course of 1250 km long. The Upper Rhine, located between Basel and Bingen-am-  
 131 Rhein, exhibits a nivo-glacial hydrological regime (Figure 1.a; Schmitt et al., 2018). The mean  
 132 annual discharge is 1059 m<sup>3</sup>/s at the Basel gauging station (Wantzen et al., 2019). In this  
 133 riffle-pool reach, the Rhine is bypassed by the 50 km-long “Grand Canal d’Alsace” (GCA)

134 between the Kembs diversion dam and Breisach-am-Rhein (Figure 1.b). The minimum flow  
135 into this bypassed reach varies between  $52 \text{ m}^3 \cdot \text{s}^{-1}$  (winter) and  $150 \text{ m}^3 \cdot \text{s}^{-1}$  (spring-summer) in  
136 relation to the flow requirements for aquatic and riparian communities (Garnier and  
137 Barillier, 2015). Spills occur when the Rhine discharge exceeds  $1400 \text{ m}^3 \cdot \text{s}^{-1}$  at Basel gauging  
138 station, which corresponds to the maximal capacity of the GCA power plants (Figure 1). This  
139 discharge was exceeded an average of 69 days per year between 1932 and 2011 (Arnaud et  
140 al., 2015a). This Rhine section exhibits poor ecological functionalities due to severe  
141 geomorphological alterations induced by successive engineering works: damming and  
142 bypassing, as well as channelization and construction of groin fields since the 19<sup>th</sup> century  
143 (Piégay et al., 2011). Channelization and groin fields induced bed incision, bed armoring and  
144 floodplain and side channel disconnection, whereas damming increased active channel  
145 narrowing and bedform simplification due to a reduction in morphogenic discharges without  
146 any upstream sediment supply (Arnaud et al., 2019).

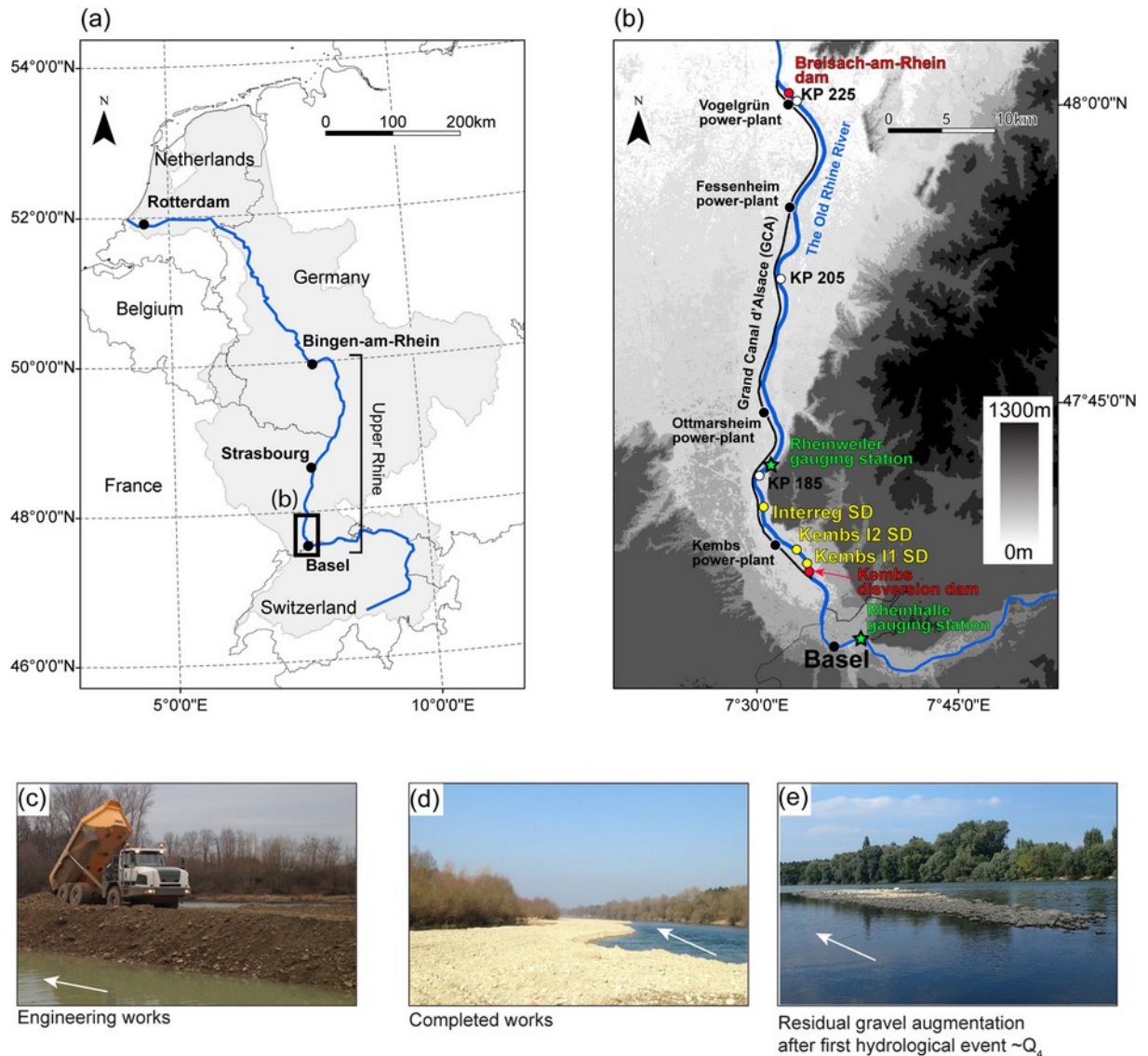
147 Since 2010, three GAs have been performed in the first 10 km of the Old Rhine (Figure 1.b)  
148 to restore bedload transport, promote bed grain size diversification and increase the  
149 heterogeneity of the channel bathymetry to enhance the ecological functionalities of the Old  
150 Rhine. The GAs were implemented following the point bar SD method (Ock et al., 2013). In  
151 October 2010, a first experimental GA, named Interreg, was achieved within an Interreg  
152 program. A SD was implemented within a concave bend and separated from the right bank  
153 (Arnaud et al., 2017). Within the framework of the Kembs dam relicensing, Kembs I1 and  
154 Kembs I2 GAs (Figure 1.c-d-e) were achieved by Électricité de France in March-April 2015  
155 and March-April 2016, respectively (Garnier and Barillier, 2015). The SDs were located in  
156 convex locations. The Kembs I1 SD was connected to the left bank, whereas the Kembs I2 SD  
157 was separated between 5 and 10 m from the left bank. The sediments were extracted from



158 the floodplain close to the SD injection areas. The SD volumes equal to 23 000 m<sup>3</sup>, 13 000 m<sup>3</sup>  
 159 and 30 000 m<sup>3</sup> (Table 2). These volumes were consistent with the mean annual bedload  
 160 transport capacity estimated to be 23,000 m<sup>3</sup>.yr<sup>-1</sup> for this part of the reach (El Kadi  
 161 Abderrezzak, 2009). The critical discharge for bedload entrainment  $Q_c$  was estimated to be  
 162 550 m<sup>3</sup>.s<sup>-1</sup> (El Kadi Abderrezzak, 2009).

SD	Implementation	KP (km)	Volume (m <sup>3</sup> )	Length (m)	Width (m)	Height (m)	Mean D <sub>50</sub>	Mean D <sub>95</sub>	D <sub>95</sub> /D <sub>50</sub>
Interreg	October 2010	182.4 - 183.1	23,000	620	11.00 - 15.00	2.00 - 3.50	35.00	100.60	3.28
Kembs I1	March - April 2015	174.10 -174.525	13,000	425	10.00 - 40.00	2.00 - 3.50	28.00	181.00	6.40
Kembs I2	March - April 2016	176.20 -176.66	30,000	460	15.00 - 40.00	2.00 - 4.50	18.50	105.00	5.95

163 Table 2: Characteristics of the three GAs performed on the Old Rhine. See Section 2.2.4 for  
 164 details on grain size measurements. The sorting coefficient was based on (Inman 1952).



165

166 Figure 1: (a) Location of the Old Rhine river in the Rhine Basin, (b) location of the river  
 167 network, the hydraulic structures, the gauging stations and the 3 GAs performed along the  
 168 studied reach, (c) Kembs I2 SD in progress, (d) Kembs I2 SD completed and (e) residual  
 169 Kembs I2 SD after a  $Q_4$  flood in May 2016. White arrows indicate the flow direction.

## 170 2.2 Data collection

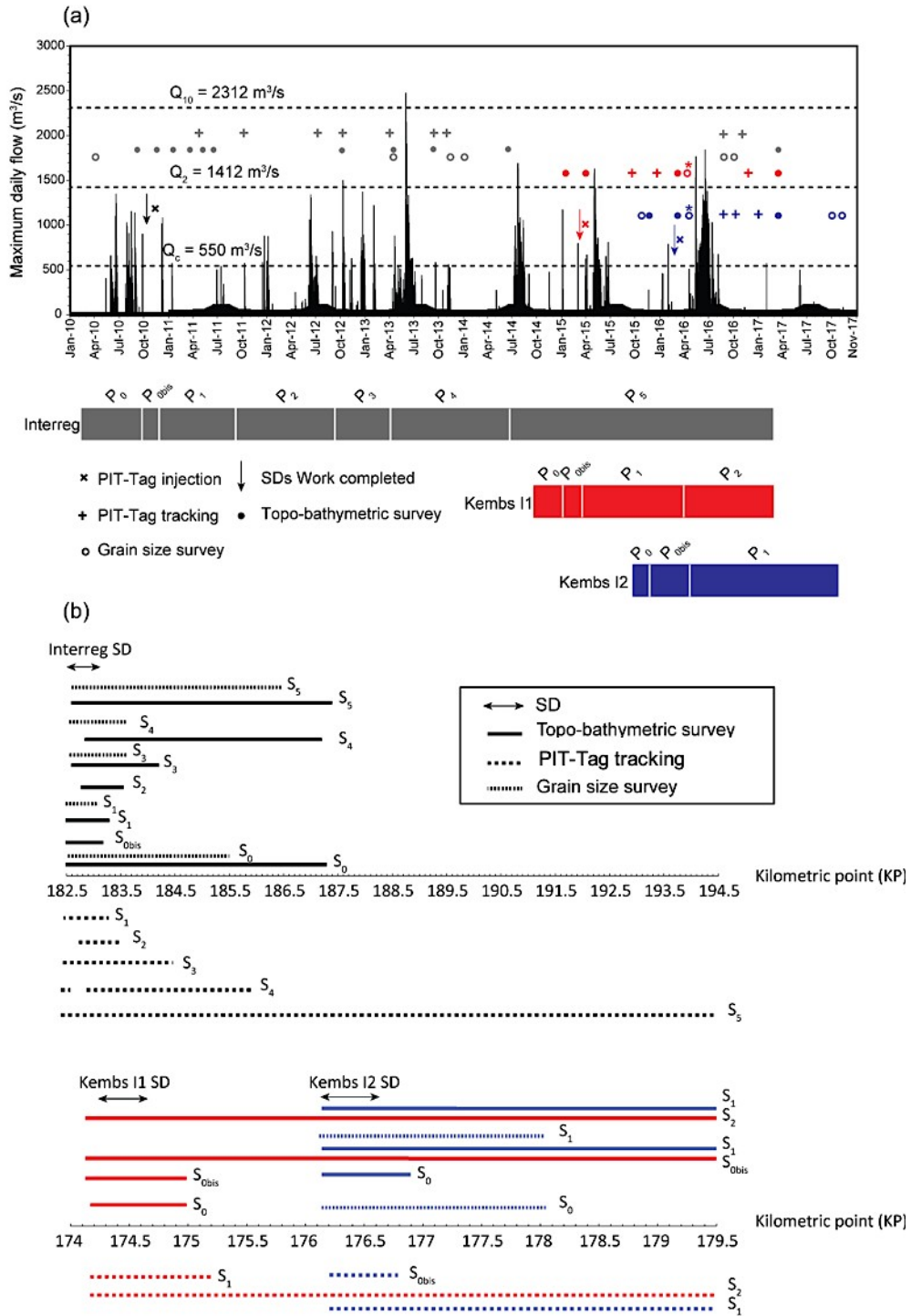
### 171 2.2.1 Monitoring framework

172 Geomorphic monitoring was applied for each GA at two spatial scales: (i) the SD and (ii) the  
 173 downstream channel reach, extending 4 to 12 km long depending on the sites. The

174 monitoring followed a before-after temporal framework that lasted two, three and seven  
175 years on Kembs I2, Kembs I1 and Interreg GAs, respectively, corresponding to three, four  
176 and seven monitoring periods (Figure 2). The beginnings and ends of each Period  $P_i$   
177 correspond to the  $S_{i-1}$  and  $S_i$  Survey dates, respectively. For each GA,  $P_0$  is the period before  
178 the implementation of the SD, and  $P_{0bis}$  is the period after the SD implementation and  
179 before the first floods. The following  $P_i$  are a series of periods following this first flood.  
180 Between one and three significant hydrological events occurred for each of these periods,  
181 and the flood intensity ranged from  $Q_1$  ( $1080 \text{ m}^3 \cdot \text{s}^{-1}$ ) to  $Q_{15}$  ( $2480 \text{ m}^3 \cdot \text{s}^{-1}$ ). The monitoring  
182 methods combined topo-bathymetric surveys, grain size surveys, sediment tracking and two-  
183 dimensional hydraulic modeling. The Interreg monitoring presented in this paper ( $P_5$  is in  
184 continuity of the work of Arnaud et al. (2017), who characterized periods  $P_0$  to  $P_4$ .

185

186



187

188 Figure 2: (a) Temporal monitoring framework related to the maximum daily flow in the Old  
 189 Rhine, obtained by subtracting  $1400 \text{ m}^3 \cdot \text{s}^{-1}$  from the discharge at the Basel gauging station  
 190 and (b) spatial monitoring framework. In (a) circles with a star indicate the volumetric  
 191 samplings conducted on the SDs.  $S_x$  indicates the Survey date and  $P_x$  the monitoring Period  
 192 between two surveys. See Table 3 for details on topo-bathymetric surveys.

## 193 2.2.2 Topo-bathymetric surveys

194 Topo-bathymetric surveys were conducted to assess accurately: (i) the erosion of SDs after  
195 first floods and (ii) the habitat diversification along the reaches located downstream the SDs.  
196 For Kembs I1 and Kembs I2,  $S_0$  was surveyed in February 2015 and November 2015,  
197 respectively, based on cross-section profiles at 5 to 50 m-spaced intervals using a Tritech  
198 PA500 single beam echo-sounder (Table 3). An airborne topo-bathymetric LiDAR survey was  
199 performed on Kembs I1 in March 2015 ( $S_{0bis}$ ), followed by another survey in March 2016 that  
200 covered both Kembs I1 ( $S_1$ ) and Kembs I2 ( $S_{0bis}$ ) (Figure 2; Table 3). Another survey in March  
201 2017 covered Kembs I1 ( $S_2$ ), Kembs I2 ( $S_1$ ) and Interreg ( $S_5$ ). All LiDAR surveys were  
202 performed at flight elevations close to 400 m using the Optec Titan sensor and during low  
203 water turbidity. The spot size was estimated to 0.08-0.12 m in above-water areas and 0.20 m  
204 in underwater conditions. The resolution of the LiDAR surveys ranged between 20 and 40  
205 pts/m<sup>2</sup> for emerged areas and 5 to 10 pts/m<sup>2</sup> in underwater conditions, depending on the  
206 water depth. Due to a sensor malfunction in March 2015, no data were recorded in  
207 underwater areas deeper than one meter for this survey. We estimated that about 70  
208 % of the submerged bed area was deeper than 1 m. For above-water  
209 surfaces the range of mean error was equal to -0.032m to 0.044m and the  
210 mean root mean square error was equal to 0.042m for the three airborne  
211 topo-bathymetric surveys. During the survey of March 2016, five cross-  
212 section profiles were performed simultaneously to control the accuracy of  
213 bathymetric data (see table 3). The range of mean error was estimated to  
214 -0.086m to +0.083m and the root mean square error equal to 0.083m.”.

215

216

GA	Survey	Methods	Characteristics	Equipment
Interreg	$S_0$ to $S_4$	DGPS and single beam echo-sounder	Topo-bathymetric cross-sections (spaced interval equal to 50 m)	Tritech PA500
Interreg	$S_5$	Topo-bathymetric LiDAR	Full topography (10 to 40 pts/m <sup>2</sup> )	Optec Titan sensor
Kembs I1	$S_0$	DGPS and single beam echo-sounder	Topo-bathymetric cross-sections (spaced interval equal to 5 to 50 m)	Tritech PA500
Kembs I1	$S_{0bis}$	Topo-bathymetric LiDAR	Full topography (10 to 40 pts/m <sup>2</sup> )	Optec Titan sensor
Kembs I1	$S_1$	Topo-bathymetric LiDAR	Full topography (10 to 40 pts/m <sup>2</sup> )	Optec Titan sensor
Kembs I1	$S_2$	Topo-bathymetric LiDAR	Full topography (10 to 40 pts/m <sup>2</sup> )	Optec Titan sensor
Kembs I2	$S_0$	DGPS and single beam echo-sounder	Topo-bathymetric cross-sections (spaced interval equal to 5 to 50 m)	Tritech PA500
Kembs I2	$S_{0bis}$	Topo-bathymetric LiDAR	Full topography (10 to 40 pts/m <sup>2</sup> )	Optec Titan sensor
Kembs I2	$S_1$	Topo-bathymetric LiDAR	Full topography (10 to 40 pts/m <sup>2</sup> )	Optec Titan sensor

218 Table 3 : Characteristics of topo-bathymetric surveys achieved in this study.

219

### 220 2.2.3 PIT-tags monitoring

221 We equipped particles with Passive Integrated Transponders (PIT-tags) to achieve several  
 222 purposes: (i) evaluate the erosion of SDs according to flow conditions and particle grain size,  
 223 and (ii) characterize the sediment mobility (travel distances and virtual velocities) and the  
 224 mode of sediment pulse (dispersion, translation, fragmentation) along the three  
 225 downstream reaches. We used 23-mm PIT tags for the Interreg GA, a combination of 23-mm  
 226 and 32-mm tags for Kembs I1, and 32-mm tags for Kembs I2. The PIT tags were developed by  
 227 Texas Instrument Enterprise and have a maximum vertical reading range of 0.95 m (Arnaud,  
 228 et al., 2015). For Interreg, bedload tracers were equally distributed between the three  
 229 principal grain size classes, whereas the tracer grain size distributions (GSD) correspond to  
 230 the GSD of a gravel bar near Kembs for Kembs I1 and Kembs I2. The PIT tags were placed  
 231 during  $S_{0bis}$  following various injection protocols depending on the GA (Table 4). Each

232 individual tracer and tracer cluster was geopositioned with a global positioning system

233 Trimble GeoXT 6000 (XY accuracy = 0.1 m).

GA	Period placement	No. of placed tracers	D <sub>50</sub> of tracers (mm)	Deployment protocols
Interreg	November 2010	1489	71	(i) 19 clusters of 50 tracers placed along 7 cross-sections spaced at 100 m intervals, and (ii) individual tracers deployed along 30 cross-sections spaced at 20 m intervals
Kembs I1	April 2015	1482	53	(i) 10 areas were placed every 50 m comprising 80 to 100 tracers, which were placed individually every meter, and (ii) 13 clusters of 50 tracers deposited in the channel at the toe of the right bank of the SD
Kembs I2	March 2016	1500	54	(i) tracers placed individually at each meter at the surface of the SD along cross sections spaced at 2 m intervals, one tracer was placed in the channel at the toe of the SD on both sides of the SD, and (ii) 16 clusters of 10 to 50 tracers spaced at 100 m intervals, placed in the channel at the toe of the SD on both sides

234 Table 4 : Characteristics of bedload tracer placed for each GA.

235

236 For each bedload tracking survey, the tracers were detected using an antenna connected to

237 a reader system developed by CIPAM Corporation. For emerged and water areas less than

238 0.6 m deep, a 0.46 m-diameter loop antenna was used, and the tracer IDs were manually

239 recorded with the GPS. In water areas deeper than 0.6 m, a rectangular antenna 1.2 m wide

240 was pulled by boat in the downstream direction, and the same GPS was used in tracking

241 mode (continuously recording each second) to map the tracked areas and determine the

242 position of each detected tracer by synchronizing the on-board GPS and the chronometer.

243 The accuracy of the tracer location was estimated to be 2 m in emerged conditions and

244 water conditions less than 0.6 m while the accuracy was estimated to 5 m in water areas

245 deeper than 0.6 m.

## 246 2.2.4 Grain size monitoring

247 We performed volumetric samplings to measure the grain size of the injected sediments  
 248 which composed Kembs I1 (n=2;  $S_1$ ) and Kembs I2 (n=2;  $S_{obis}$ ) SDs. We sampled a minimum  
 249 mass of sediment according to the grain size of the surface layer, following the equation  
 250 proposed by Church et al., (1987):

$$mmw = 2,882 * D_{max} - 47,6 \quad (1)$$

251 where mmw corresponds to the minimum mass weight and  $D_{max}$  the mean diameter of the  
 252 30 coarsest particles of the surface layer.

253 For the Interreg SD ( $S_0$ ), volumetric sampling was performed in the floodplain sediment  
 254 excavation area (Dittrich et al., 2010). In addition, surface changes in bed grain size were  
 255 evaluated after the first morphogenic flood ( $S_1$ ) on the three emerged residual SDs using the  
 256 Wolman (1954) technique, to evaluate if a coarser surface layer has been developed, which  
 257 may reduce the residual SD erodibility by the subsequent floods. Moreover, surface grain  
 258 size changes were also evaluated along the downstream reaches, in both emerged and  
 259 underwater (water depth < 0.6 m) areas of the active channel, to verify if the GAs diversified  
 260 and lowered the grain size distributions. For the Interreg downstream reach, the grain size  
 261 sampling in  $S_5$  (n=414) followed the same protocol as Arnaud (2012), who characterized  $S_0$   
 262 (n=310),  $S_3$  (n=192) and  $S_4$  (n=143): random sampling of 10 particles at each node of  
 263 quadrats (10 x 10 m). The surface sampled in  $S_0$ ,  $S_3$ ,  $S_4$  and  $S_5$  is equal to 14, 8, 6 and 14% of  
 264 the monitoring reach, respectively. These relatively low sampled surfaces are explained by  
 265 the water level which exceeded 0.6 m in the major part of the monitoring reach (> 80%). For  
 266 Kembs I1 and I2 downstream reaches, an underwater photosieving protocol was applied  
 267 along transects spaced at 60 m intervals, with sampling points spaced at 5 - 10 m intervals.  
 268 This photosieving strategy was adopted because the water depth exceeded 1 m in most of



269 the study areas and reached 4 m locally. For  $S_0$  at Kembs I2, the data collection (n=240) was  
270 performed by diving and using a GoPro Hero4+ camera with a constant height equal to 0.52  
271 m. For  $S_1$ , high definition (1080p) subaquatic films were obtained along the same transects,  
272 by using an Olympus TG-4 camera placed perpendicularly on an aluminum telescopic bar, all  
273 deployed from a boat. A rule was placed at the bottom of the telescopic bar to determine  
274 the pixel size. Digital images (n=324) were extracted from the subaquatic films using  
275 VirtualDub software v.1.10.4. Chardon et al. (2020) showed the capacity of photosieving in  
276 underwater conditions to quantify bed grain size. Fisheye deformation on all photos was  
277 corrected by using a correction algorithm with Photoshop software. Photos were then  
278 cropped to eliminate the corners impacted by the correction. We digitized the ten largest  
279 particles in each photograph and calculated the  $D_{50}$ , as this metric is close to the  $D_{95}$  of the  
280 total apparent particles on each photography. Indeed, Houbrechts et al. (2011)  
281 demonstrated the advantage to use the mean diameter of ten largest particles to estimate  
282 the  $D_{95}$  of the grain size distributions. We assumed that this metric is sensitive to bed grain  
283 size fining.

#### 284 2.2.5 Two-dimensional hydraulic modeling

285 We evaluated the local hydraulic conditions at the SDs by performing two-dimensional  
286 hydraulic unsteady flow modeling to compare the intensity of the erosional processes  
287 between them. We used the HEC-RAS v.5.0.3 software between the Kembs dam (KP 174.00)  
288 and the Rheinweiler gauging station (KP 186.2), which is located 4 km downstream of the  
289 Interreg GA (Figure 1). The model contains 146 619 mesh cells with an average cell area of  
290 16 m<sup>2</sup>. The digital elevation model (DEM) used is based on the airborne topo-bathymetric  
291 LiDAR of March 2017 because it included a detailed topography of the channel for the entire  
292 study reach. The geometries of the three SDs measured in  $S_{obis}$  were integrated into the

DEM. Water levels and instantaneous discharges recorded at the Rheinweiler gauging station during the flood event between May and June 2017 (time step = 15 min) were used as downstream boundary conditions because these discharges ranged between 52 and 2000  $\text{m}^3 \cdot \text{s}^{-1}$ , which included the peak discharge of periods  $P_1$  for the three SDs (Figure 2). We assumed that no significant discharges were provided by tributaries along the modeling reach. Only a small tributary is present, the Kander River, for which the 100-year flood is estimated to  $56.4 \text{ m}^3 \cdot \text{s}^{-1}$  (information from the RPF). Thus, information from the Rheinweiler gauging station were also used as upstream boundary conditions. The Manning's coefficients implemented in the model are close to those calculated by Béraud (2012) and equal to 0.035 for the active channel and 0.066 for the vegetation areas on the groin fields. Modeling output provided the maximal flow velocities for the peak discharges that occurred during periods  $P_1$  for the three SDs.

## 2.3 Data processing and analysis

### 2.3.1 Morphological changes in the SDs

DEMs were produced from point clouds obtained by the airborne topo-bathymetric LiDAR and the terrestrial topo-bathymetric cross-sections datasets conducted along Kembs I1 and Kembs I2 using the 3D Analyst toolbox of ArcMap v.10.3 (cell size = 0.5 m). Cross sections spaced at 25 m intervals were extracted from the DEMs using the ETGeoWizards add-on to calculate the surface eroded on each SD and related to the modelled flow conditions. For the Interreg SD, surface eroded were directly calculated from topo-bathymetric cross-sections (Arnaud et al., 2017). We calculated for each profile the section area at  $S_i$  (in  $\text{m}^2$ ):

$$Section\ area_{(S_i)} = \sum_{i=1}^n \delta_i (x_{i+1} - x_i \delta_i) \vee \delta_i \left( \frac{Z_{i+1} + Z_i}{2} \right) \delta_i \quad (2)$$

314

315 where  $x_i$  and  $x_{i+1}$  are the lateral positions and  $Z_i$ , and  $Z_{i+1}$  are the elevations of successive  
 316 points (m).  $n$  defines the number of points. The reference used to calculate the section area  
 317 was the toe at the left bank of the SD at  $S_0$ .

318 From the previous equation, we estimated the resulting eroded surface for each cross-  
 319 section for each SD (in  $m^2$ ) between two surveys:

$$\text{Eroded surface}_{S_i \rightarrow S_{i+1}} = \text{Section area}_{(S_{i+1})} - \text{Section area}_{(S_i)} \quad (3)$$

320 We estimated the elevation changes uncertainties between  $S_{0bis}$  and  $S_x$  for Kembs I1 and  
 321 Kembs I2 SDs by estimating the combined elevation change errors of two paired DEMs from  
 322 airborne topo-bathymetric LiDAR and according to the equation of Brasington, Langham,  
 323 and Rumsby (2003):

$$\sigma_{diff} = \sqrt{(\theta_{S_i})^2 + (\theta_{S_{i+1}})^2} \quad (4)$$

324 where  $\theta_{S_i}$  and  $\theta_{S_{i+1}}$  are the estimated registration errors at  $S_i$  and  $S_{i+1}$ , respectively. The  
 325 estimated registration error was estimated to 0.1 m on the Z-axis for all surveys.  
 326 Following Bennett et al. (2012), a statistical t-test was performed to identify significant  
 327 elevation changes for Kembs I1 and Kembs I2 SDs, between two paired DEMs from airborne  
 328 topo-bathymetric LiDAR and for a given, when  $|t| > 1$ , corresponding to 66% confidence  
 329 interval:

$$t = \frac{Z_{S_{i+1}} - Z_{S_i}}{\sigma_{diff}} \quad (5)$$

330 Where  $Z_{S_i}$  and  $Z_{S_{i+1}}$  are the mean elevation of the DEM cell at  $S_i$  and  $S_{i+1}$ . From this equation,  
 331 the elevation changes smaller than  $\sigma_{diff}$  were considered uncertain and not integrated in the  
 332 analysis of elevation changes (Bennett et al., 2012) but also for sediment budgets.

333 We calculated the sediment budgets for the Kembs I1 and Kembs I2 SDs from the DEM of  
 334 Differences (DoD):

$$\Delta V_{S_i \rightarrow S_{i+1}} = \sum_{i=1}^n A * (Z_{S_{i+1}} - Z_{S_i}) \quad (6)$$

335 where  $A$  is the area of the DEM cell, and  $Z_{S_i}$  and  $Z_{S_{i+1}}$  are the mean elevations of the DEM cell  
 336 at  $S_i$  and  $S_{i+1}$ , respectively.

337 We estimated the volume errors for Kembs I1 and Kembs I2 SDs following the equation  
 338 developed by (Lane et al., 2003):

$$\sigma_v = d^2 \cdot \sqrt{n} \cdot \sigma_{diff} \quad (7)$$

339 where  $d$  is the cell size of the DEM (m) and  $n$  is the number of cells in each area of  
 340 signification elevation changes identified by the statistical t-test. For Interreg SD, see Arnaud  
 341 et al. (2017) for the method used to calculate both the sediment budget and the volume  
 342 errors.

### 343 2.3.2 Suitable areas to implement SDs

344 We identified suitable areas in terms of best hydraulic conditions to implement future SDs in  
 345 order to minimize deposit fixation because the success of GA is dependent on SD erosion.

346 This study was performed for frequent peak flood equal to the  $Q_2$  ( $1417 \text{ m}^3 \cdot \text{s}^{-1}$ ). We  
 347 developed a suitability index ratio (SIR) for each 500 m length of the active channel and  
 348 calculated as follows:

$$\text{Suitability Index Ratio} = \frac{\text{Area of flow velocity} \geq 2.5 \text{ m} \cdot \text{s}^{-1}}{\text{Area of active channel}} \quad (8)$$

349 We used a flow velocity threshold equal to  $2.5 \text{ m}\cdot\text{s}^{-1}$  because it was found to be the minimal  
 350 velocity to erode significantly the SDs (see section 3.1.3).

### 351 2.3.3 Tracer mobility analysis

352 We evaluated the mean tracer cloud travel distance for each period  $P_i$  using the tracer cloud  
 353 centroid metric  $CP_{(Si)}$  (Piégay et al., 2016; Arnaud et al., 2017):

$$CP_{(Si)} = \frac{\sum_{i=1}^{n_{recovered}} X_i}{n_{recovered}} \quad (9)$$

354 where  $X_i$  is the longitudinal position (in m) of each tracer linearly referenced along the active  
 355 channel centerline. For Interreg, the first 12 m of the SD were excluded from the analysis  
 356 because the tracers do not move. For Kembs I1, tracers detected in the residual SD were not  
 357 integrated into the calculation of the tracer cloud centroid metric. For each period  $P_i$ , the  
 358 travel distance of the tracer cloud centroid (in m) was calculated as follows:

$$L_{cp} = CP_{(Si+1)} - CP_{(Si)} \quad (10)$$

359 Then, we calculated the virtual velocity (in  $\text{m}\cdot\text{s}^{-1}$ ) for each period  $P_i$  by using the travel  
 360 distance of the tracer cloud centroid:

$$V_{pi} = \frac{L_{CP}}{t_{\geq Q_c}} \quad (11)$$

361 where  $t_{\geq Q_c}$  is the time during which the discharge is greater than or equal to  $Q_c$  (Church and  
 362 Hassan, 1992). To calculate this time duration, we used the instantaneous discharge  
 363 estimated at the Basel gauging station every 10 min and compared it to  $Q_c$ .

364 In order to study the relation between the sediment mobility and the flow competence, we  
 365 used the two metrics calculated for each period  $P_i$  as follows:

366 (i) The excess unit stream power:

$$\omega_{P_i} = \frac{\rho_w g (Q_p - Q_c) S}{W} \quad (12)$$

367 where  $\rho_w$  is the water density ( $\text{kg.m}^{-3}$ ),  $g$  is the acceleration due to gravity ( $\text{m.s}^{-2}$ ),  $Q_p$  is the  
 368 maximum peak discharge ( $\text{m}^3.\text{s}^{-1}$ ),  $Q_c$  is the critical discharge ( $\text{m}^3.\text{s}^{-1}$ ),  $S$  is the average local  
 369 bed slope ( $\text{m.m}^{-1}$ ) estimated from topo-bathymetric surveys, and  $W$  is the mean active  
 370 channel width (m).

371 (ii) The cumulative excess stream energy (Schneider et al., 2014) which assess the excess  
 372 stream energy for an entire period  $P_i$ :

$$\sum (\omega_{(t)} - \omega_c) \quad (13)$$

373 where  $\omega_{(t)}$  is the stream energy for a discharge value greater than the critical discharge and  
 374  $\omega_c$  is the stream energy for the critical discharge value. ( $\text{J.m}^{-2}$ ). As the time-step  
 375 measurement at the Basel gauging station is 10 min, we multiplied the excess stream energy  
 376 by 600 s to calculate all excess stream energy of the period time between two discharges  
 377 measurements and cumulated all values for the entire period  $P_i$ .

378 In order to identify partial or full bedload mobility, we calculated the mean dimensionless  
 379 travel distance of the tracer cloud centroid for each grain size class as follows:

$$\text{Mean dimensionless travel distance } \dot{\delta} = \frac{L_i}{L_{d50}} \quad (14)$$

380 where  $L_i$  is equal to the mean travel distance of the tracer cloud centroid for each grain size  
 381 class of the recovered tracers, and  $L_{d50}$  is the mean travel distance of the median grain size  
 382 class of the recovered tracers for each survey.

383

#### 384 2.3.4 Channel geometry diversification analysis

385 The evolution of the channel geometry in response to GA operations was assessed using the  
 386 cross-section diversity index (CSD) developed by Gostner et al. (2013) from topo-bathymetric  
 387 cross sections along the downstream channel reaches:

$$CSD = \frac{\sum_{i=2}^n |\Delta Z_i|}{\sum_{i=1}^{n-1} Y_i} \quad (15)$$

with

$$|\Delta Z_i| = Z_{i-1} - Z_i \quad (16)$$

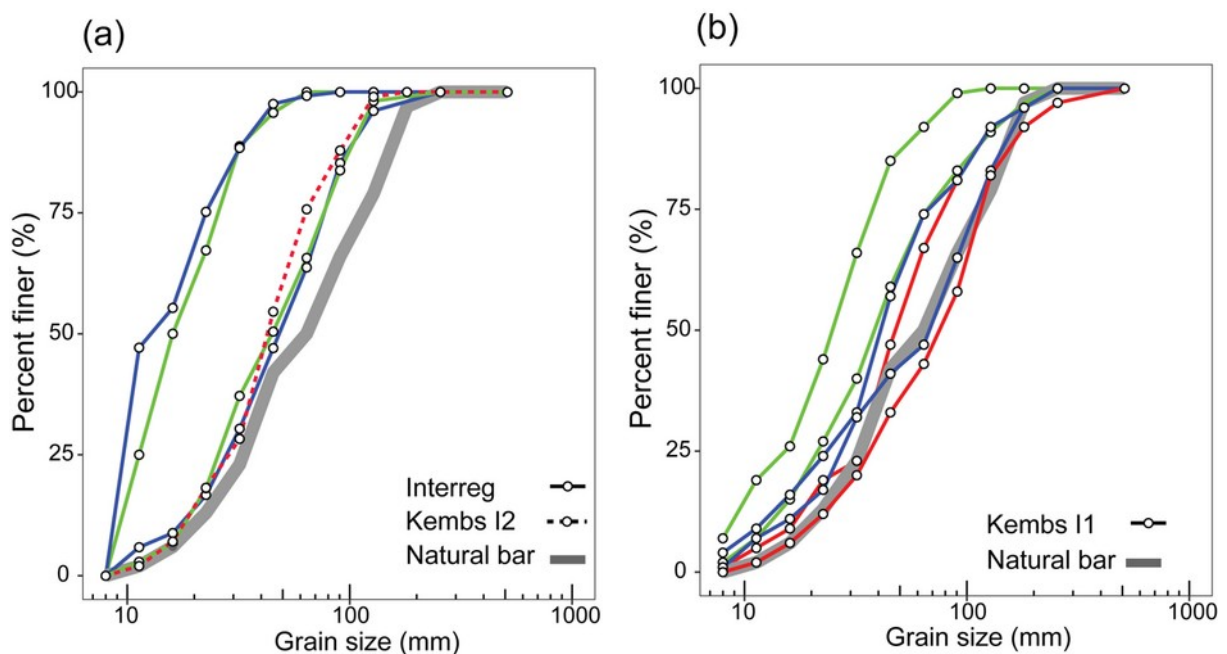
388  $|\Delta Z_i|$  is the absolute elevation difference between two consecutive points on a cross section  
 389 and  $Y_i$  is the distance between them. The CSD calculation for Kembs I1 and Kembs I2 in  $S_0$   
 390 was based on cross sections surveyed by the RPF in 2009 (not indicated in Figure 2) because  
 391 the LiDAR surveys of 2015 were only extended 200 m downstream from the two SD sites  
 392 (Figure 2.b). We also used topo-bathymetric datasets for the period 1985/93-2009 provided  
 393 by the RPF to compare the CSD of GAs with longer-term changes in the Old Rhine.

### 394 3. Results

#### 395 3.1 Monitoring of the stockpile deposits

##### 396 3.1.1 Grain size comparison and evolution

397 The  $D_{50}$  calculated from the volumetric samples in  $S_{obis}$  was globally similar for the Interreg  
 398 and Kembs I1 SDs, and lower for the Kembs I2 SD (Table 2). Regarding the  $D_{95}$ , introduced  
 399 sediments were coarser for Kembs I1 than for the two other SDs. The range of the  $S_1/S_{obis}$   $D_{50}$   
 400 ratio was 1.36 to 2.67, 0.45 to 1.27 and equal to 2.35 for Kembs I1, Interreg and Kembs I2,  
 401 respectively. The surface grain size of the upstream and downstream parts of the Kembs I1  
 402 residual SD was very close to the coarse surface layer GSD of a historical gravel bar located  
 403 at KP 178.2 ( $D_{84} = 90.5$  mm), indicating partial mobility conditions (Figure 3.b). For Interreg  
 404 and Kembs I2, no coarse layer was appeared comparatively with the surface GSD of the  
 405 historical gravel bar (Figure 3.a).



406

407 Figure 3: Surface grain size of the three residual SDs in  $S_1$  (a) for Interreg ( $n=4$ ) and Kembs I2

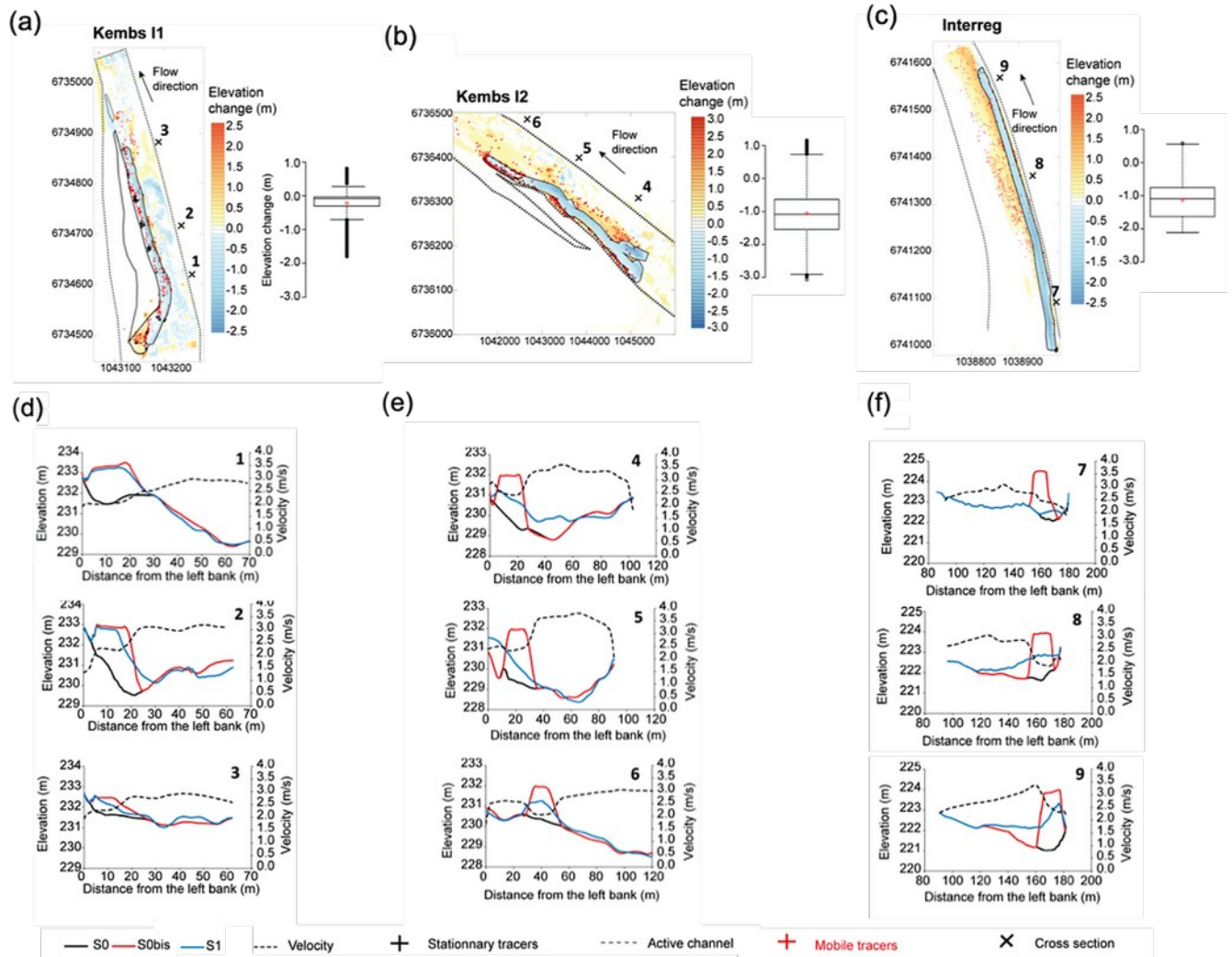
408 ( $n=1$ ), and (b) for Kembs I1 ( $n=6$ ). Gray lines indicate the surface grain size of a gravel bar



409 located between the Kembs I2 and Interreg SDs (KP 178.2). Blue, green and red colors  
410 indicate the upstream, middle and downstream parts of the SDs, respectively.

### 411 3.1.2 Morphological evolutions and sediment balance comparison

412 We studied both morphological changes and sediment balances of each SD to identify  
413 erosion processes. We found statistically significant differences in morphological changes  
414 between the three SDs during  $P_1$  (ANOVA-test, p-value =  $2e-16$ . Fewer morphological  
415 changes occurred for Kembs I1 ( $\mu=-0.19 \text{ m} \pm 0.28 \text{ m}$ ) compared to changes for Kembs I2 ( $\mu=-$   
416  $1.05 \text{ m} \pm 0.68 \text{ m}$ ) and Interreg ( $\mu=-1.12 \text{ m} \pm 0.53 \text{ m}$ ) (Figure 4.a-c). Sediment budgets were  
417 equal to  $-793.00 \text{ m}^3 (\pm 12.00 \text{ m}^3)$ ,  $-15,600 \text{ m}^3 (\pm 10.00 \text{ m}^3)$  and  $-11,250 \text{ m}^3 (\pm 199.00 \text{ m}^3)$  for  
418 Kembs I1, Kembs I2 and Interreg, respectively. These eroded volumes correspond to 6%, 55%  
419 and 48% of the initial SD volumes. Two erosional processes occurred for Kembs I2 and  
420 Interreg: a toe erosion and a mass failure of the stockpile (Figure 4.e-f). For Kembs I1, only  
421 toe erosion occurred (Figure 4.d). The cumulative eroded volumes during  $P_2$  were equal to  
422 12% and 95% of the initial SD volumes for Kembs I1 and Interreg, respectively.



423

424 Figure 4: (a) to (c) DEM of differences from  $S_{obis}$  to  $S_1$  for the Kembs I1, Kembs I2 and Interreg

425 SDs, with the location of mobile (red) and stationary tracers (black). Boxplots correspond to

426 the elevation changes along each SD surface from  $S_{obis}$  to  $S_1$ . Intervals correspond to the 25<sup>th</sup>427 and 75<sup>th</sup> percentiles, and the lower and upper whiskers correspond to 1.5 times the interval

428 quartile range. Black lines correspond to the median values, and the red points correspond

429 to the mean values. (d) to (f) three cross sections extracted from DoD (cross symbol on (a) to

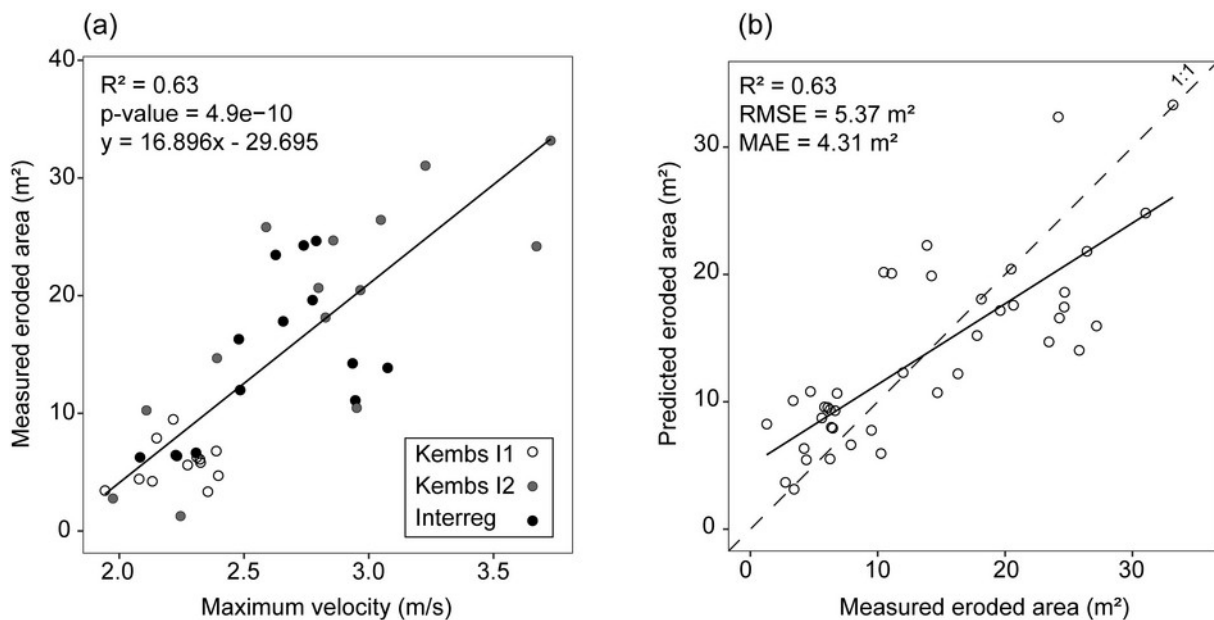
430 (c)) illustrate the morphological changes for each SD from  $S_0$  to  $S_1$ .

## 431 3.1.3 Relations between flow conditions and morphological changes of the SDs

432 We explain the significant differences of the eroded volumes of the SDs due to significant

433 differences on local hydraulic conditions. Statistically significant differences in modeled flow

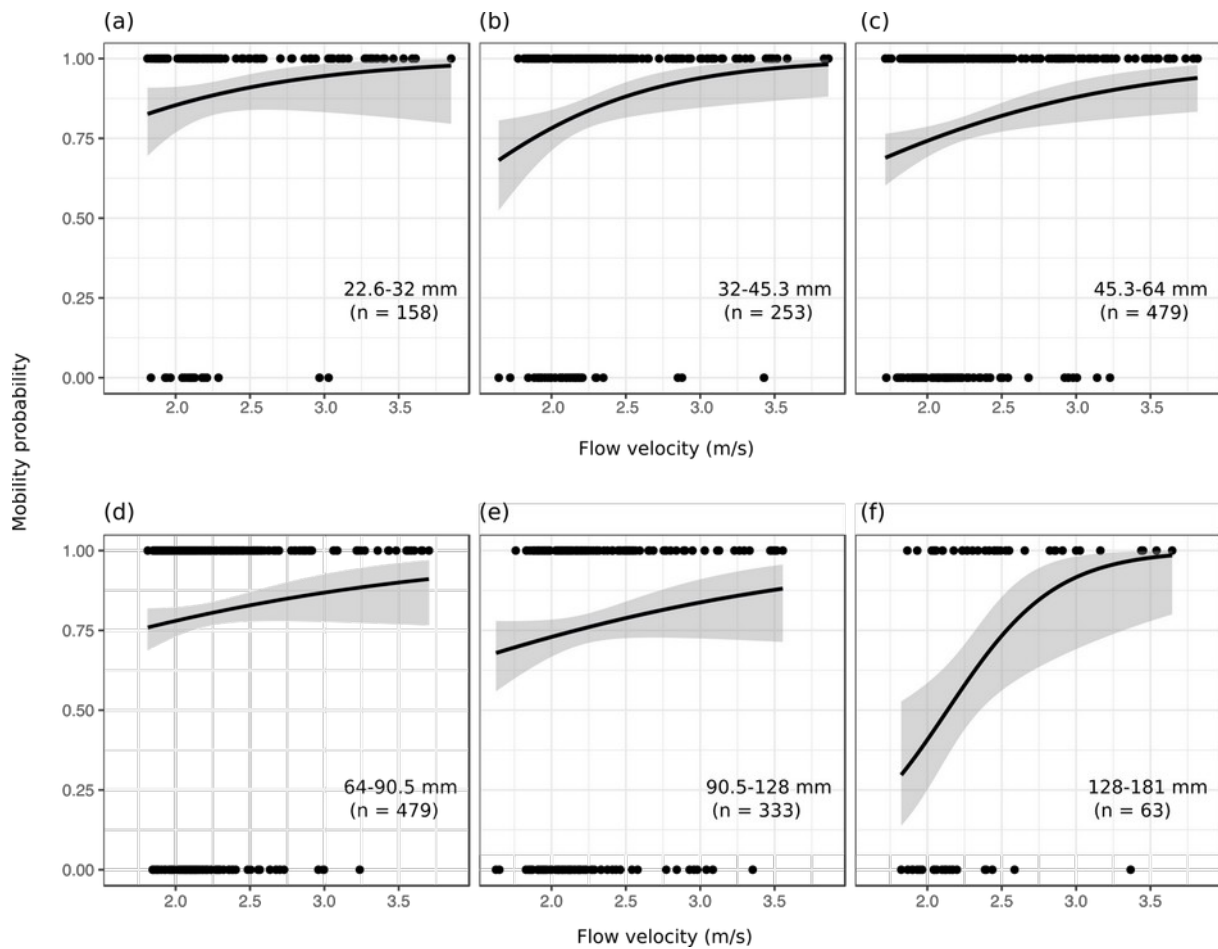
434 velocities were found between the three SDs during  $P_1$  (ANOVA-test, P-value =  $2e-16$ ).  
 435 Velocities were lower for Kembs I1 ( $\mu=2.06 \text{ m.s}^{-1} \pm 0.24 \text{ m.s}^{-1}$ ) compared to those for Interreg  
 436 ( $\mu=2.20 \text{ m.s}^{-1} \pm 0.26 \text{ m.s}^{-1}$ ) and Kembs I2 ( $\mu=2.52 \text{ m.s}^{-1} \pm 0.41 \text{ m.s}^{-1}$ ). A statistically significant  
 437 relation at the 95% confidence level exists between the eroded areas and the maximum  
 438 velocity areas calculated on each cross section ( $R^2 = 0.63$ ; P-value =  $4.9e-10$ ; Figure 5.a).  
 439 Using the maximum velocity as a proxy of the measured eroded areas, the root mean square  
 440 error (RMSE) and the mean absolute error (MAE) between the predicted eroded areas and  
 441 the measured eroded areas were equal to  $5.37 \text{ m}^2$  and  $4.31 \text{ m}^2$ , respectively (Figure 5.b).



442  
 443 Figure 5: (a) Measured eroded areas according to the maximum velocity calculated for peak  
 444 floods during  $P_1$  along each SD, and (b) predicted eroded areas by maximal velocities  
 445 compared with the measured eroded area (m<sup>2</sup>). The dashed line corresponds to the 1:1 line.

446 The recovery rates of the tracers tracked in  $S_1$  were equal to 42%, 33% and 43% for Kembs  
 447 I1, Kembs I2 and Interreg, respectively. For all SDs, the percentage of mobile tracers ranged  
 448 from 68% to 87%. Based on logistic regressions, we observed that the tracer movement  
 449 probability is linked to the flow velocity (P-value < 0.0001). Partial tracer mobility occurred

450 by flow velocities lower than  $2.5 \text{ m}\cdot\text{s}^{-1}$  with a much lower mobility for the coarsest fraction  
 451 (128-181 mm). A quasi-full mobility was observed for higher velocities (Figure 6).

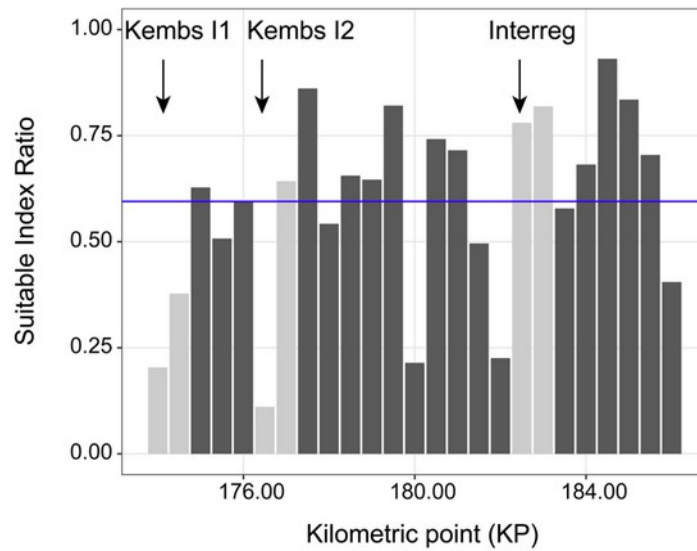


452  
 453 Figure 6: Logistic regressions of the tracer mobility according to flow velocity at their initial  
 454 positions on the three SDs for peak floods during  $P_1$  as a function of their grain size classes.  
 455 Grey areas indicate the 95% confidence level of the logistic regression lines.

#### 456 3.1.4 Assessment of suitable areas for implementing SDs according to flow velocity

457 In order to define the best areas in terms of hydraulic conditions for implementing future  
 458 GAs on the Old Rhine, we used the empirical relationship found between the measured  
 459 eroded areas and the maximum flow velocity. The critical flow velocity was fixed to  $2.5 \text{ m}\cdot\text{s}^{-1}$   
 460 as shown in Section 4.1.3 (Figure 5.a and Figure 6). For a modeled discharge equal to the  $Q_2$   
 461 flood, the mean value of the Suitability Index Ratio (SIR) calculated on elementary reach of

462 500 m length is equal to 0.59 with minimum and maximum values of 0.11 and 0.93,  
 463 respectively (Figure 7). The majority of the upstream reaches of Kembs I2 were characterized  
 464 by values lower than the mean SIR and inversely for the downstream reaches of Kembs I2.  
 465 Moreover, our analysis showed that the velocity values were systematically lower than 2.5  
 466  $\text{m}\cdot\text{s}^{-1}$  along the emerged bars at low flow for this modeled discharge.



467  
 468 Figure 7: Longitudinal distribution of the SIR value for a  $Q_2$  flood along the bypassed reach  
 469 for each elementary reach of 500 m length. The blue line corresponds to the mean value of  
 470 the SIR, black arrows locate the three SDs and gray bars are the reaches covered (completely  
 471 or partly) by the SDs.

## 472 3.2 Monitoring of the downstream channel reaches

### 473 3.2.1 Assessment of tracer mobility

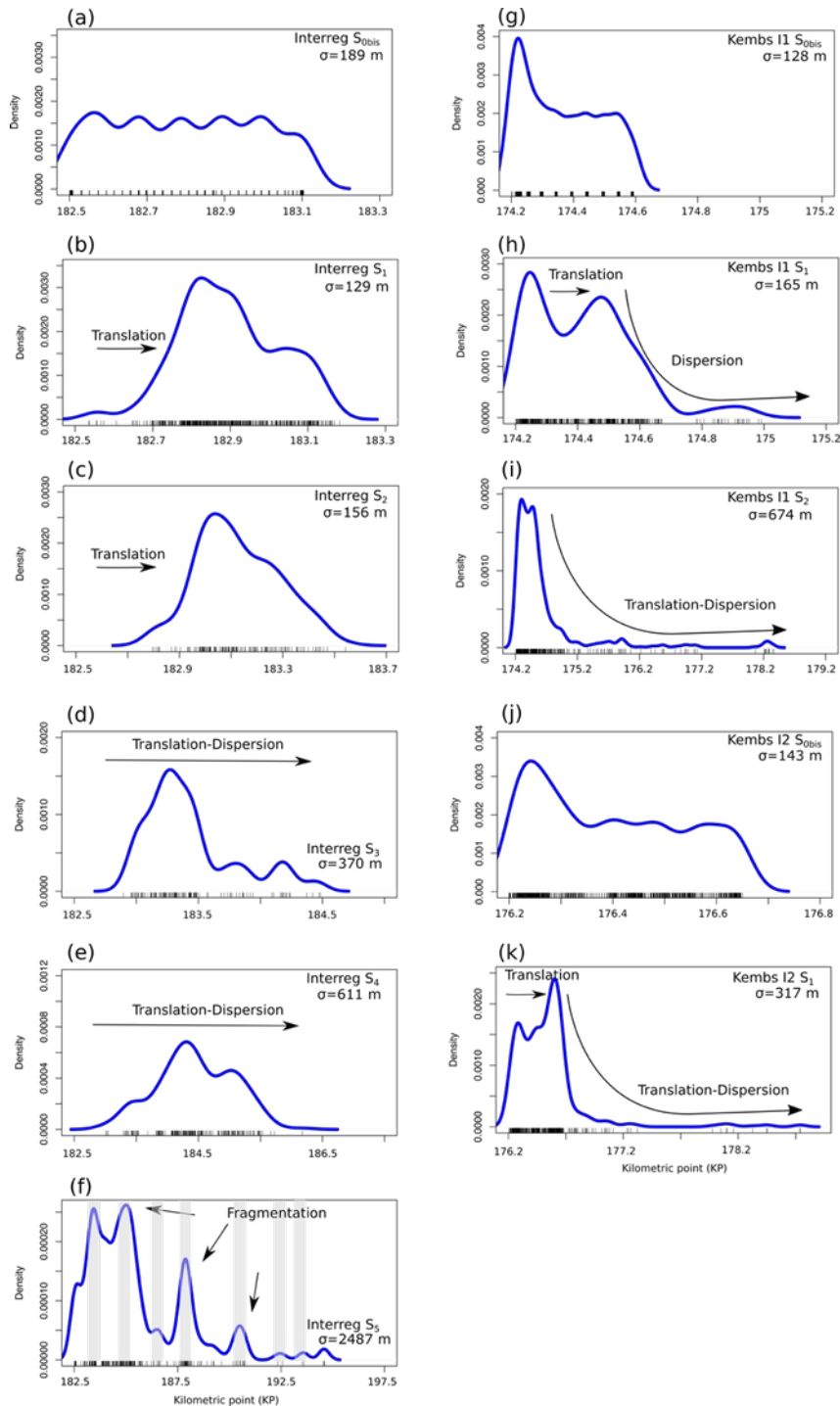
474 The tracer recovery rates ranged between 11% and 43% on the three studied reaches over  
 475 the monitoring periods (Table 3). The recovery rates globally decreased over time, which  
 476 was notably due to the decrease in the sampling pressure related to the tracer cloud  
 477 propagation (Table 5). Translation occurred in the upstream part of the Interreg reach during  
 478  $P_1$  and  $P_2$  (Figure 8.a-b). During  $P_3$  and  $P_4$ , tracers travelled through a clear translation-

479 dispersion mode (Figure 8.c-d). During  $P_5$ , the sediment pulse showed a fragmentation  
480 mode with preferential tracer deposition on riffles (Figure 8.e). For Kembs I1, a translation-  
481 dispersion mode also occurred during  $P_1$ , with only local translation in the medium part of  
482 the SD due to higher local flow velocities (Figure 8.f). During  $P_2$ , the distribution again  
483 showed a translation-dispersion pulse materialized by a heavy-tailed distribution due to a  
484 lower mobility of the tracers as some of them were trapped in the residual SD (Figure 8.i).  
485 The heavy-tailed distribution can be explained by (i) a lower mobility of tracers trapped in  
486 the residual SD in comparison with tracers traveling in the water channel (Liébault et al.,  
487 2012) or by (ii) a bedload partial mobility (Church & Hassan, 1992; Lenzi, 2004; Hassan et al.,  
488 2013; Schneider et al., 2014). For Kembs I2, the displacement of the tracer cloud showed a  
489 translation-dispersion pulse during  $P_1$ , with local translation in the upstream part of the SD  
490 due to higher velocities (Figure 8.h).  
491

Gravel augmentation	Period	Qp (m <sup>3</sup> .s <sup>-1</sup> )	Qi (m <sup>3</sup> .s <sup>-1</sup> )	Number of days > Qc	Recovery rate (%)	Number of same tracers between two successive surveys	Travel distance of the tracer cloud centroid (m)	Maximum downstream tracer position (m)	Standard deviation of tracer cloud (m)
Kembs I1	$P_{0bis}$	-	-	-	-	-	-	394	128
Kembs I1	$P_1$	1630	~Q <sub>3</sub>	25	42	625	194	791	165
Kembs I1	$P_2$	1842	~Q <sub>4</sub>	55	42	368	390	4166	674
Kembs I2	$P_{0bis}$	-	-	-	-	-	-	450	143
Kembs I2	$P_1$	1842	~Q <sub>4</sub>	54	33	501	138	2260	317
Interreg	$P_{0bis}$	-	-	-	-	-	-	604	189
Interreg	$P_1$	1080	<Q <sub>2</sub>	5	43	644	101	682	129
Interreg	$P_2$	1340	<Q <sub>2</sub>	20	12	111	232	1042	156
Interreg	$P_3$	1500	~Q <sub>2</sub>	24	11	48	302	1982	370
Interreg	$P_4$	2480	~Q <sub>15</sub>	29	15	39	1022	3677	611
Interreg	$P_5$	1842	~Q <sub>4</sub>	106	18	58	1034	12099	2487

492 Table 5 : Statistical parameters for each sediment tracking survey conducted on each GA. The Interreg results between  $P_1$  and  $P_4$  were provided

493 by Arnaud et al. (2017).



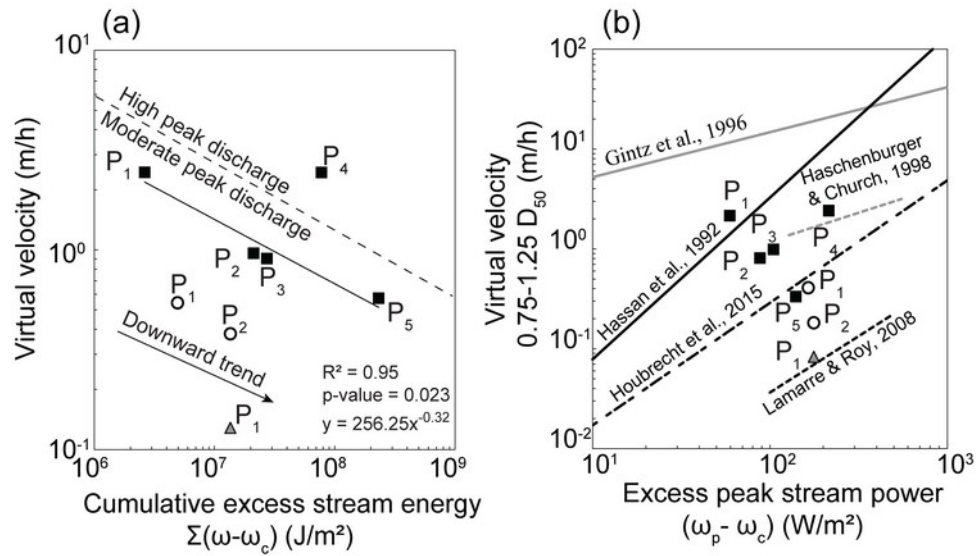
494

495 Figure 8: Probability density function of the longitudinal position of the tracers recovered for  
 496 each survey on the (a-f) Interreg, where gray columns locate riffles, (g-i) Kembs I1 and (j-k)  
 497 Kembs I2 downstream reaches.

498 The tracer cloud centroids travelled between 101 m and 390 m for moderate floods ( $Q_{ix} \leq$   
 499  $Q_4$ ) on the three GA reaches. During the highest flood in May 2013, the tracer cloud centroid



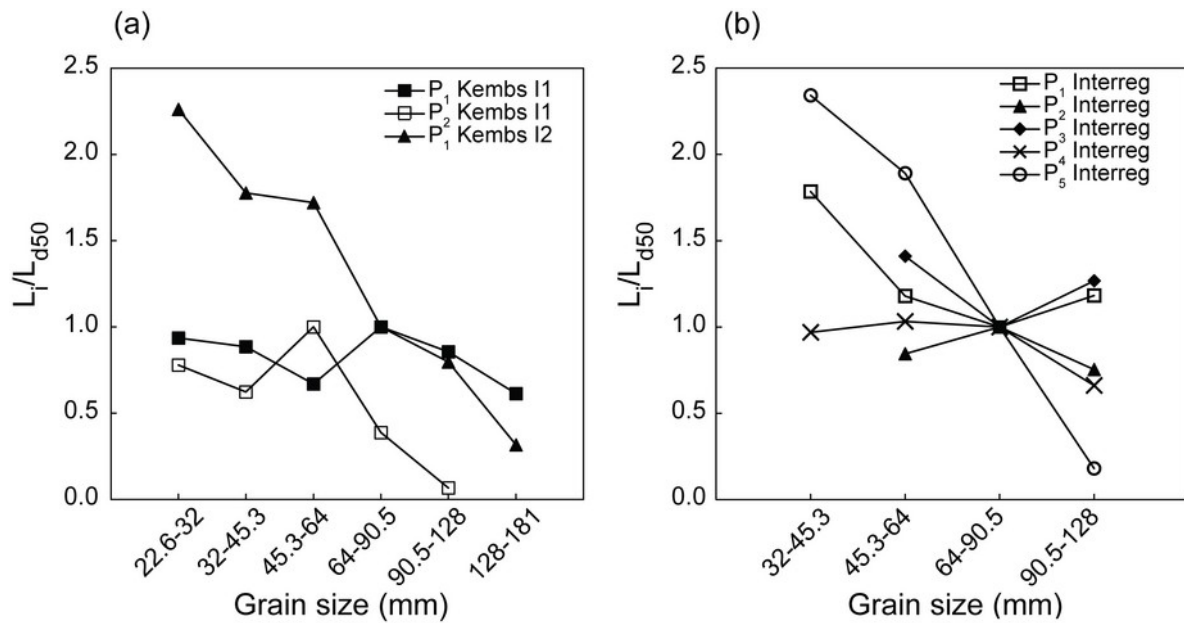
500 of the Interreg reach travelled up to 1022 m. The farthest travelling tracer was found 12099  
501 m downstream (Table 3). A statistically significant negative correlation (95% confidence  
502 level) following a power function was found between the virtual velocities and the  
503 cumulative excess stream energy on the Interreg reach ( $R^2 = 0.95$ ,  $p\text{-value} = 0.023$ ) (Figure  
504 9.a). We did not take into account  $P_4$  because the peak flow was significantly higher than  
505 that for the other periods ( $\sim Q_{15}$ ), inducing different bedload processes (Figure 9.a). The  
506 virtual velocity decreased over time (except for  $P_4$ ) with  $2.34 \text{ m}\cdot\text{h}^{-1}$ ,  $0.96 \text{ m}\cdot\text{h}^{-1}$ ,  $0.95 \text{ m}\cdot\text{h}^{-1}$ ,  
507  $2.44 \text{ m}\cdot\text{h}^{-1}$  and  $0.57 \text{ m}\cdot\text{h}^{-1}$  for  $P_1$ ,  $P_2$ ,  $P_3$ ,  $P_4$  and  $P_5$ , respectively. Inter-GA comparison  
508 showed that the virtual velocities were lower for Kembs I1 and Kembs I2 than for Interreg  
509 for a similar range of cumulative excess stream energy with  $0.54 \text{ m}\cdot\text{h}^{-1}$ ,  $0.38 \text{ m}\cdot\text{h}^{-1}$  and  $0.13$   
510  $\text{m}\cdot\text{h}^{-1}$  for the  $P_1$  of Kembs I1, the  $P_2$  of Kembs I1 and the  $P_1$  of Kembs I2, respectively.  
511 Comparison of our virtual velocity dataset with the literature suggests that our values are  
512 close to those of studies on riffle-pool rivers (Figure 9.b) (Gintz et al., 1996; Haschenburger  
513 and Church, 1998; Hassan et al., 1992; Houbrechts et al., 2015; Lamarre and Roy, 2008),  
514 except for Kembs I2, where the virtual velocity during  $P_1$  is the lowest, comparable to steep-  
515 pool streams. In our case, the decrease in the virtual velocities was inversely correlated with  
516 the excess flood energy.



517 ■ Interreg ○ Kembs I1 △ Kembs I2

518 Figure 9: (a) Virtual velocity of the tracer cloud centroids for each  $P_i$  according to the  
 519 cumulative excess stream energy and (b) virtual velocity of the tracer cloud centroids  
 520 composed of tracers whose grain size ranges between 0.75 and 1.25 of the channel bed  $D_{50}$   
 521 as a function of the excess unit stream power for each  $P_i$  (modified after Houbrechts et al.,  
 522 2015). The class 22.6-32 mm of Kembs I1 and Kembs I2 was excluded to make possible  
 523 comparisons with Interreg.

524 No relationship between the dimensionless travel distance of the tracer cloud centroid and  
 525 the grain size classes of recovered tracers was found for Kembs I1 during  $P_1$ , while a relation  
 526 was observed during  $P_2$ , indicating a partial mobility for this period (Figure 10). For Kembs  
 527 I2, a marked negative relationship is observed between the two variables during  $P_1$ , also  
 528 indicating selective sediment transport. For Interreg, no relationship was found between the  
 529 two variables up to  $P_4$ . Thereafter, a marked negative relationship was established during  $P_5$   
 530 , again showing selective transport.



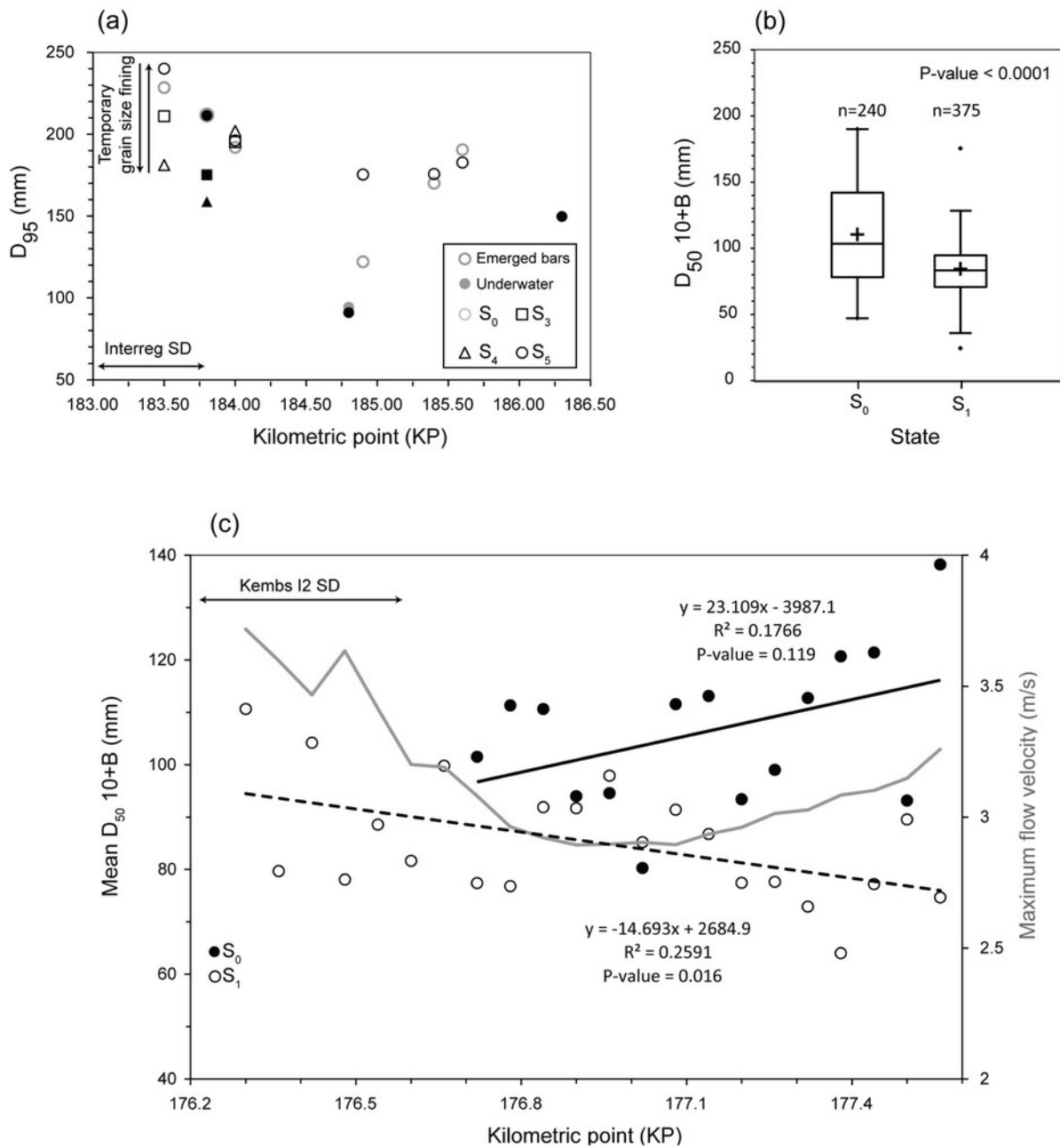
531

532 Figure 10: Mean dimensionless travel distance of the tracer cloud centroid for each grain size  
 533 class, (a) for Kembs I1 and Kembs I2 and (b) for Interreg. Tracer clouds composed of less than  
 534 10 particles were excluded from the analysis because they were considered not statistically  
 535 significant. For Kembs I1, only tracers recovered in the channel were included in the analysis.

### 536 3.2.2 Assessment of spatiotemporal grain size evolution

537 On a gravel bar sampled in the upstream part of the Interreg surveyed reach, the  $D_{95}$   
 538 decreased from  $S_0$  to  $S_3 - S_4$  (Figure 11.a). The grain size fining reached 36 mm between  $S_0$   
 539 and  $S_3$  and 53 mm between  $S_0$  and  $S_4$ . New coarsening appeared in  $S_5$  with grain size values  
 540 close to the  $S_0$  values. For Kembs I2, a statistically significant bed fining (95% confidence  
 541 interval) was observed (Kruskal-Wallis test, p-value < 0.0001) between  $S_0$  and  $S_1$ , with a  
 542 decrease in the mean  $D_{50}$  of the ten largest particle samples from 110 to 84 mm (Figure  
 543 11.b);. In  $S_0$ , a downstream grain size coarsening (from KP 176.3 to KP 177.5) was observed  
 544 and was probably related to the downstream increase in the flow velocities (Figure 11.c). In  
 545  $S_1$ , a statistically significant downstream bed fining (95% confidence level) was observed ( $R^2 =$   
 546 0.26; p-value < 0.016). The bed fining may be related to the partial mobility identified by the

547 bedload tracking surveys on the Kembs I1 surveyed reach during  $P_2$ , and the Kembs I2  
 548 surveyed reach during  $P_1$  (see Section 3.2.1).

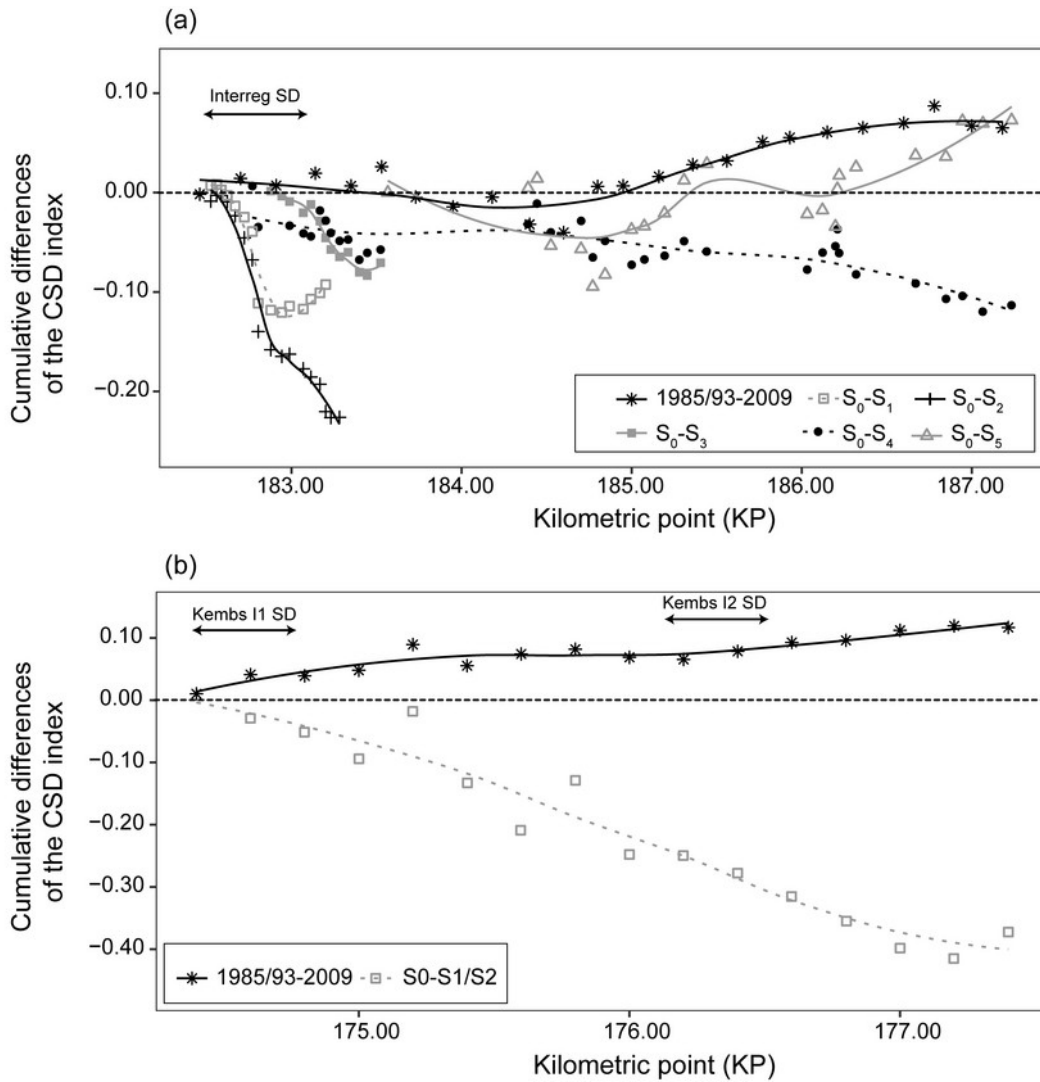


549  
 550 Figure 11: (a)  $D_{95}$  measured on each macroform and each survey along the Interreg restored  
 551 reach with filled and empty symbols indicating the underwater and emerged samplings,  
 552 respectively. (b) Boxplots of the  $D_{50}$  of the ten largest particles digitalized on each  
 553 underwater digital image close to and downstream of the Kembs I2 SD for  $S_0$  and  $S_1$  and (c)  
 554  $D_{50}$  of the ten largest particles digitalized on each underwater digital image for  $S_0$  and  $S_1$

555 close to and downstream of the Kembs I2 SD; the gray line indicates the maximum velocity  
556 for the peak flow during  $P_1$  for each grain size transect; the black line and black dashed line  
557 correspond to the linear regression lines of  $S_0$  and  $S_1$ , respectively.

### 558 3.2.3 Assessment of the spatiotemporal evolution of the channel diversity

559 Figure 12 shows the temporal and longitudinal evolution of the cumulative differences in the  
560 cross-section diversity index (CSD) between 1985/93-2009 and the successive monitoring  
561 surveys along the three restored reaches. The results show a negative downstream trend in  
562 the cumulative differences of the post-GA index along all the reaches, which is an inverse  
563 tendency by comparison with the 1985/93-2009 dataset. Moreover, the rates of changes  
564 were higher after GA compared with those in the historical dataset. The results for the  
565 Interreg reach show that the negative trend intensity decreased over time due to the  
566 sediment dispersion along the channel bed. Marked positive trends of the index were first  
567 observed in  $S_5$  (Figure 12.a), which seems to be correlated to the fragmentation of the  
568 bedload pulse (Figure 8.f).



569

570 Figure 12: Cumulative differences in the CSD between the initial state and the successive  
 571 surveys in the downstream direction (a) for the period 1985/93 - 2009 and  $S_0$  to  $S_5$  for the  
 572 Interreg restored reach and (b) for the period 1985/93 - 2009 and  $S_0$  to  $S_2$  for Kembs I1 and  
 573  $S_0$  to  $S_1$  for Kembs I2.

## 574 4. Discussion

### 575 4.1 Optimal stockpile deposit design

576 The topo-bathymetric monitoring showed that the erosion of the three SDs included two  
 577 processes closely interlocked: SD toe erosion and mass failure. This is consistent with

578 previous field and modeling studies on GA operations (Battisacco, 2016; Heckmann et al.,  
579 2017). Battisacco et al, (2016) and Vonwiller et al, (2018) showed that toe erosion is the  
580 predominant process, followed by the mass failure of the upper part of the SD. In our case,  
581 both processes occurred from a flow velocity of  $2.5 \text{ m.s}^{-1}$  (Figure 5.a), which caused full  
582 mobility of the introduced sediment (Figure 6). For flow velocities lower than this critical  
583 value, only a limited toe erosion was observed with a selective mobility of gravels, which  
584 generated a reduction in the erosion intensity and the establishment of a coarser layer on  
585 the residual SD, as observed in the upstream and downstream part of Kembs I1 (Figure 3.b).  
586 This coarser layer can significantly reduce the erosion of the residual SD during future flood  
587 events, as observed in studies conducted on sediment starved rivers (Rollet et al. 2013;  
588 Houbrechts et al. 2012), and explain the lower eroded volumes during  $P_2$  compared to  $P_1$ ,  
589 despite higher and longer flood events (Figure 2.a).

590 These results highlight the fact that SDs should be implemented/designed in suitable  
591 hydraulic areas to maximize the SD erosion probability for a  $Q_{1.2}$  flood, considering that  
592 entrainment must be performed for frequent floods to avoid any risk of vegetation  
593 encroachment and increase in phytostabilization. Based on the critical flow velocities (Figure  
594 5 and Figure 6), we determined the suitable areas for GA along the first 15 km of the studied  
595 reach (Figure 7). From this study, we estimate that the potentially suitable areas correspond  
596 to 53% of the study area. This approach is useful to plan further GAs in the Old Rhine, and it  
597 should be transferable to other rivers. Our results also show that SD implementation on bars  
598 is not suitable for a  $Q_2$  peak flow due to flow velocities lower than the critical value.

## 599 4.2 Bedload transport patterns

600 At a short term (1 to 3 years), our results show that the mode of sediment transfer varies  
601 among a translation pulse for Interreg and a combination of translation and dispersion for  
602 Kembs I1 and Kembs I2 (Figure 8). Such processes were also observed in both modeling (Koll  
603 et al., 2010; Sklar et al., 2009) and field studies on GA operations (Downs et al., 2016). The  
604 mode of sediment pulse depends on the grain size of the introduced sediment compared to  
605 the predisturbance in-channel grain size, sediment sorting and sediment volume (Lisle et al.,  
606 2001; Sklar et al., 2009; Sims et al., 2017). Dispersion occurs in high bed roughness contexts  
607 and when the input volumes exceed the bedload transport capacity (Lisle et al., 2001; Sims  
608 et al., 2017). At mid-term (~ 5 years), the mode of sediment pulse for the Interreg GA was  
609 non-random and fragmented (Gaeuman et al., 2017), driven by the bed morphology,  
610 particularly riffle-pool sequences (Sear, 1996) (Figure 8).

611 Virtual velocities show the same order of magnitude as those in other studies conducted on  
612 riffle-pool rivers for the same exceeding peak flow energy, which indicates that the GA  
613 sediment transport dynamics were equivalent to the sediment mobility in natural conditions.

614 A decrease in the virtual velocities occurred during the monitoring period despite the  
615 increase in the excess flow energy (Figure 9.a). This decreasing tendency of sediment  
616 mobility over time was observed in other field studies (Ferguson et al., 2002; Haschenburger,  
617 2011) and modeling works (Koll et al., 2010). This tendency is explained by a vertical mixing  
618 of gravels where tracers are progressively buried, which reduces their mobility (Ferguson et  
619 al. 2002). Sediment mobility can also be slowed by the bed roughness (Hassan et al., 1991)  
620 and the variability in the bed morphology (Pyrce and Ashmore, 2003; Sear, 1996). The  
621 relations between bedload mobility and hydrology are more complex because of numerous  
622 determinant parameters, such as peak flow intensity, hydrogram shape (duration and peak



623 number) and initial conditions, such as low flow duration preceding the flood event and  
624 sediment transport processes during the previous morphogenic flood (Humphries et al.,  
625 2012). Vázquez-Tarrío et al. (2018) showed on the Rhône River that a coarser armor layer is  
626 frequently located just below dams due to the propagation of sediment starvation  
627 conditions in the downstream direction. Rollet et al. (2013) observed on the Ain River that  
628 sediment tracers travel relatively slowly on sediment-starved reaches due to sediment  
629 trapping in the interstices of the armor layer. Thus, the differences in the sediment pulse  
630 patterns and the virtual velocities among the three GAs can be explained by both lower  
631 bedload transport capacities and higher bed roughness for Kembs I1 and I2 compared to  
632 Interreg. Overall, the results reinforce the conclusions of Arnaud et al. (2017) that no  
633 important sediment volumes travel rapidly downstream in the Old Rhine. Consequently,  
634 there is no risk of navigation perturbations downstream of the Breisach dam (Figure 1).

### 635 **4.3 Channel morphodynamic responses**

636 In the short term, a significant bed grain size fining was observed in the channel and on  
637 some emerged bars (Figure 11.a-b-c), while the topo-bathymetric results revealed a  
638 simplification of the channel bed geometry (Figure 12). These results are consistent with a  
639 modeling study conducted by Battisacco et al. (2016), which demonstrated that SDs having  
640 characteristics similar to ours produce sediment spreading along the restored reach, thus  
641 favoring bed grain size fining and a limitation in the bed incision tendency rather than  
642 increasing habitat heterogeneity. At mid-term, the grain size fining observed in the Interreg  
643 reach was temporary due to the downstream bedload transfer without any new supply. A  
644 relationship appeared between the dimensionless distances of the tracers and their grain  
645 size when the dispersion was advanced (Figure 10), indicating a partial mobility (Church and

646 Hassan, 1992). This may reveal the formation of a new armor layer due to new sediment  
647 starvation conditions explained by the lack of upstream sediment supply (Piégay et al.,  
648 2016). All results show that the positive geomorphic effects of the three GAs are transitory,  
649 with a duration of approximately 3-4 flood events depending on the remobilized sediment  
650 volumes, the flow velocities and the bedload transport processes (Sklar et al., 2009). An  
651 increase in the channel diversity downstream of the Interreg SD occurred due to a  
652 preferential sediment deposition on riffles (Figure 12) and explain notably by lower flow  
653 velocities and shear stresses than in pools during flood events (Sear, 1996). This result  
654 indicates that a diversified downstream channel morphology tends to enhance the positive  
655 morphological effects of GAs and should be taken into account, in addition to local flow  
656 conditions around the SDs, for designing GA operations.

657 The sediment wave fragmentation along the Interreg reach has been highlighted because  
658 the monitoring was conducted over a long period (7 years) and an important channel length  
659 (maximum of 12 km). Thus, monitoring must be performed on extended lengths (several  
660 kilometers) and over mid to long temporal scales to adequately evaluate the effects of GAs.  
661 We can hypothesize that a fragmentation of the sediment wave of both of the Kembs GAs  
662 will also occur more or less rapidly depending on flow conditions.

663 Our results showed that even if GA operations are repeated over time in the Old Rhine, it is  
664 unlikely that a sustainable diversification of aquatic habitats may be obtained due to the  
665 narrow and homogeneous channel geometry of the study reach. Channel widening by  
666 removal of bank protection, partial removal of groin fields and/or excavation of floodplain  
667 areas connected to the channel should be tested downstream of GAs so as to promote a  
668 reduction and a diversification of flow conditions, inducing the deposition of a part of the  
669 introduced sediments and potentially creating new fluvial forms, such as side channels and

670 bars colonizable by pioneer vegetation (Arnaud et al., 2017; Staentzel et al., 2018b).  
671 Sediment excavated from channel widening should be stored temporarily and introduced  
672 upstream with a rhythm depending on the hydrological regime. The success of this mode of  
673 sediment management has been demonstrated along the Mur River by Klösch (2011), which  
674 highlighted that channel widening locally decreased the bedload transport capacity of the  
675 river, favoring bedload deposition and, consequently, local bank erosion as a positive  
676 retroaction loop. However, the self-sustaining of geomorphic processes is strongly  
677 dependent on the upstream bedload supply (Klösch, 2011).  
678 In terms of risks, our results show that the evolution of channel topography at the mid-term  
679 is relatively low (Figure 12). Our results confirm the absence of risk of uncontrolled bed  
680 degradation, which was also noticed by Arnaud et al. (2017) over a shorter monitoring  
681 period for the Interreg GA. Furthermore, the hydrological functioning of the excavated areas  
682 in terms of flow retention may not be impacted either. In addition, no significant bank  
683 erosion was observed during the monitoring period.

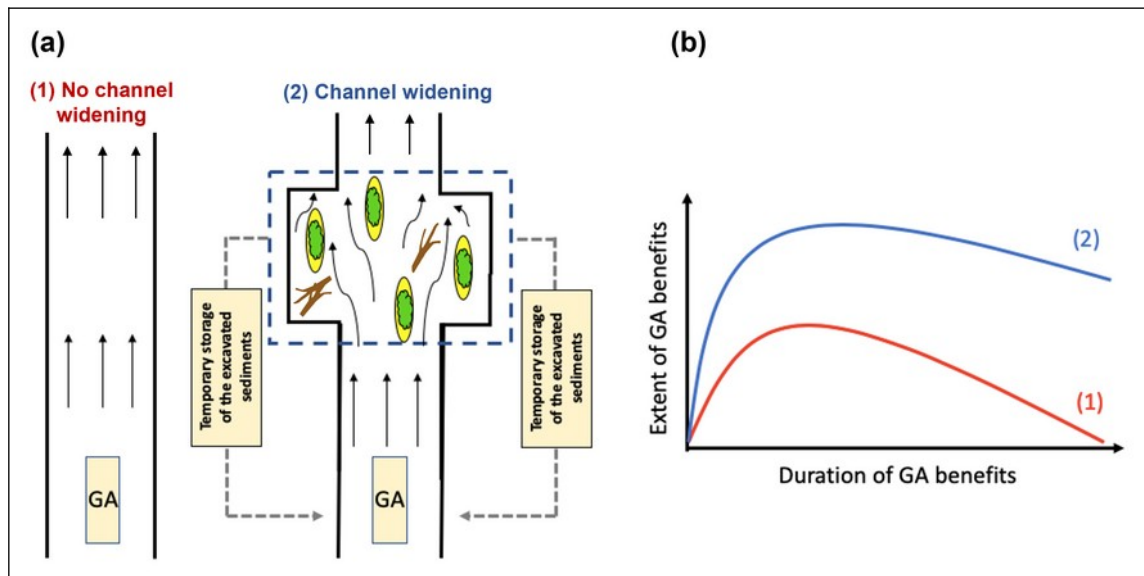
#### 684 **4.4 Recommendations and management scenario to improve the efficiency and** 685 **sustainability of GAs**

686 Following this study, several recommendations and management scenario can be addressed  
687 for improving the efficiency of GA operations and the sustainability of their effects at the  
688 scale of the SDs as well as the scale of the downstream reach:

- 689 1. perform hydraulic modeling to identify the most suitable areas for SD  
690 implementation;

- 691 2. on this basis, prioritize areas with high flow velocities during frequent floods to  
692 implement SDs to limit the risk of SD fixation accentuated by the development of the  
693 vegetation;
- 694 3. adapt the grain size of the GAs to the local flow competence to minimize the risk of  
695 the formation of a coarser layer at the top of the residual SD, which would decrease  
696 the SD erodibility;
- 697 4. implement SDs upstream of reaches showing the highest diversity of macroforms and  
698 flow conditions to favor a fragmentation of the sediment transport and thus  
699 maximize potential habitat diversification, notably by bed grain size fining.
- 700 5. Test channel widening downstream of GAs to lower flow conditions, and to induce  
701 sediment deposition (and a general slowdown of the sediment waves), the  
702 establishment of pioneer vegetation and the diversification of aquatic and riverine  
703 habitats (Arnaud et al. 2017), as bars and secondary channels (Figure 13.a). Sediment  
704 deposition may also induce local bar/bank erosion, provoking local bedload supply  
705 into the channel in a positive feedback loop. Widening areas should be performed  
706 ideally close to riffles to reinforce the sediment wave fragmentation by gravel  
707 deposition, extending spawning areas for salmonid fish species. Riffle aggradation  
708 and bar formation may also foster hyporheic water exfiltration areas, which are  
709 summer thermal refuges favoring the adaptation of aquatic ecosystems to climate  
710 change (Eschbach et al., 2017). Furthermore, habitat diversification may also limit the  
711 relative development of invasive species (Staentzel et al., 2018a) and raise the  
712 recreative value of the Old Rhine (Arnaud et al., 2017). The resulting excavated  
713 sediments should be stored temporarily close to the channel and introduced  
714 upstream iteratively (Figure 13.a.2). This management scenario would increase both

715 the extent and the durability of the GA benefits, in comparison with the management  
 716 scenario consisting only in GA (Figure 13.b).



717

718 Figure 13: (a) Restoration scenarios based on 1-GA only, 2-combination of GA with  
 719 downstream channel widening, (b) benefits of both scenarios in terms of spatial extent  
 720 and duration.

## 721 5. Conclusions

722 This study provides original feedback based on multi-compartment monitoring of three *in*  
 723 *situ* GAs conducted along the bypassed section of the Rhine River downstream of Kembs,  
 724 notably in terms of SD erodibility, sediment transport dynamics and channel responses. The  
 725 erosion of SDs is dependent on local flow velocities and also on the grain size of the  
 726 introduced sediment according to the local transport capacity. The Interreg GA was the best  
 727 GA design compared to the two others. More generally, 53% of the 15 km upstream of the  
 728 Old Rhine are suitable to implement GAs for flood flows or higher  $Q_2$ . Along the reaches  
 729 affected by the GAs in the short term, bathymetric simplification was observed due to the  
 730 transfer of sediments mostly along the thalweg and a transitory grain size fining. At mid-

731 term (~ 5 years), local habitat diversification was observed due to fragmentation of the  
732 sediment wave with preferential bedload deposition on riffles, which is a positive effect for  
733 fish spawning habitats. Our results also show that GAs induce no risk for human activities.  
734 This study highlights that to improve restoration efficiency and sustainability, GAs must be  
735 implemented in upstream reaches characterized by the highest hydromorphological  
736 diversity to increase positive effects. However, new sediment starvation conditions appeared  
737 > 5 years due to the lack of upstream sediment supply, showing that GAs must be repeated  
738 over time. To increase the efficiency of GA operations, channel widening should be  
739 performed downstream of the GAs to improve the sustainability of the GA effects. Sediment  
740 excavated from channel widenings should be stored temporarily and introduced upstream  
741 iteratively.

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